Lessons from the past

Historical landscape elements for passive outdoor microclimate control

Michiel Bakx
Msc Thesis Landscape Architecture
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Historical landscape elements for passive outdoor microclimate control in contemporary Dutch cities

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Abstract

The development of cities and their urban fabric has resulted in two distinctive phenomena that are problematic to thermal comfort: the urban heat island effect and urban wind nuisance. Since the urban heat island effect becomes more severe with climate change and more people start living in cities, it becomes ever more urgent to provide passive urban microclimate control measures. One way to come up with new measures for microclimate control is through studying precedents from the past. This is based on the belief that historical landscapes evolved from centuries of knowledge about dealing with climatic conditions.

In order to identify and describe historical landscape elements for microclimate control, this thesis starts with exploratory open-ended interviews, followed by in-depth historical literature and imagery review. From this, it appears that tree lanes, vertically shaped trees ("leilindes"), berceaux, hedges, shelterbelts, green walls, umbrella trees ("etagelindes") and weeping trees were in some cases purposefully developed for microclimate control. Then, through a scientific literature review the microclimatic performance of tree lanes, green walls, hedges and shelterbelts is identified. As there is no scientific literature on the microclimatic effects of vertically shaped trees, berceaux, umbrella trees and weeping trees, the software ENVI-met is used to simulate their microclimatic effects. The simulations indicated that all historical landscape elements for microclimate control have the potential to improve thermal comfort.

Finally, new prototypes of the earlier identified historical and often non-urban landscape elements are developed that fit contemporary Dutch shopping streets. This is done by adjusting the landscape elements for test beds that are representative of the shopping streets of the three largest Dutch cities. First, the historical landscape elements are adjusted to reduce heat stress. These prototypes are evaluated and the prototypes that score highest on heat stress reduction are adjusted to reduce cold stress as well. Eventually, the most efficient prototypes are implemented in two real streets. By means of this research through design process, it becomes clear which landscape elements are able to significantly improve thermal comfort in shopping streets and how they have to be adjusted to this context.

Keywords: *thermal comfort, urban microclimate; passive microclimate control, historical landscape elements, green landscape elements, ENVI-met, design prototypes, shopping streets*

II

Preface

This thesis is written as part of the master track landscape architecture at Wageningen University. With my thesis I aspire to provide new insights into urban microclimate control. I am drawn towards this topic as the urban microclimate is an important aspect of outdoor public space quality that is largely affected by urban design. For that reason, I believe it is the responsibility of landscape designers, amongst other disciplines, to create thermally comfortable public spaces.

In my aim to contribute to this responsibility, I have written my MSc thesis with great pleasure. During my thesis I achieved novel skills in researching historical landscapes and designing for the urban microclimate. I could not have achieved this without the great help from others. First of all, I would like to thank my interviewees, Hans Renes, Jelle Vervloet, Reinout Rutte, Oscar Borsen and Kees van Dam for providing me with a great start of my thesis. Then, I want to give special thanks to Bert Heusinkveld for helping me with completing the microclimate simulations in ENVI-met.

Next to that, I am very grateful for the help from my supervisor Sanda Lenzholzer, who helped me to make important decisions throughout my thesis. I am also very thankful for the organisation of the Climatelier sessions, in which I could receive feedback from João Cortesão and fellow students with a special interest in the urban microclimate. Last but not least, I want to thank my family and friends for their endless support and patience.

With my thesis I hope to inspire and challenge others to take their responsibility for the urban microclimate and thereby create aesthetically appealing and thermally comfortable public spaces.

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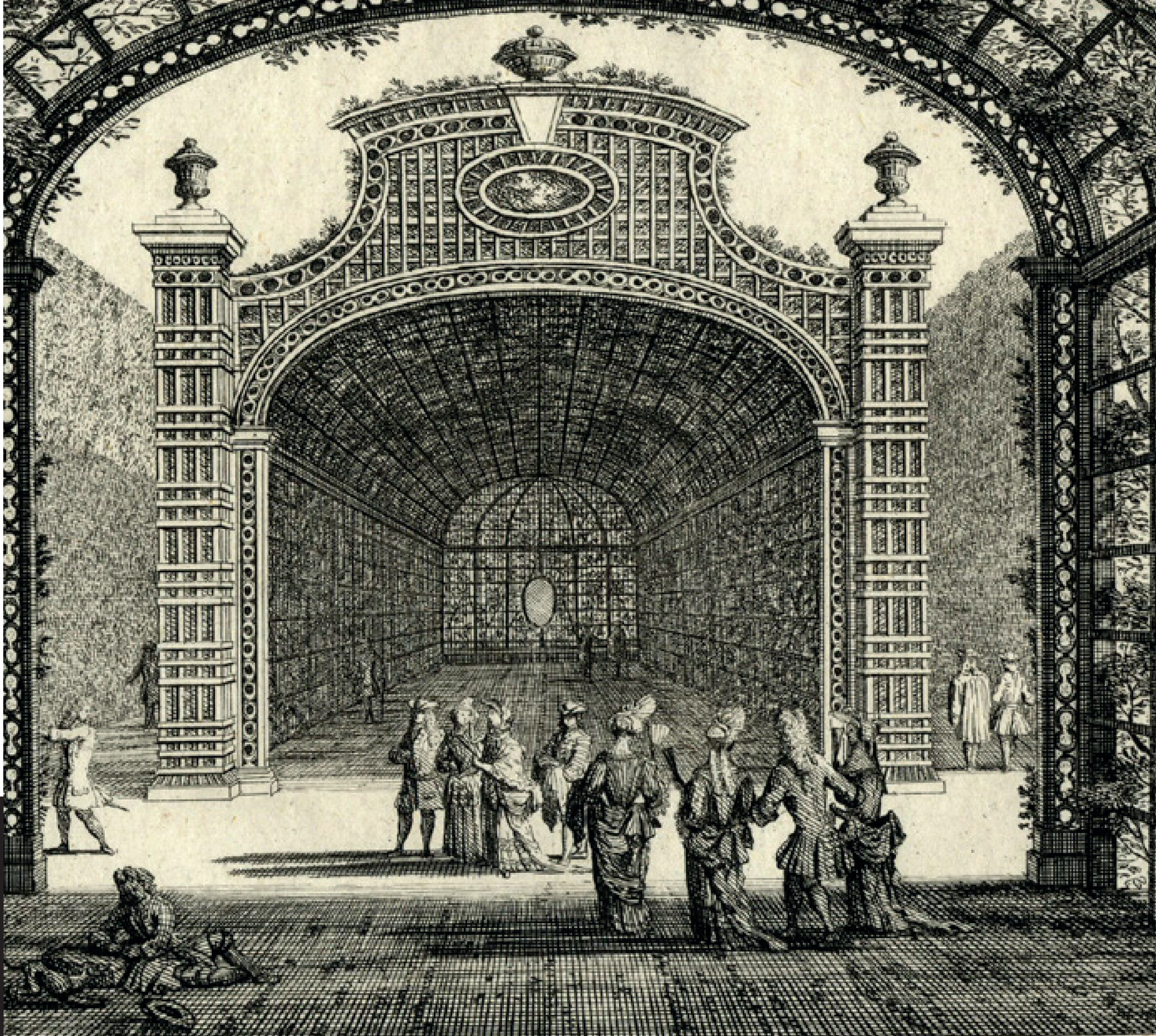

Figure I
Berceaux at estate Heemstede, in Houten (Moucheron, 1695-1700)

Chapter 1

Introduction

1.1 Introduction

Urbanisation

It is predicted that the number of people living in cities will increase globally from 55% to 68% until 2050 (United Nations, 2018). Not only globally, but also nationally it is expected that the four biggest Dutch cities (figure 1.1.1) and most mid-sized Dutch cities will continue to grow (CBS, 2016). Therefore, the need to control the urban (micro-) climate increases.

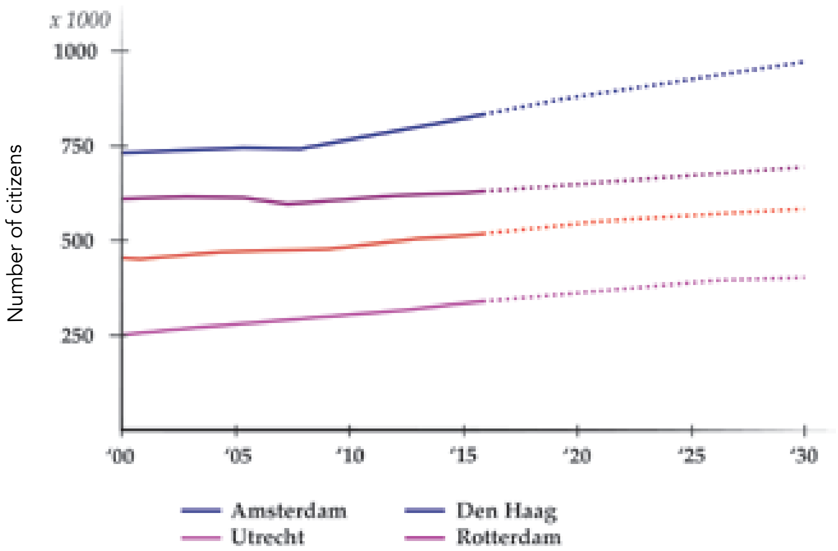

Figure 1.1.1 Urban growth of the four biggest Dutch cities (after Kooiman, et al., 2016)

Urban microclimate

The urban microclimate is different from the rural microclimate, which mainly manifests itself in two distinct phenomena. First of all, urban air temperatures are generally higher than their surrounding rural air temperatures (Oke, et al., 2017). This phenomenon is called the urban heat island (UHI) effect and was already observed by Luke Howard for the city of London in 1833 (Oke, et al., 2017). Secondly, while large scale wind patterns are not influenced much by the often-flat Dutch countryside, they are radically modified above urban surfaces due to their high surface roughness. This higher roughness is the result of buildings, that act as impermeable obstacles that force all wind to flow around them. As a result, a lot of turbulence can be caused around buildings, resulting in locally very high wind speeds.

Both the urban heat island and wind nuisance affect thermal comfort and thereby the amount of time people spent in outdoor public spaces such as parks, squares, and streets (Kleerekoper, et al., 2012). For that reason, thermal comfort is a critically important indicator for outdoor space quality (Ghasemi, et al., 2015). Besides that, the urban microclimate is also important through its effects on safety (Szűcs, 2013), buildings' energy consumption (through heating and ventilation; McPherson, 1994) and potential health effects on vulnerable people (e.g. dehydration, kidney failure, exhaustion, heat cramps and heat rash; Lenzholzer, 2015), On top of that, it is estimated that the heat wave in the Netherlands in 2003 caused between 1400-2200 deaths (Albers, et al., 2015).

Climate change
The urban microclimate will change due to the effects of climate change. For the Netherlands, the KNMI (2015) developed four different climate scenarios. These scenarios are the result of the combination of two parameters: a moderate (G) or high rise in temperature (W) and a low (L) or high (H) change in air flow patterns. All scenarios indicate that the average air temperature will rise (figure 1.1.2). In the worst-case scenario the number of hot days with a minimum temperature of 25 °C are expected to triple by 2050 (KNMI, 2015). Consequently, the urban heat load and its afore-mentioned effects on the human population are expected to be exacerbated by climate change.

Microclimate control
In the light of urbanisation and climate change, policy makers increasingly recognise the need to improve the urban microclimate. So far, multiple climate adaptation strategies have been developed and applied. Yet, some of these measures consume excessive amounts of energy. Examples of such measures include evaporative cooling systems (Montazeri, et al, 2015) and pedestrian ventilation systems (Mirzaei, & Haghighat, 2010). While these measures consume energy, they emit greenhouse gasses and thereby even contribute to climate change (figure 1.1.3). In order avoid this, it is essential to apply energy passive microclimate control measures.

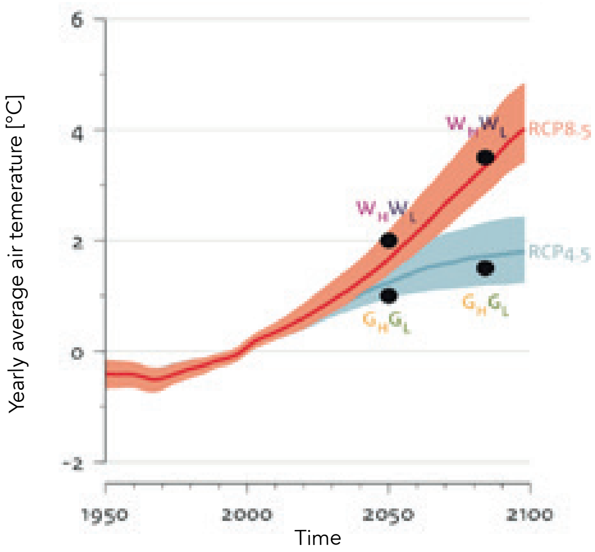

Figure 1.1.2 Climate change scenarios (KNMI, 2015)

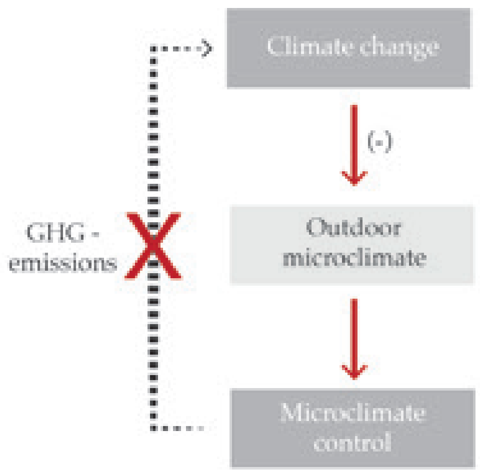

Figure 1.1.3 Relationship microclimate control and climate change

1.2 Problem statement

Historical green landscape elements
Historical landscapes were shaped by the people who lived and worked within it and were the result of pragmatic adaptation to local circumstances. In relation to the microclimate, the landscape evolved from centuries of knowledge about dealing with the exposure of climatic conditions (Chandel, et al, 2016).

Next to that, as historical landscape elements for microclimate control were built before the large-scale abstraction of fossil fuels, they effectively used energy in a passive way. In other words, historical landscape elements for microclimate control were limited by energy available from direct sunlight, wind and running water (Hough, 1984). Therefore, studying historical landscape elements for outdoor microclimate control will help to broaden the scope of passive low energy microclimate control measures for the future.

1.3 Knowledge gap

Between 1996 and 2011, 175 studies have been published that examine what can be learned from the sustainable character of historical architecture (Vellinga, 2013). In relation to climate control specifically, numerous articles have been published on what can be learned from passive warming and cooling systems of vernacular buildings (Dili, et al, 2010; Zhai, & Previtali, 2010; Desogus, et al, 2016).

Yet, in the field of landscape architecture, only one non-scientific book (Sullivan, & Treib, 2002) and two scientific studies (Attia, 2006; Hagen, 2011) have been published on the performance of historical landscape elements for outdoor microclimate control. While these studies focused on arid or warm climates no research has been published on these historical landscape elements for temperate climate zones (Köppen classification 'Cfb'). Nevertheless, many landscape elements that seemed to have a role in outdoor microclimate control exist(ed) for temperate climate zones: pruned trees, shelterbelts, tree lanes, vegetated walls and many others.

Hence, exploratory research into historical landscape elements for outdoor microclimate control will contribute to new knowledge and adapting these landscape elements to fit contemporary cities will broaden the scope of much desired passive microclimate control measures.

1.4 Research questions

This research aims to create new versions of historical landscape elements for microclimate control in cities. It focusses on the microclimate of street canyons in specific, as these are the most common type of urban outdoor space.

First, this research aims to identify historical landscape elements for microclimate control in temperate climate zones. Next, the performance of these landscape elements on the microclimate is assessed. Finally, these landscape elements will be implemented and adjusted to testbeds in order to adapt them to enhance thermal comfort in the context of contemporary Dutch streets.

Therefore, the general research question of this study is:

Which historical landscape elements for microclimate control could be adjusted in favour of thermal comfort in contemporary Dutch urban streets?

This research question will be answered through addressing the following three sub-research questions:

SRQ 1: What are historical landscape elements for microclimate control in the Netherlands?

SRQ 2: How do these historical landscape elements perform on microclimate control?

SRQ 3: How to implement these historical landscape elements in favour of thermal comfort in contemporary Dutch urban streets?

1.5 Research design

To answer the first sub-research question, open in-depth interviews with Dutch experts in historical geography, garden history and history of urban planning are conducted. The suggestions following from these interviews are researched through studying both written and visual data (maps, paintings, drawings).

The second sub-research question is answered through studying scientific literature that describes the microclimatic performance of the previously identified landscape elements. For the landscape elements whose climatic effects were not described in scientific literature yet, ENVI-met is used to examine their microclimatic effects. ENVI-met is a three-dimensional model that simulates the urban microclimate, based on vegetation-surface-air interactions.

The final sub-research question is answered through testing the fitness of new versions of historical landscape elements for contemporary streets. First relevant test beds were identified, which are generalised abstractions of existing streets for which the landscape elements are refitted. In the first design phase, the landscape elements were adjusted to reduce heat stress and in the second design phase landscape elements were altered to reduce cold stress as well. Finally, the landscape elements that scored highest on both cold and heat stress reduction were selected and virtually implemented in real streets.

A graphic overview of the research design is presented is represented in figure 1.5.1. A more extensive description of the methodology used to answer each research question is given at the beginning of chapter 3,4, 5 and 6.

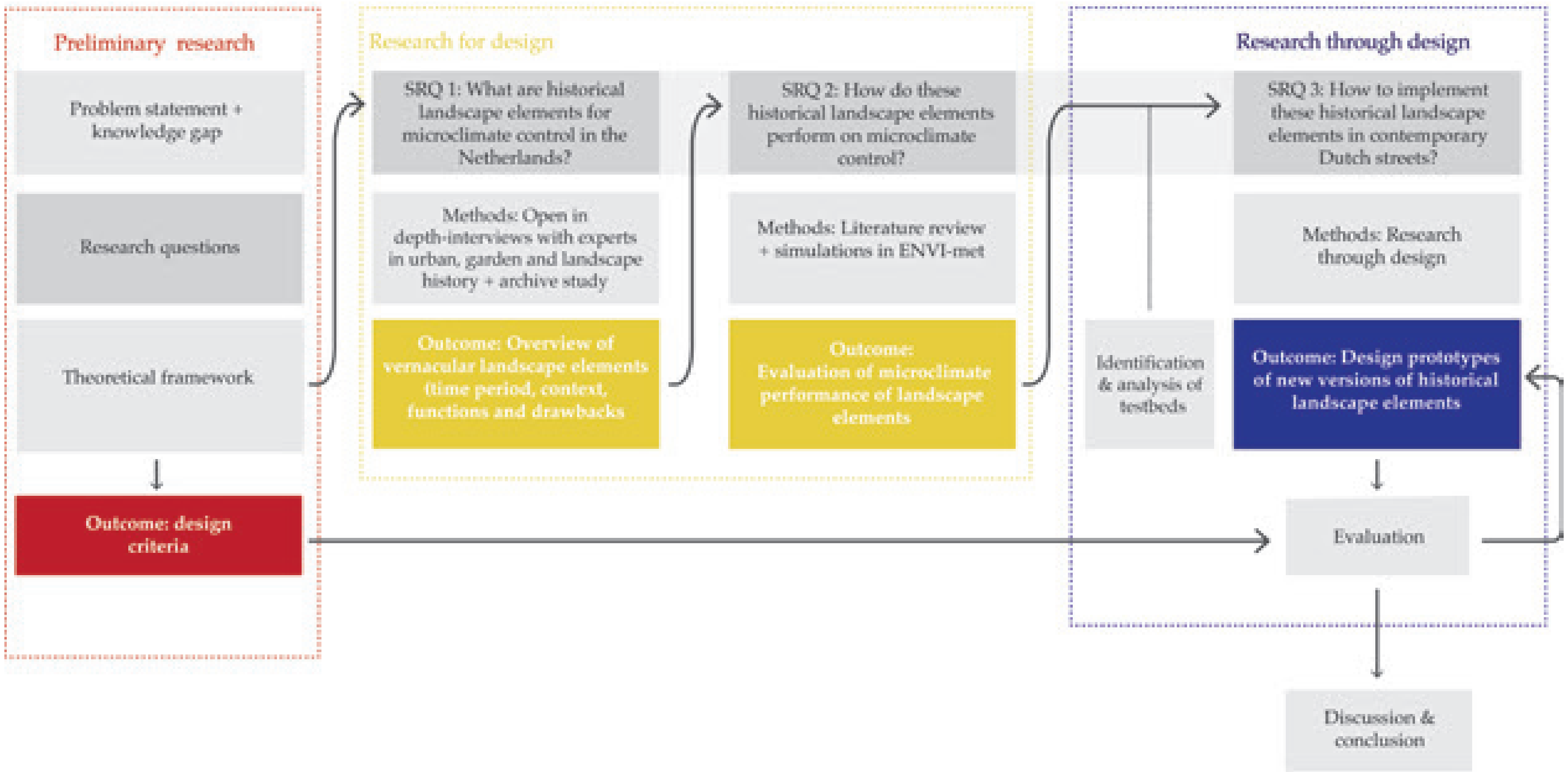

Figure 1.5.1 Overview research methods

Figure II
Berceau at
'slot Zeist'
Stoopendaal (1670-
1680)

Chapter 2

Theoretical framework

2.1 Introduction

The theoretical framework explains the two most important concepts of this research. First it explains thermal comfort and its relationship with the urban microclimate. Next, it describes historical landscape elements and their ability to influence the urban microclimate in favour of thermal comfort.

2.2 Thermal comfort

As stated before, thermal comfort is one of the most important indicators of outdoor public space quality (Ghasemi, et al., 2015). Thermal comfort can be defined as "the condition of mind that expresses satisfaction with the thermal environment (Höppe, 2002)." It is associated with three kind of factors: personal, psychological and climatological (figure 2.2.1). The personal factors that influence thermal comfort include age, gender, thermal history, metabolism, activity, climate habituation and clothing (Lenzholzer, 2015). Apart from activity level, these personal factors cannot be influenced with landscape or urban design interventions and are therefore not taken further into account in this thesis.

Besides these personal factors, several psychological factors influence thermal comfort. For example, Nikolopoulou and Steemers (2003) found that naturalness, expectations, experience (short-/long-term), time of exposure, perceived control and environmental stimulation contribute to thermal comfort. In line with this, more studies found that green areas are perceived as more thermally comfortable (Klemm, et al., 2014). While some of these aspects can be influenced by small-scale design interventions, it is difficult to quantify and evaluate the effects of these design interventions on thermal comfort.

Figure 2.2.1 Factors influencing thermal comfort

Finally, the climatological factors that influence thermal comfort include wind speed, air temperature, relative humidity and mean radiant temperature (figure 2.2.2). Mean radiant temperature is the combination of shortwave radiation, which is emitted by the sun, and longwave radiation, which is emitted by urban materials. This thesis focusses on these climatological aspects as they can both be influenced by small-scale design interventions, either directly or indirectly, and are quantifiable (Lenzholzer, 2015).

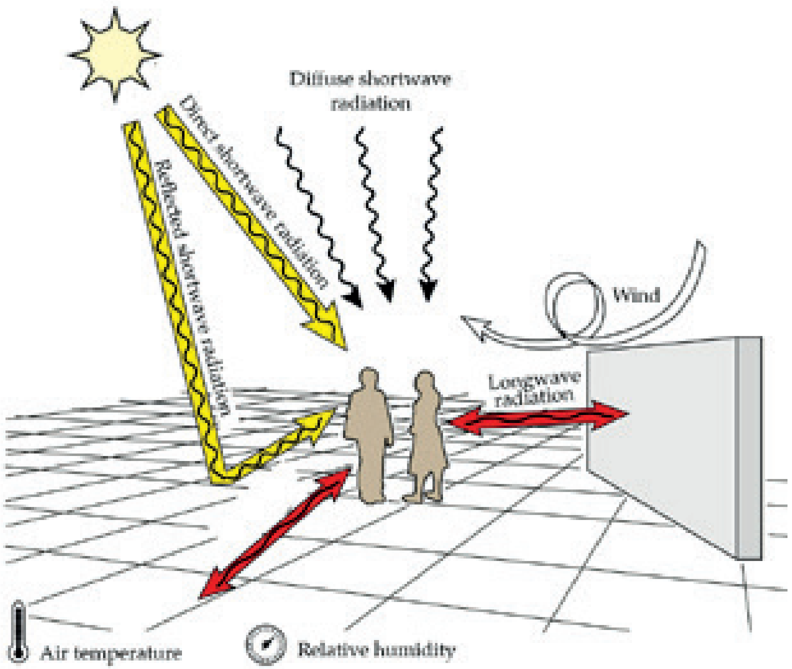

Figure 2.2.2 Climatological influence on thermal comfort (Lenzholzer, 2015)

One way to quantify the climatological factors in relation to thermal comfort is through the human energy balance. The human energy balance is calculated as the difference between the incoming and outgoing energy fluxes of the human body. If the energy balance is close to zero, the body is well able to keep a constant body temperature and no thermal stress is experienced. In order to establish a correlation between the energy balance and thermal comfort, Fanger (1972) exposed a panel of 1565 people to controlled climatological conditions and asked them to express thermal comfort on a scale ranging from +3 (very hot) to -3 (very cold). This resulted in the development of the Pedicted Mean Vote (PMV) index (figure 2.2.3)

PMV	Physiological stress level	Physiological responses
-3.5	Extreme cold stress	Decrease in core temperature and shivering.
-2.5	Strong cold stress	Vasoconstriction, core to skin temperature gradient increases.
-1.5	Slight cold stress	Localized cooling, need for gloves.
-0,5/0.5	No thermal stress	Comfortable, sweat rate < 100 g/h.
1.5	Slight heat stress	Positive change in rate of sweating, and skin temperature.
2.5	Strong heat stress	Sweat rate > 200g/h.
3.5	Extreme heat stress	Increase in core temperature, maximum sweat rate (>650 g/h)

Figure 2.2.3 Description of PMV in relation to physiological stress levels and responses (Taleghani, et al., 2015).

2.3 Urban microclimate

Due to the focus on the climatological aspects of thermal comfort in this thesis, it is important to understand the two distinct urban microclimate phenomena as defined in the introduction. For that reason, the urban heat island and urban wind nuisance are discussed in detail in this paragraph.

2.3.1 Urban heat island

As mentioned before, the temperature difference between urban and rural areas is called the urban heat island (UHI). The urban heat island is caused by five main factors (Albers, et al., 2015; Kleerekoper, et al, 2012; Lenzholzer, 2015). These are illustrated in figure 2.3.1 and include an increased amount of surface that receives shortwave radiation (1), increased heat storage and release of urban materials (2), reduced ventilation (3), reduced evaporation through lack of vegetation and soil sealing (5), and anthropogenic heat emissions (5).

Seasonal variation

The UHI-effect follows a seasonal cycle that is strongly related to the yearly changing solar path (Oke, et al., 2017). In summer the sun is positioned much higher and its path is much longer. This results in shorter shadow patterns compared to those in other seasons. At June 21st the sun reaches its highest point and has its longest path, casting the least amount of shadow and resulting in the greatest number of irradiance hours. So, for a sunny 21st June, the effect of shortwave radiation on the urban heat island will be most severe (Lenzholzer, 2015).

Besides that, the seasonal variation of the UHI is also related to the seasonal variation in wind speed and cloud cover. Wind influences the UHI effect as it contributes to atmospheric mixing and thereby brings in cooler rural air into the street canyon and reduces the UHI-effect (Oke, et al., 2017). Finally, cloud cover is related to the UHI as clouds absorb long- and shortwave radiation (Oke, et al., 2017). On cloudy days, less shortwave radiation is expected to reach the urban canopy layer and the UHI-effect will be less severe. In summary, the UHI effect occurs most strongly for days with low wind speeds and clear skies.

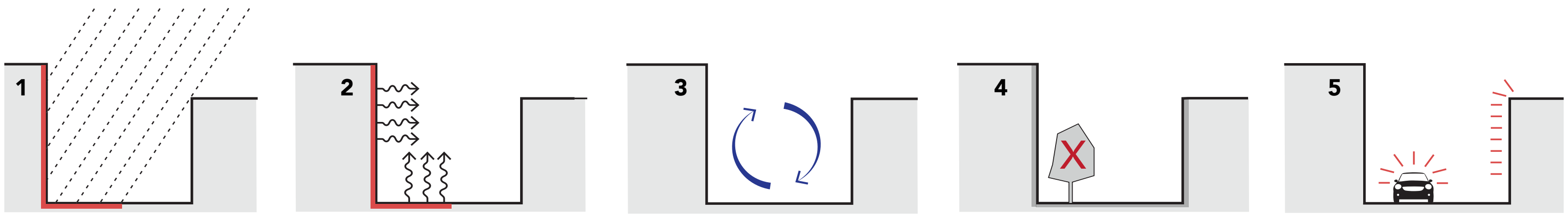

Figure 2.3.1 Causes of urban heat island effect: increased amount of surface receiveing shortwave radiation (1), heat storage and release of urban materials (2), reduced ventilation (3), reduced evaporation (4) and anthropogenic heat emissions (5). (Based on Kleerekoper, 2016).

Spatial variation
Apart from its seasonal variation, the UHI also varies spatially. This can be explained by the relationship of the UHI with the urban surface cover (figure 2.3.1; causes 2 & 3) and urban structure (figure 2.3.1; causes 1 & 4) . In other words, the UHI-effect is worst in high density urban areas with a significant amount of paved surface.

2.3.2 Wind nuisance

While large-scale wind patterns generally have a horizontal direction above the Dutch flat countryside, their direction becomes immensely diverse in urban areas. This is due to the presence of buildings, that act as impermeable and inflexible obstacles, forcing all wind to flow around them (Oke, et al., 2017). In the next part of this paragraph, simplified wind patterns for freestanding buildings and typical street canyons are explained.

Freestanding buildings
Freestanding buildings generally influence perpendicular winds as shown by figure 2.3.2. In front of the wind ward walls air pressure increases due to the compression of wind. Air pressure reaches its maximum at two third of the building height above the centre of the wind facing wall, from where it diverges vertically and horizontally over and around the building (Oke, et al., 2017). The compression of air around the building causes corner streams with higher wind speeds. Then, behind the building there is a wake zone with decreased wind speeds. Located within this wake zone lies the cavity zone, which has restricted air exchange outside this zone (Oke, et al., 2017).

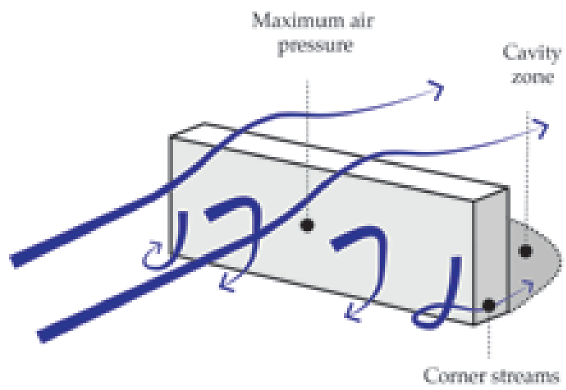

Figure 2.3.2 Air flow around individual buildings (Based on Lenzholzer, 2015)

As a rule of thumb, the dimensions of the cavity zone are defined by those of the building. For cubic buildings the cavity zone generally reaches up to 2 to 3 times the height of the building from the leeward facing wall (Oke, et al., 2017). Next to that, the length of the cavity zone is also influenced by the building depth: if the building depth increases, the length of the cavity zone decreases (Lenzholzer, 2015). Consequently, for buildings with a small H/L ratio, the cavity zone can grow to about 12 times the building height (Oke, et al., 2017).

Finally, for buildings with heights exceeding 20 metres, additional phenomena occur: more wind is deflected downwards, called downwash, and additional corner streams will develop (Lenzholzer, 2015). This can cause dangerously high wind speeds at pedestrian level.

Street canyons

If buildings are part of a street canyon, different wind patterns occur depending on the height and width of the street canyon and the wind direction relative to the street canyon.

Height and width (H/W ratio)

If streets are relatively narrow and have a H/W ratio above 0.7, a skimming flow will occur (figure 2.3.3a). In these streets the main wind does not interfere with the street canyon. As a result, these street canyons are rather sheltered (Lenzholzer, 2015). When the street is more wide (H/W ratio between 0.3 and 0.7), winds do enter the street canyon (figure 2.3.3b), but wind speeds remain limited (Lenzholzer, 2015). Finally, for widely spaced street canyons (with H/W below 0.35) wind patterns look similar to those of wind patterns along freestanding buildings (figure 2.3.3c). While the width of the street exceeds twice the height of the building, wind will almost regain its original speed. In this type of streets most wind nuisance is experienced (Oke, et al., 2017)

Wind direction

Wind patterns within the street canyon are the result of the original wind direction relative to the street canyon. The three situations explained previously only occur for perpendicular wind directions. For wind directions that run parallel to the street canyon, a channelling effect will occur and for wind directions with an intermediate angle towards the street canyon, a helical vortex will occur (figure 2.3.4; Oke, et al., 2017).

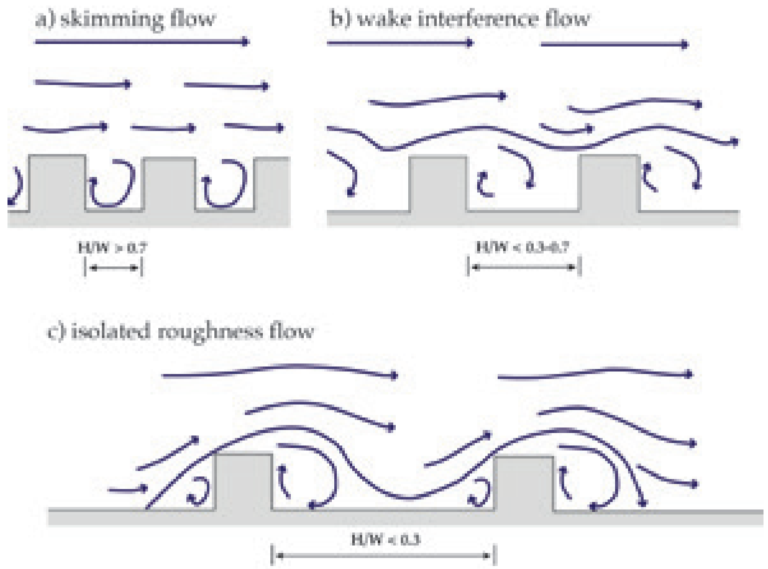

Figure 2.3.3 Air flow in street canyons for different H/W ratios. (Based on Oke, 1988)

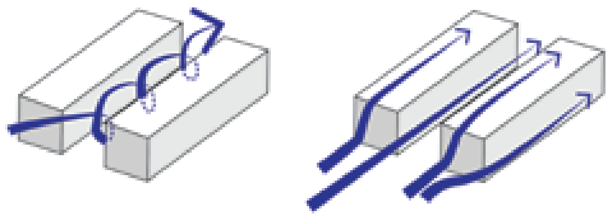

Figure 2.3.4 Influence of wind direction on air flow. (Based on Oke, et al., 2017).

2.4 Microclimate control

Under certain climatological circumstances the aforementioned UHI-effect and urban wind nuisance will exacerbate thermal discomfort. For that reason, microclimate control measures should be taken to enhance thermal comfort. This can be achieved through controlling the most important climatological factors that determine thermal comfort, which include mean radiant temperature (short- and longwave radiation), wind speed, air temperature and relative humidity (figure 2.2.2).

1. Shading/solar allowance
Shortwave radiation affects thermal comfort both directly and indirectly. While a part of the incoming shortwave radiation reaches the skin and directly influences the physiological energy balance, most shortwave radiation reaches urban materials and is stored as heat (Oke, et al., 2017). Then, as a result of the temperature difference between these heated urban surfaces and the ambient air, heat is exchanged from the urban surfaces to the air. This leads to increased air temperatures that affect thermal comfort as well. Due to this relationship between shortwave radiation exposure and thermal comfort, heat stress can be minimised by reducing the amount of incoming shortwave radiation and cold stress can be minimised by allowing maximum solar exposure.

The influence of green landscape elements on shortwave radiation depends on their leaf area index (LAI) and shape (Smithers, et al., 2018). The LAI is species dependent and describes foliage density (Chen, & Black, 1992). The LAI determines the shading intensity, varying from deep shade for trees with high LAI values to dappled shade for trees with low LAI values. Then, the shape of the green landscape elements directly determines its shading pattern. Compared to evergreen trees, deciduous trees better allow shortwave radiation in seasons when cold stress is most severe.

While shading directly reduces shortwave radiation - which is the most significant climatological factor determining thermal comfort (Lenzholzer, 2015; Taleghani, et al., 2015) - and it indirectly reduces air temperature, shading/solar allowance most significantly influences thermal comfort.

2. Ventilation/wind blocking
Wind influences thermal comfort through the uptake of transpiratory moist from the body and through convective cooling (Lenzholzer, 2015). Depending on the climatological context, wind can both be beneficial and detrimental to thermal comfort. On cold days, green landscape elements can improve thermal comfort through channeling wind away from pedestrian levels. However, on days with air temperatures above 21°C wind improves thermal comfort (Kleerekoper, 2016). The ability of green landscape elements to influence wind speed depends on their porosity, which influences the length of the wake zone and the maximum wind speed reduction (Cornelis, & Gabriels, 2005). Similarly to buldings, the height and width of the landscape element also influences the size of the wake zone (see section 2.3.2). Due to the relative importance of wind speed on thermal comfort (Cocolo, et al., 2017) and the ability of landscape elements to directly influence wind speed, ventilation and wind blocking are considered the second most significant aspect in relation to thermal comfort.

3. Longwave radiation trapping/allowance

Urban materials cool down through emitting longwave radiation (Oke, et al., 2017). The cooling rate of urban materials is dependent on the sky view factor, defined as the relative amount of sky that can be viewed from a certain point in the city (Svensson, 2004). If green landscape elements reduce the sky view factor through obstructing the sky, longwave radiation will be trapped. While this has a negative effect on heat stress, it will reduce cold stress. Both the LAI and crown width of the landscape element determine the amount of longwave radiation trapping. However, longwave radiation cooling especially manifests itself after sunset (Oke, et al., 2016), when not many people use public space. Next to that, longwave radiation contains less energy than shortwave radiation (North Carolina Climate Office, 2012). Therefore this aspect influences thermal comfort less significantly.

4. Evaporative cooling potential

Green landscape elements can help to cool the ambient air temperature through the process of evapotranspiration, which converts sensible heat into latent heat (Moss, et al., 2019). However, the evaporative cooling potential of green landscape elements is species dependent and related to the LAI, transpiration rate and crown volume (Stratópoulos, et al., 2018; Moss, et al., 2019). Besides that, the cooling potential of vegetation is also related to environmental factors. Amongst these factors, water availability is the most critical factor. As heat waves are often related to periods of ground water deficit (Shashua-Bar, et al., 2011), it is important to select drought resistant species. To indicate the relative importance of evaporative cooling, Shashua-Bar and Hoffman (2000) found that shading accounted for 80% of air temperature reduction underneath a tree canopy, while evaporation only accounted for the remaining 20%. While evaporative cooling accounts for a small amount of reduction in air temperature, it influences thermal comfort less significantly.

Summary

In summary, landscape elements can reduce heat stress through shading and evaporation. In doing so, these landscape elements should not obstruct ventilation and longwave radiation (figure 2.4.1). In autumn landscape elements can reduce cold stress through blocking wind and trapping longwave radiation. In blocking wind and trapping longwave radiation, it is important that these landscape elements do allow maximum solar radiation (figure 2.4.2).

Figure 2.4.1 Influence of landscape elements on heat stress

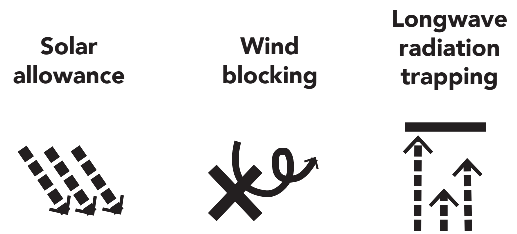

Figure 2.4.2 Influence of landscape elements on cold stress

2.5 Historical landscape elements

First, in order to explain what is meant with historical landscape elements, it is necessary to define the word landscape. The original word for landscape - landschap - consists of two words; 'land' and 'schap'. 'Land' means a demarcated area or plot of land. 'Schap' translates to the noun shape and denotes that the land is shaped by man. In other words, society shaped the environment in favour of its existential, economic, social, cultural and mental needs by means of available knowledge, technologies and resources (Bastian, et al., 2013).

Each landscape consists of landscape elements. Landscape elements are defined as the building blocks that determine the visual structure of the landscape. Next to that, landscape elements can be interpreted as documents of the cultural and economic life of former human generations in the landscape (Bastian, et al., 2013). In this thesis historical landscape elements are defined as elements that existed before 1900. From then on, the invention of heating, ventilation and cooling technologies led to the neglect of landscape elements for energy passive microclimate control.

As landscape elements are always the combined result of their environmental and socio-cultural context, they cannot be studied separate from their context (Bastian, et al., 2013). Furthermore, landscape elements often provided multiple functions at the same time. For example, a hedge could have been planted to demarcate boundaries, but also as barrier to wind, sight, cattle and intruders. As some of these functions might still be relevant in contemporary cities, it is important to describe the multifunctionality of the hisotircal landscape elements for microclimate control.

There are different ways to categorise landscape elements. One of these categories distinguishes landscape elements based on their function, such as Renes (1992) and Schuyf (1986). These categories describe either their contemporary or historical functions. Another way to categorise landscape elements is based on their spatial characteristics and divides landscape elements into linear, point and surface elements (Koomen, et al., 2007). Due to the relationship between spatial form and microclimate, this categorisation is more relevant for this thesis.

In this thesis the scope is limited to green landscape elements. Green landscape elements are opted for as they have the ability to improve thermal comfort through evaporative cooling (section 2.3). Next to that, green landscape elements have the additional benefit of improving psychological thermal comfort through increasing the perceived naturalness (section 2.1). Finally, green landscape elements are most preferred as they are not only able to improve thermal comfort, but also have numerous side-benefits. Green landscape elements can for example promote mental and physical health, attract urban wildlife, offer aesthetical experiences, contribute to urban stormwater management, reduce CO_2 concentrations, and produce food and timber resources (Niemelä, et al., 2010). In the next part of this paragraph their ability to influence the microclimate is discussed further.

Figure II
Malie Baen
Amsterdam
(Stoopendaal,
± 1725)

Chapter 3

Historical landscape elements for microclimate control

3.1 Method

Until now, no research has been done to document the historical landscape elements that were originally created for microclimate control in temperate climate zones. In order to get a first overview of these landscape elements, interviews were held with three experts on historical geography (Hans Renes, Jelle Vervloet, & Oscar Borsen), one expert on garden history (Kees van Dam) and one expert on urban history (Reinout Rutte). The interviewees were chosen based on their expertise to cover a range of rural, garden and urban landscape elements.

As the interviewees were not likely to be experts on the urban microclimate, the interviews started with a short presentation about the urban microclimate phenomena and the principles of landscape elements to mitigate heat and cold stress (see chapter 2). After this short presentation, the interviewees were asked to come up with historical landscape elements that either aimed to influence the microclimate or had an important microclimatic side-effect. An open-ended interview followed that took approximately one hour per interview in which the interviewees came up with several historical landscape elements.

The interviewees mentioned water features such as city-canals, fountains and water meadows for their indirect effect on the microclimate for their evaporative cooling potential. Next to that, historical urban materials such as permeable pavements and white plastered walls were mentioned for their side-effect. Then, the landscape elements of which the interviewees beleived that they were originally created for their microclimatic effects, consist of green and non-green landscape elements. Amongst the non-green landscape elements, fruit walls were mentioned by multiple interviewees. These walls were purposefully constructed to create a microclimate favourable for the growth of fruit. Finally, amongst green landscape elements for microclimate control, vertically shaped trees, tree lanes and berceaux were mentioned most often. The results of the interviews are represented in figure 3.1.1. The font size of the landscape element represents the number of interviewees that mentioned the element.

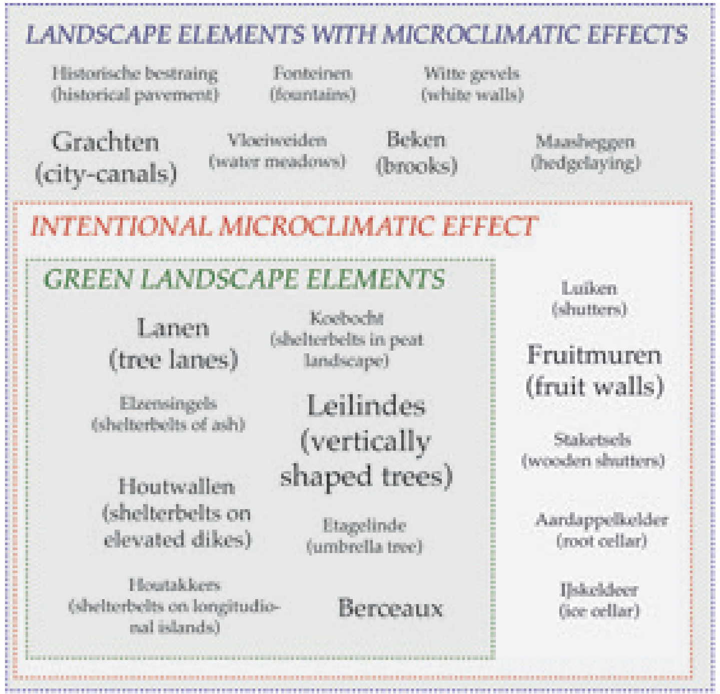

Figure 3.1.1 Overview of the landscape elements mentioned by the interviewees.

After achieving a first overview of relevant historical landscape elements, their microclimatic purpose, spatial characteristics, multifunctionality and context was researched. Historical literature about their microclimatic purpose was found in the special collections department of Wageningen University, the digital library for Dutch letters (DBNL) and Google Books. Search terms included different names of each landscape element in relation to its potential microclimatic effects (e.g. sun, shadow, shelter, wind) and was restricted to literature published before 1900.

Then, information about the spatial characteristics of the landscape elements was obtained through scrutinizing historical drawings, paintings and photographs from books with historical images of estate gardens and urban and rural landscapes. These books were found in the special collections department of Wageningen University. Next to that, images were searched more specifically in provincial and national online image libraries, such as Rijksdienst voor het Cultureel Erfgoed (n.d.), Het Utrechts Archief (n.d.) and Beelbank Groningen (n.d.). Search queries included different names for each landscape element and results were limited to images made before 1900. These historical sources often provided information about the multifunctionality and context of these landscape elements as well.

Lastly, additional information was obtained from contemporary books, magazines and online documents through searching for different names of each landscape element in the Wageningen University library and in the Google search browser.

The following part of this chapter describes the microclimatic purpose, spatial characteristics, multifunctionality and context of the identified historical landscape elements.

3.2 Vertically shaped trees

Vertically shaped trees are defined as trees with vertically dimensioned branches, supported either without (1) or with the help of a trellis (2).

Without trellis

At least since the Middle Ages pruned trees have been planted along Southern facing facades to shade buildings. This helped to passively cool buildings and contributed to the perseverance of dairy products (van der Veen, 2004). Pruning was done to restrict the size of the trees and resulted in a space-efficient sunscreen that simultaneously provided wood as a resource (Veen, 2005). As these pruned trees required limited maintenance, they proved to be a cost-effective cooling method.

The most common type of vertically pruned trees within the Netherlands are candelabrum shaped (figure 3.2.1; Veen, 2005). Generally, their lowest branches started at a height between 2.2-2.4 metres. This helped to screen the hot summer sun and allowed the lower spring and autumn sun to shine underneath (Mauritz, 2014). In winter the trees have lost all of their leaves and allow the sun to reach the building all day. According to Veen (2005) different tree species were pruned in this vertical shape. In general, wealthier farmers planted varieties of lime (tilia) and less wealthy farmers planted varieties of salix (willow) and poplar (populus).

Figure 3.2.1 Vertically shaped trees without trellis (Groninger Archieven, 1885-1895).

Espaliered trees

Espaliered trees are shaped vertically with a two-dimensional trellis. The word espalier originates from the Italian word spalliera, meaning “something to rest the shoulder (spalla) against” (Online Etymology Dictonary, 2018). It is likely that espaliered trees were originally created for fruit production as alternative to a free growing fruit tree. Compared to a free growing fruit tree, espaliers required a limited amount of space and received a high amount of sunlight (Robles, 2004). In relation to the latter, Knoop (1753, p. 425) wrote that this method allowed branches to receive more sunlight:

> *...”of als ze plat uitgespreid zyn, gelyk Espalier-Bomen, zo kunnen de Takken zo wel asl de Vrugten overal door de Stralen der Zon wel beschenen en aangedaan worden...”*

However, from historic literature it is known that espaliers did not only exist for fruit production.

The Belgian horticulturists Burvenich (1878, p. 42) described that it is common use in the Netherlands to plant lime or olm in front of houses, of which their branches are guided by a trellis in order to restrain sunlight intrusion into the houses:

> *…”buiten is het algemeen de gewoonte voor de huizen hoogstammige, aan latwerk geleide boomen te planten om indringen der zonnestralen binnen de woningen te belet-ten. Tot dit doel gebruikt men bij ons te lande gewoonlijk de Lindeboom”...*

As espaliered trees had to be cut and guided two or three times a year, they were rather expensive (Robles, 2004). For that reason, espaliers were found more often in gardens of wealthier people (van der Veen, 2004).

3.3 Tree lanes

Tree lanes are rows of trees planted in a repetitive manner alongside a road or path. Austrian researchers Kurz & Machatschek (2008) believe that first tree lanes originate when the agricultural fields arose in Western Europe during the Middle Ages. In this context, tree lanes served farmers by casting shade, reducing wind and producing wood and fruits (Kurz, & Machatschek, 2008). However, only in the Baroque tree lanes became popular landscape elements for their functional properties that matched the idealised productive landscape (Kurz, & Machatschek, 2008), and their ability to represent wealth and create space for hunting and playing (Maes & Albers, 2001). Historically, tree lanes existed in three different types of contexts: cities, the countryside and estates.

Figure 3.3.1 Tree lane at Lange Voorhout *(Braun en Hogenberg, 1595)*

Cities
While urban tree lanes only became more common in the 17th century (Kipp, 2003), it is known that the tree lane at the Lange Vijverberg, The Hague, was planted even before 1481(Maes & Albers, 2001). About fifty years later, in1536, another tree lane was planted in the Hague along the Lange Voorhout. These two tree lanes are illustrated on the map of The Hague made in 1595 (figure 3.3.1).

In 1621, Christiaan Huygens (Genootschap Constanter, 1824, p. 17) wrote a poem about the Lange Voorhout in which he praised the cool climate underneath the lime trees:

"Noch en ben ick niet verlegen,
Noch en schrick ik niet voor 't nat,
Koel in hitte, droogh in regen,
Sit men onder 't Lindenblad.
Wat en had ick niet to spreken
Van de soete Zephyr-suaht,
Die door 't borne loov komt breken
Met,een' ruysschende genucht
Met een' flauwe Somer-soelte?
Ah ! wat heb ick disk geseit,
Sit ick in een' groene koelte,
Of een' koele groenigheit?"

Countryside
The road from the Hague to Scheveningen was the first paved countryside road in the Netherlands (Gieskes, 2015). It was designed by Constantijn Huygens in 1665, the same person who wrote about the cooling effect of lime trees at the Lange Voorhout in 1621. Huygens designed two dykes and six rows of alder trees around the road to Scheveningen (figure 3.3.2). In order to convince the municipality of building this road, Huygens wrote the poem Zeestraet (1667) in which he wrote that the six lanes of alder trees provided shelter from sun and wind:

"Is 't niet genoech gesorght voor all wat u kan deeren?
De Son, die boose Son, heeftm' u gesocht te keeren,
En siet de schaduw komt van menigh groenen tack,
Die in geen' lange wijl sal groeijen tot een dack.
Gebreeckt 'er noch meer sorghs, en schrickt ghij voor de Winden?
Die sullen oock eer lang haer' krachten in sien binden,
Eer langhe staet die straet gemantelt op een' rij
Met drijmael dobblen Elst aen d'een' en d'ander' zij."
(Huygens, 1667, p. 31)

Another example mentioned by several interviewees are the tree lanes along the road network that Napoleon aimed to build throughout the Netherlands between 1810 and 1813. Napoleon obliged by law to complement these roads with trees to protect the army from the burning sun (van Zijderveld, 2001).

Figure 3.3.2 Alder tree lanes along Zeestraet *(Elandts, 1681-1728)*

Estates

First recommendations to plant tree lanes at estates were made in Italy during the Renaissance (Overmars, 1992). While these tree lanes were originally restricted to the garden of the estate, they were extended from the garden into the landscape in the 16th century (van Driessche, et al., 2015). These tree lanes started/ended at the estate and aimed to direct the visitors view towards the estate. A map from 1625 of Honselaarsdijk portrays a six-double tree lane that continued into the countryside (figure 3.3.3).

The shading potential for different tree species is described by Van der Groen (1699). He found plane and lime tree most suitable in casting shade. Simliarly, De la Court van der Voort (1737) and Knoop (1790, p. 53) mentioned the lime tree as the best species to cast shade.

> *"Op veel plaatzen vind men Linde-bomen, ... , om zig daar in by de warme Zomer-dagen te vermaken, wordende de schaduwe van deze Boom ook voor de gezondste gehouden; en de vermakelykheid en aangemane schaduwe van deze boom.."*

An interesting example that illustrates the cooling function of tree lanes was found at estate Elswout. On a map with the historical layout of Elswout a 'parasollaan' (translated: sunshade lane) is found (figure 3.3.4). This name likely describes the microclimatic purpose of this lane. The fact that this tree lane is planted with lime trees might not be coincidental.

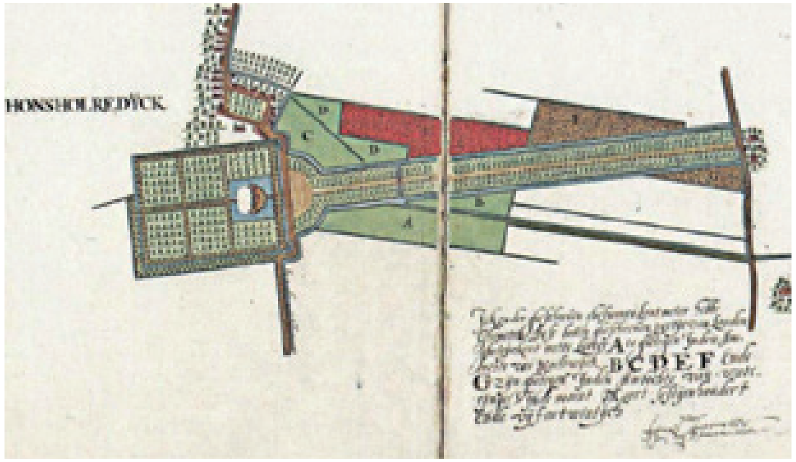

Figure 3.3.3 Tree lanes at Honselaarsdijk *(Jacobs, 1625)*

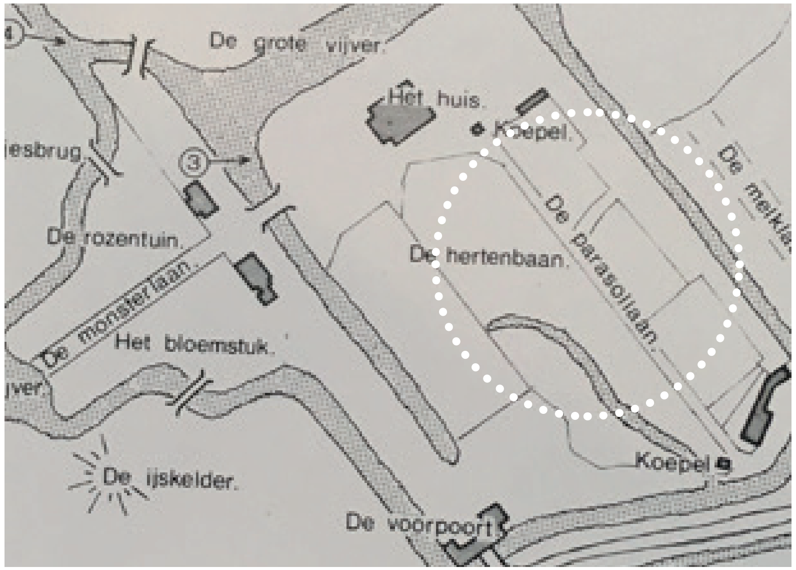

Figure 3.3.4 Shunshade lane Elswout *(Vrijland, 1957)*

3.4 Berceaux

Berceaux are pathways covered with vegetation. There are two different types of berceaux: freestanding and supported by trellis. It is believed that berceaux already existed in ancient Greece and Rome to provide protection from the burning sun (van Dijk, 1999). In the Renaissance this landscape element became popular again, as it allowed the elite to maintain a light skin tone and thereby differentiate themselves from the working class (van Wetten, 2009).

Next to the ability of berceaux to cast shade, they were also valued for their aesthetic and function as (sight) barrier. Sometimes berceaux were made of fruit trees, offering the additional benefit of fruit production (Van Sypesteyn, 1910).

Dutch berceaux were mostly planted with beech (fagus sylvatica), common hornbeam (carpinus betulus), lime (tillia cordata) and pear subspecies (pyrus communis; Moens, 2001). Beech was the most popular choice, as it loses its leaves late in winter, allowing the shape of the berceau to be visible for a long time (Moens, 2001).

Van der Groen (1699, p. 81) described how to build the most beautiful berceaux that create a very comfortable microclimate:

> *..."Gevende dit alles / behalven een aengenaem gezicht/ oock bequame en vermakelijcke Schuil-plaetsen / en Wandelingen / Daer men van de Somerse Sonne-stralen bevrijt kan zijn."*

Van der Groen (1699) suggested several models with a clear focus on the aesthetical function of the berceau (figure 3.4.1).

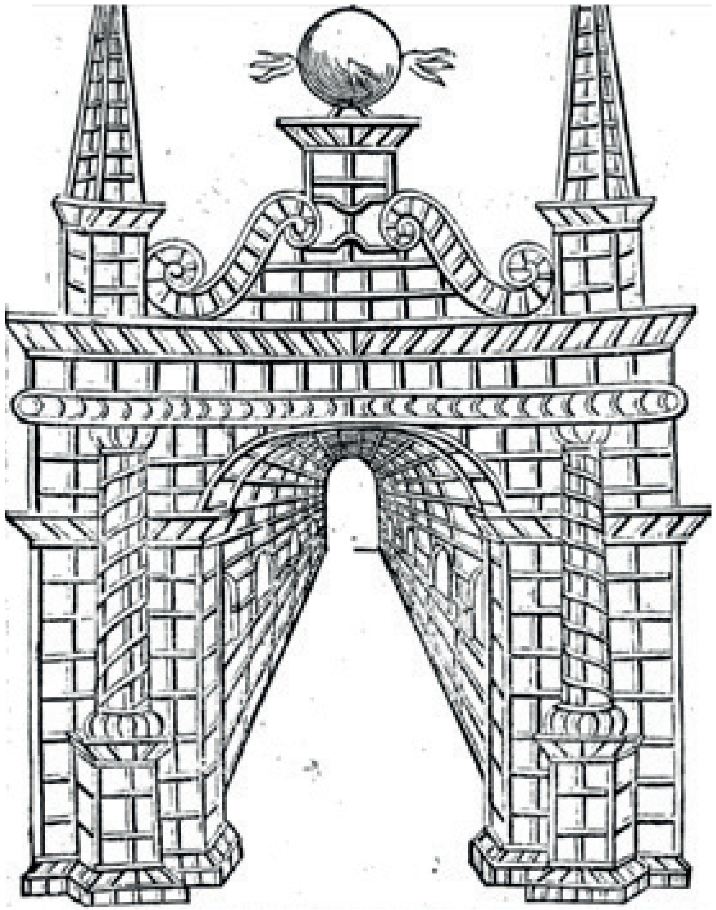

Figure 3.4.1 Model for berceaux *(Van der Groen, 1699)*

Berceaux were created in many different shapes, from berceaux completely covered with vegetation (figure 3.4.2) to berceaux with only covered roofs (figure 3.4.3) and alll kind of varieties inbetween (figure 3.4.4). While this variety of shapes had important architectonic implications, it also clearly resulted in a different microclimate underneath the berceaux

Out of the hundred berceaux that existed in the Netherlands, only a few remained. This is likely due to their high maintenance costs (Moens, 2001).

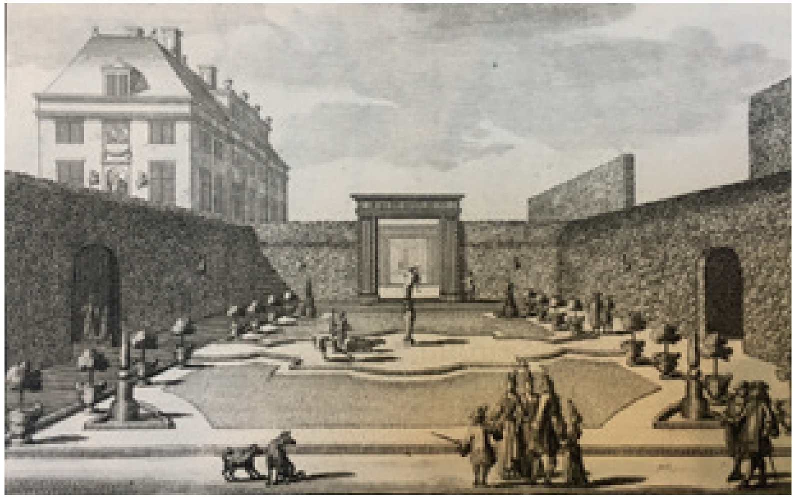

Figure 3.4.2 Berceaux as sight barrier, Clingendaal *(Stoopendaal, 1700)*

FIgure 3.4.3 Open berceaux, Slot Zeist *(Stoopendaal, 1670 - 1680)*

Figure 3.4.4 Semi-open berceaux, Huis ter Meer *(de Leth, 1740).*

3.5 Shelterbelts

Shelterbelts are dense linear landscape elements that consist of both tree and shrub species. As these landscape elements consist of tree species, they can reach significant heights. By coppicing these landscape elements periodically, they grew into dense linear landscape elements that served as a barrier to people, cattle and wind. Next to that, the coppiced wood was used either as fuel or building material.

Shelterbelts around fields
The oldest type of Dutch shelterbelts were originally served as cattle barrier and property demarcation and are called "houtsingels" and "houtwallen". The difference between these landscape elements is that "houtsingels" grew on a flat surface, whereas "houtwallen" grew on small dikes (figure 3.5.1). These dikes improved the barrier function of "houtwallen" and limited tree roots from taking up nutrients from the neighbouring field (Nooren, 1975).

Due to their barrier function, "houtwallen" were often planted in landscapes where water levels in summer were too low for ditches to function as a year-round cattle barrier (Dirkmaat, 2006). In some of these relatively dry landscapes, shelterbelts also prevented the wind from blowing away the fertile top layer of the soil. Planting trees to limit soil erosion goes back to the Middle Ages. In 1443 Philips allowed the plantation of trees on the communal grounds of Bakel to prevent sand drifts (Nooren, 1975).

Apart from preventing sand drifts, these shelterbelts also protected wind sensitive crops. One example of a wind sensitive crop is rye, which used to be a commonly grown crop in the Netherlands (Nooren, 1975). Thys (1792, p. 300) mentioned the importance of shelterbelts in protecting crops and humans from wind:

..."De sluytzels zyn ook zeer voordeelig en is't dat ik mag zeggen, zeer noodzaekelyk aan alle landen, als dienende tot beschudding van vrugten en bewaernisse der selve, zoo voor de beesten als winden." .... "Dat men op de zelve ten minsten dry reyen Boomen kan planten, om geheel het land van dien schraeln en kouden wind te beschudden"...

Figure 3.5.1 Houtsingels (left) and houtwallen (right; Maters & De Vries, 2005).

Historical shelterbelts are for instance found at Vlagheide, North Brabant (figure 3.5.2). This former heathland was cultivated after the invention of artificial manure in the late 19th century. However, its bare dry sand soil easily drifted by the wind. To mitigate this problem, shelterbelts were created along the fields (Koppen & Brongers, 2008).

Houtakker

A 'houtakker' is another specific type of shelterbelt. It consists of several rows of trees and shrubs on a longitudinal island surrounded by ditches. Houtakkers were planted in Boskoop around the 18th century, when tree nurseries became more common. They are unique elements as they are surrounded by ditches on both sides that were used to transport trees. Houtakkers were pruned to harvest wood and provide wind protection, as well as to minimise the amount of shade they would cast on the nursery plants.

Knowledge about the importance of shelterbelts around tree nurseries is also found in historical literature. Brouwer (1824, p. 34) described the importance of shelterbelts planted with ash on the North and West side of tree nurseries:

...."Een goede beschutting, voor naadelige winden, die het jeugdig plantsoen schade kunnen aanbrengen, is zeer noodzakelijk aan den Noord-, maar vooral aan den West-kant ... Eene dichte heg van Elzenout, die met inplanting goed moet onderhouden worden, om geene openingen tusschen beide te krijgen, waardoor de wind op het plantoen werken kan is daartoe zeer dienstig"...

Figure 3.5.2 Singels at heathland to prevent sand drifts (Topo Tijdreis, 2019-a)

Figure 3.5.3 Aerial picture of houtakkers *(FTDL, 1920-1940).*

Koebocht
A 'koebocht' is mostly an L-shaped shelterbelt that is located in the corner of a meadow (figure 3.5.4; Busz & Hine, 2001). Other names for this landscape element are 'melkbocht', 'veebocht' or 'huftbosje'. It is believed that these landscape elements date from the middle ages (Baas, et al., 2005). Koebochten were planted in the open peat landscapes that exposed the farmers and their cattle to wind, rain and sun. In order to mitigate this microclimatic exposure, these shelterbelts were created. These L-shaped shelterbelts were used to milk and sometimes even keep cows overnight (Busz & Hine, 2001). Unfortunately, no historical literature was found that described the microclimatic effect of this landscape element.

Figure 3.5.4 Melkbocht *(De Zwart, 1862-1931).*

Shelterbelts around farmyards
Windbreaks not only existed around fields, but also around farmyards. Farms that were built in open landscapes most commonly were surrounded by shelterbelts, as these experienced most wind nuisance. Providing shelter around the farm helped to protect the orchard, vegetable garden and farm building. Shelterbelts never completely surrounded the farm, but were mostly planted on the North-, West and Eastside. The absence of shelterbelts on the Southside allowed the sun to reach the farmyard throughout the day.

One example that shows farms with shelterbelts is found in the open sea clay landscape of Groningen (figure 3.5.5). In this landscape, farms were built on sand ridges for flood security. Due to that, these individually located farms were completely exposed to the open landscape.

Figure 3.5.5 Wind shelters around farms in North-East Groningen in 1907 (Topo Tijdreis, 2019-b)

Shelterbelts around estates

Similar to shelterbelts around farms, it was common for estate owners to plant shelterbelts on at least the North- and West-side of their garden. Shelterbelts around estates can be found by looking at historical maps and imagery of estates, for example figure 3.5.6 and are often mentioned in historic literature. Van der Groen (1699), La Court van der Voort (1766), and Knoop (1790) all described the importance of planting a shelterbelt around an estate garden. For example, according to Knoop (1790), alder, elm and willow trees are especially suitable for the creation of shelterbelts.

La Court van der Voort (1766, p. 15) even urges new estate owners to start with creating a proper shelterbelt before realising the estate and its garden:

...“Het eerste daer voor men, na zodanigen verkregen grond, moet bezorgt zyn, is dat men eene goede buiten-manteling aenlegt om luuwte te verkyrgen, zonder welke geen vrugten nog moeskruiden te teelen zyn, ook is zodanige beschutting voor Buiten-hiuzen van de uiterste nootzakelykheid, vermids ze anders in ’t kort bouwvallig en onbewoonbaer zouden werden”...

Knoop (1790, p. 5) advised on how to construct shelterbelts. According to him, trees had to be planted close to each other in order to create a more instant shelter. He provided different ways to plant such wind breaks, varying from one row of trees to multiple rows of combined tree species:

...“Wat aanbetreft de Bomen die men tot mantelinge en windbrekinge plant, hier mede word de Plantinge op geen of niet zo veel cieraad gezien, als wel op de nuttigheid; men plant dezelve doorgaans op de buitenkant van de Tuinen, en inzonderheid na de Noord- en West-kanten, als van welke kanten men by ons de meeste koude Winden ontfangt, en men stelt ze doorgaans wat digt, namelyk op 4 a 5 Voeten distantie in de Rey, min of meer, naar maate de Bomen in haar zoort sterker of min sterker uitkroonen, op dat dus de Takken te eer aan malkander zouden fluiten, en haare uitwerking doen: En om zulks nog meer te bevorderen, zo plant men ook wel twee Reyen Bomen op een kleine distantie 8 a 10 Voeten, Alleés-wyze, naast malkander, in het verband: Of men plant agter de enkele Reyen, hooge Bomen, of ook, als er twee Reyen geplant zyn, indien het de ruimte toelaat, dikwijls nog 2, 3 of meer Reyen Els of Willige, de Reyen, 3 a 4 Voeten van malkanderen, waar door het Gewas, het eene het andere dekkende, beter tegen de wind opgroeijen zal”...

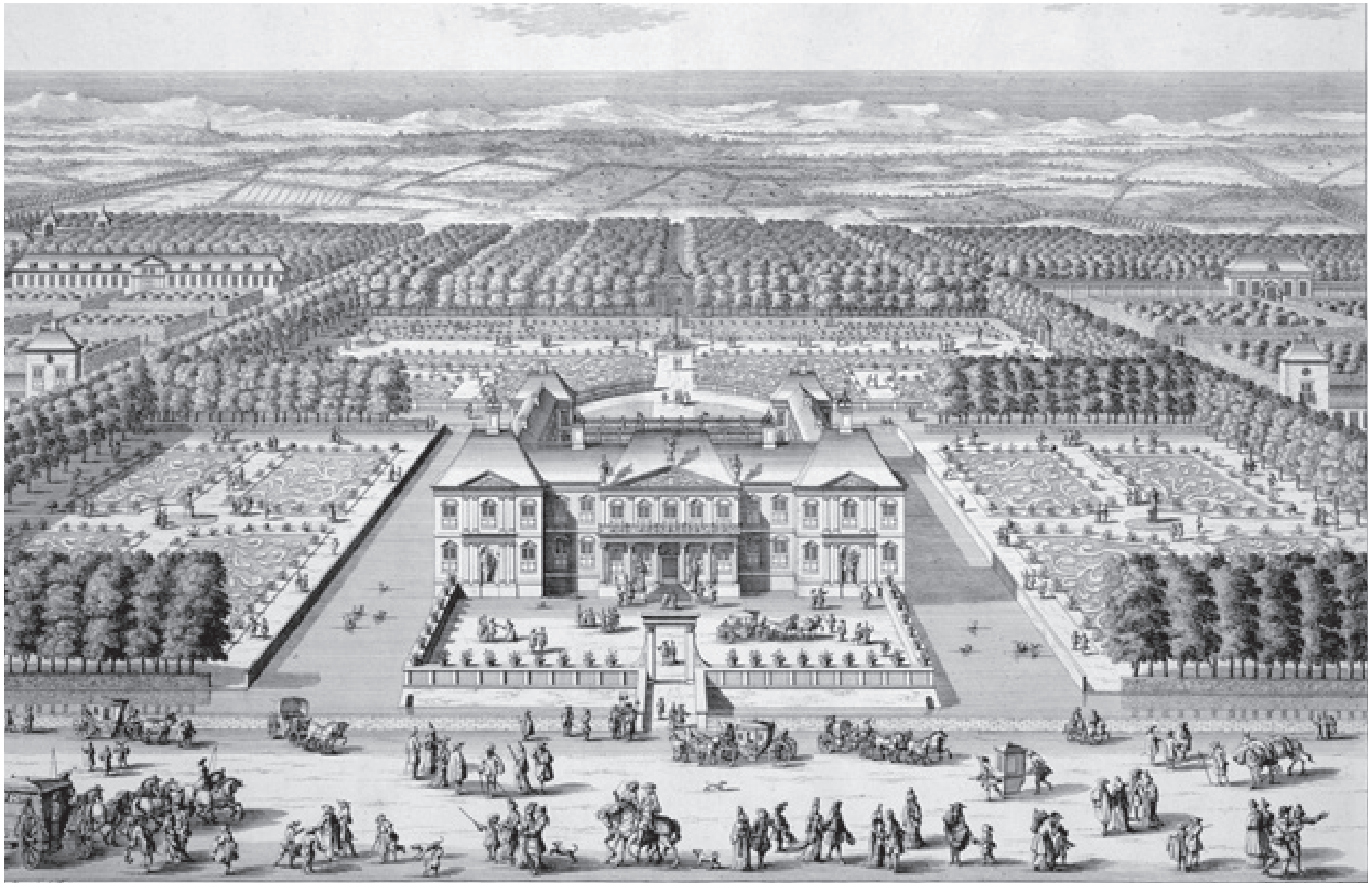

Figure 3.5.6 Shelterbelts around Honselaarsdijk *(Stoopendaal, 1682-1726).*

3.6 Hedges

In this thesis, hedges are defined as dense linear landscape elements that consist only of shrub species. For that reason, hedges have much smaller dimensions compared to shelterbelts.

Agriculture
Hedges originate from the countryside where they served similar functions as shelterbelts: they demarcated property and functioned as cattle barrier (Nooren, 1975). Originally those barriers were woven out of dead wood, called 'tuun'. While those barriers were easy to move and took up only a small amount of space, they required regular renovation. When wood became scarcer, barriers of living plants became a better alternative. Due to their barrier function, hedges consisted mostly out of thorny plants, such as hawthorn (crataegus) and bramble (Nooren, 1975). Besides these two functions, it is found that hedges functioned as wind barriers as well in some agricultural contexts. For example hedges around tobacco fields as described by van der Kroe (1761, p. 330):

..."De Landeryen, met Tabak bepoot, zyn doorgaans rondom voorzien met levendige Elzen heggen, voornamelyk aan de westzyde, alwaar de zwaarste gevonden worden, die men windhouders noemt; alhoewel tusschen beide nog ligter platgeschoren heggen, mede van Elzenhout, geplant zyn.. dienende alles om de Tabak, zo veel 't mogelyk is, voor de wind te dekken en te bevryden..."

Estates
Like more rural landscape elements, hedges became popular elements of the estate gardens during the 17th Century. However, for the estate gardens the originally more free-growing rural hedges were transformed into tall and narrow architectural elements with a straight upward character. In order to achieve this, hedges were often grown against espaliers (Knoop, 1753, p. 395):

"...Wyders zo dient by de Planting van allerley Heggen, inzonderheid als de Plantsoenen wyt gestelt zyn, en de Heggen hoog zullen worden, in agt genomen en is volstrekt nodig, als men in het vervolg Cierlyke Heggen, en die ras en wel bekleed zullen zyn, hebben wil, dat men er Latwerken by doet maken, waar aan de uit gewassene jongen Takken kunnnen uitgebreid en vast gehegt worden.."

Hedges served both an architectonic and a functional purpose. Architectonically they added structure and depth to the garden. Functionally, hedges served as barriers to wind and people. Looking at historical images of estates, hedges are often seen around vegetable gardens and orchards (figure 3.6.1). This is likely due to their function as wind barrier.

De la Court van der Voort (1766, p. 215) described hedges for their ability to maintain solar heat and shelter vegetables from wind, which would result in better growth. Later, he also warns for the shade casted by such elements:

"...Behalven de voorgemelde beplanting van zeer hooge Noordelyke, Ooster- en Wester-scheer-heggen, plant men ook, op kleinder verdeelingen, scheer-heggen van laeger gewas, om de Zonnestraelen tussen deze kleinder verdeelingen nog meer te behouden: door zodanige beluwinge of bemantelingen tegen de winden zal men meerder en groeizaemer warmte verkrygen.."

In relation to their sheltering effect, Knoop (1790, p. 12) described beech as a suitable species as it holds its leaves nearly year-round:

"...dat ze haar dorre Bladen de Winter over meest behouden, en niet eerder laten vallen als in het Voorjaar, wanneer de nieuwe weer staan uit te botten, waardoor het dan geberut, dat in die tydt, als men meent de Tuinen schoon en zuiver te hebbenm dezelfde met dorre Bladen bezaait zyn; Dog ik meen dat dit met een weinig moeite of kosten verholpen kan worden, en daarom deze Boom niet te verwepren is; daar en boven brengen deze dorre Bladen in de Winter eenig voordeel aan, namelyk dat de Heggen daar door beter de Winden breken en afkeeren..."

Figure 3.6.1 Vegetable gardens surrounded by trained hedges (van den Aveele, 1727).

3.7 Green walls

Green walls are defined as walls covered with vegetation. In this thesis two different types of green walls are discussed: (1) façades covered by fruit trees that are attached to the wall (figure 3.7.1) and (2) façades covered by climbing plants that require no support (figure 3.7.2)

Fruit trees

First recommendations to grow fruit trees against these walls were made in France and England at the start of the 17th century (Kuitert, & Freriks, 1994). As these walls retained solar heat and provided protection from cold winds, they created a microclimate that was favourable to the growth and ripening of fruit (Kooij & Olde Meierink, 1997). Their popularity in the 17th and 18th century seems to be related to the colder climate of these centuries (Kuitert, & Freriks, 1994).

Knoop (1753, p. 375) described the microclimate of different oriented walls and argued that the South-Eastern exposed walls are most favourable for growing fruit. However, the exposition of a wall needs to be matched with the type of fruit:

"Het komt er dan hooftzakelyk op aan, dat men kennisse hebbe van de verschillige Voordelen, die de eene Expositie boven de andere heeft, en wat Soorten van Vrugten aan deze of geene Expositie met voordeel kunnen gegeplant worden; want dewyl de eene Expositie meer avantage van de Warmte heeft als de andere, en de eene Soort van vrugt meer Warmte begeert als de andere, derhalven zo dienen dezelfve ook verscheidentlyk geplaatst te worden.. "

Figure 3.7.1 Fruit walls castle Genhoes (Jongsma, & Loosjes, 1912-1922).

Climbing plants

Different from fruit trees, climbing plants grew against walls without support. Depending on the orientation of the wall, different species were used. For example, Northern facing walls were best planted with ivy, an evergreen climbing plant (Hibberd, 1872).

Images of estates and castles made in the 17th century show no climbing plants at all. Earliest examples date from the 18th century, for example the drawing of estate Park het Utrecht (figure 3.7.2). Green walls became more popular with the idealisation of nature during the English landscape movement.

While green walls were able to conceal bad-looking parts of the wall, they also created a more natural look to the originally geometric estate buildings. Craandijk (1880, p. 132) describes that the monotonous character of a building could be improved with the use of climbing plants:

..."De strenge vormen van dezen burgt zouden behoefte hebben aan de poëzij der tinten, door den tijd op het muurwerk getooverd, aan klimop en kamperfoelie en wilden wingert, die hier en daar de eentoonigheid braken"...

However, green walls not only had an aesthetical purpose, but also sheltered buildings from wind and rain (Knoop 1790 and Hibberd, 1872).

Knoop (1790, p. 50):
"Men plant die zomtydts tegen de Muuren, aan de Noord- en West-zyde van Oranje-Huizen, Stook-en Trek-kasten en van andere Gebouwen, om die daar mede te bekleden, en daar door de aandoening en indrang van Lugt, Koude, Regen en Wind af te keeren, het welk hy ook zeer kragtig doet, als de Muuren, enz. wel digt daar mede bekleed zyn."

While green walls must have had a positive side-effect on the microclimate through the process of evaporation and by shading the wall surface, it seems that this effect was unknown before 1900.

Figure 3.7.2 Green façade estate Park Het Utrecht (Gezicht op het huis Het Park te Utrecht, vanuit de tuin, 1744)

3.8 Weeping trees

Weeping trees have pendulous branches that cascade down to the ground. Due to their morphology, weeping trees form natural arbours. This landscape element became popular in the 18th century when nature was romanticised and weeping trees were seen as the perfect arbours made from nothing more than nature.

Figure 3.8.1 and 3.8.2 show a weeping ash above a seating area. Witte (1876, p. 20) described this weeping tree as a large tree that shades the resting area:

"De rustplaats ligt hooger dan de omliggende grond, en wordt door een grooten Treur-Esch overschaduwd."

Moens (1826, p. 94) praised a weeping ash 'build by nature' that forms 'green curtains' that provide 'shelter from sun':

"Vind ik u hier? Lieve kinderen! waarlijk gij hebt wel een lieve rustplaats uitgekozen; hier onder dezen treuresch, die zijne takken en bladen als levendige groene gordijnen om u heen laat hangen. Ik wil hier ook eenige oogenblikken de koele schaduw genieten. Welk eenen liefelijken geur verspreiden hier de door mijn lieve Lotje geplante rozenstruiken; die heden zo bevallig bloeijen, en door het kleinste koeltje zacht gewiegd worden. Kinderen! wij zitten hier in eene bekoorlijke loofhut, die de natuur zelve gebouwd heeft, hoe schoon is hier niet de gouden gloed, dien de afgeweerde zonnestralen door het zachte groen, dat voor ons nederhangt, verspreiden."

Figure 3.8.1 Weeping tree provides shelter (Witte, 1876).

Figure 3.8.2 Sheltered seating area underneath weeping tree (Lenzholzer, n.d.)

3.9 Umbrella tree ("Etagelinde")

The umbrella tree is defined as a solitary tree of which its branches are bent into a horizontal plane. Their branches are pruned repeatedly to create a thick roof. One historical example of such a tree includes the "etagelinde", which are parasol trees that were trimmed into three levels of horizontal planes. The "etagelinde", existed mainly in Germany, but also in some of its neighbouring countries such as Poland, Switzerland, Czech Republic and the Netherlands (Zehnsdorf & Czegka, 2007).

The "etagelinde" used to be located at the central place of a village. Underneath its canopy markets were held, important announcements were made and jurisdiction took place (Maes, 1990-a). In some Dutch villages it was a tradition to dance underneath the tree (Maes, 1990-b).

Two reasons for shaping trees into this specific shape are found in medieval literature. First of all, it can be seen as an act of care and affection for the lime trees that symbolised 'love' and 'Maria' (Peeters, 1992). A second reason found in literature is related to its microclimate (Graefe, 1987). Its roof-like structure provided shelter from sun that made the open-air activities that took place underneath this tree more comfortable and help to preserve the quality of the market products.

Brockes (1721, p. 451) wrote about their shading effect:

"Kühles Schirm-Dach in der Hitze, Schmuck der Lüffte,
Pracht der Erde,
Schatten-reicher Lindenbaum, der du meine
Wohnung deckest,
.....
Der du deine schlancke Zweige in der
Runde von dir streckest,
Ein grüne Dämmrung zeugst, wann Licht,
Kühlung Wärm und Schatten,
Unter den gebognen Aesten, ihre Kräfft'
einander schwächen."

Similarly to many landscape elements, this originally rural landscape element was later implemented in gardens as well (figure 3.9.1)

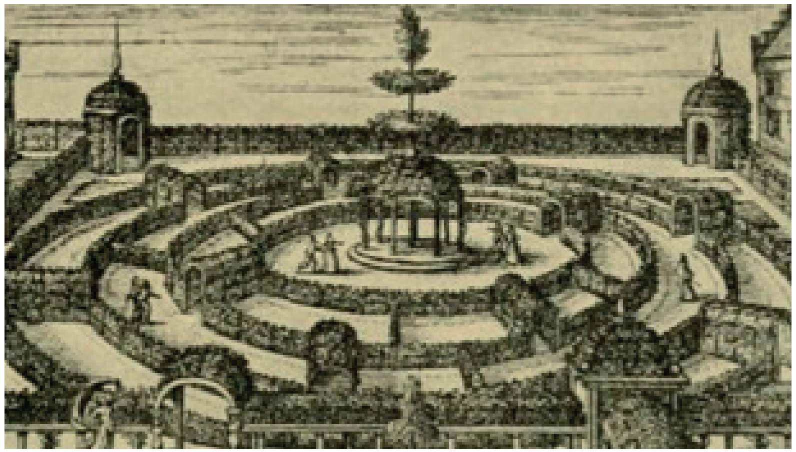

Figure 3.9.1 Umbrella tree in 16th Century garden. (Vredeman de Vries, 1583)

3.10 Summary

In this chapter an answer is given to the first research question: what are vernacular landscape elements for microclimate control in the Netherlands?

Some of the green landscape elements that were brought up by the interviewees showed overlap with other green landscape elements, as their name defined their function rather than their spatial characteristics. In order to create a structured overview of all of the landscape elements, a diagram is created that describes landscape elements based on their spatial dimensions. It starts with the often-used division of landscape elements into point, plane and solitary elements. After that, the landscape elements are further categorised based on their cross-sectional and longitudinal shape. This resulted in an overview of the following landscape elements: vertically shaped trees, tree lanes, berceaux, shelterbelts, hedges, green walls, weeping trees and umbrella trees (figure 3.10.1).

For most of the landscape elements evidence about their microclimatic functions was found in historic literature on garden design. Most important resources include Van der Groen (1699), La Court van der Voort (1766), Knoop (1753) and Knoop (1790). Apart from historical literature, historical imagery helped to reveal the shapes and context of these landscape elements. Finally, contemporary literature provided further information about these landscape elements in relation to their spatio-temporal context, side-effects and drawbacks. All this information is summarised in figure 3.10.1.

While there is no historical knowledge available about the quantitative effects of these historical landscape elements on the microclimate. For that reason, the next chapter describes quantitatively how these historical landscape elements perform on microclimate control.

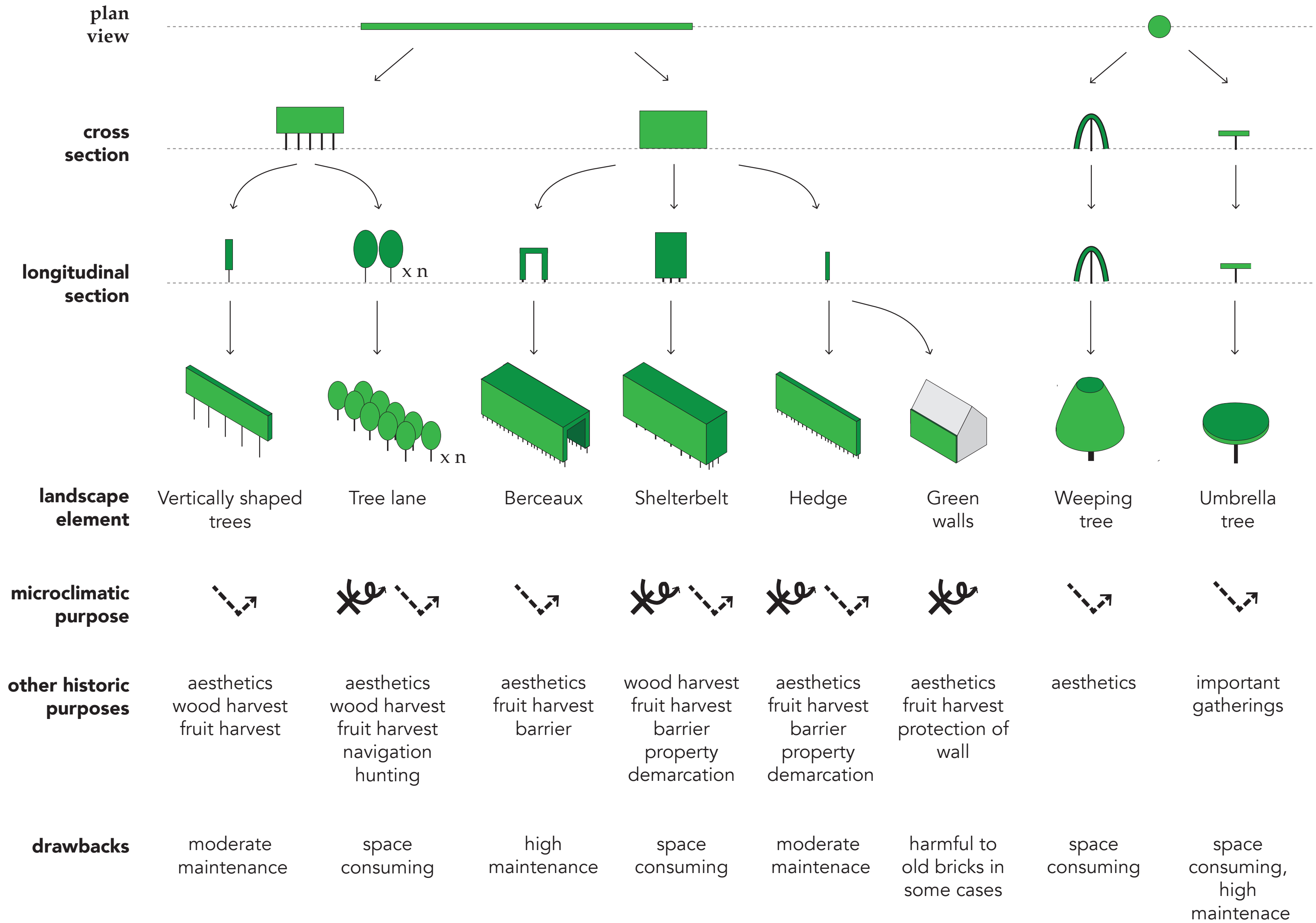

Figure 3.10.1 Overview of historic landscape elements for microclimate control, their purposes and drawbacks

Figure IV
Vertically
shaped trees at market
square Arnhem
(Beijer, 1742)

Chapter 4

Influence of historical landscape elements on the microclimate

4.1 Introduction

In this chapter the microclimatic effects of the earlier described historical landscape elements are evaluated. This evaluation consists of two parts. In the first part, an overview is given of the scientific literature about the microclimatic performance of the historical green landscape elements. However, from this literature review it appears that the microclimatic effects of some of the historical landscape elements have not been researched yet. Therefore, in the second part of this chapter the microclimatic effects of these landscape elements were simulated in ENVI-met.

4.2 Literature review

Method

The literature review is conducted with the Google Scholar browser. Key words that were entered included "the name of each landscape element" AND "shortwave radiation" OR l"ongwave radiation" OR "air flow" OR "wind" OR "evaporative cooling", as these are their most important effects on thermal comfort (section 2.4). For the landscape elements for which relevant search results came up, a snowballing strategy was used within these results to identify more scientific aritcles for these landscape elements. This process continued until the influence of the landscape elements on the microclimate was understand sufficiently for a successful implementation in the research through design process in the third sub-research question.

Tree lanes

Tree lanes most significantly improve thermal comfort by reducing the mean radiant temperature through casting shade (Morakinyo, et al., 2017). Wang and Akbari (2016) used ENVI-met simulations to model the microclimatic performance of tree lanes with different planting densities, canopy densities and heights for a summer day in Montreal. They found significant reductions in mean radiant temperature for densely planted tree lanes, reaching to a maximum reduction in Tmrt of 40°C around 10AM.

By casting shade, tree lanes do not only reduce shortwave radiation, but also indirectly reduce air and surface temperature below their canopy (Coutts, et al., 2015). To illustrate this, Souch and Souch (1993) found air temperature reductions of 0.7 to 1.3°C directly below tree canopies on a

summer day in Indiana.
On top of that, tree lanes also reduce air temperature by the process of evaporation. On average, 30% of the shortwave radiation that radiates upon the tree foliage is converted from sensible into latent heat flux (Konarska, et al., 2016). This evaporative cooling effect manifests itself around and shortly after sunset (Konarska, et al., 2016). As mentioned before, Shashua-Bar and Hoffman (2000) found that shading accounted for 80% of air temperature reduction underneath a tree canopy, while evaporation accounted for the remaining 20%.

Despite from the fact that trees can improve thermal comfort during hot summer days, heat stress can also increase underneath trees during hot summer nights. This holds true as tree canopies inhibit the longwave cooling after sunset (Bowler, et al., 2010; Sanusi, et al., 2017; Coutts, et al., 2015). Figure 4.2.1 illustrates that a street canyon without trees (OPN) cools down more quickly after sunset than the street canyon with a dense tree canopy cover (TRD) (Coutts, et al., 2015).

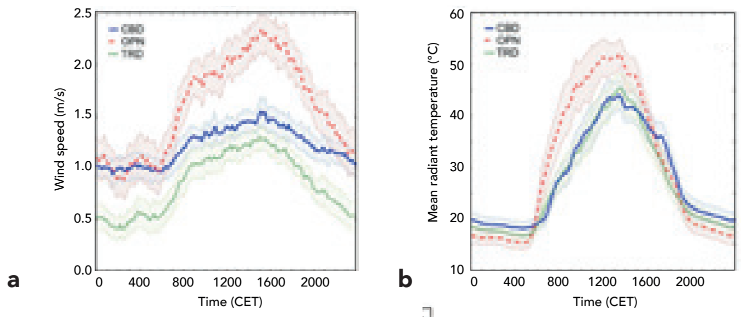

Figure 4.2.1 Difference in wind speed (a) and mean radiant temperature (B) between street with (TRD) and without tree canopy cover (OPN)(Coutts, et al., 2015).

As depicted by figure 4.2.1, tree lanes may also reduce wind speed (Coutts, et al., 2015; Mochida, et al., 2008; Gromke, & Ruck, 2009; Salim, et al., 2011; Park et al., 2012). For example, Park et al. (2012) found that four sidewalk trees could reduce wind speed inside the canopy by up to 51%. However, the influence of tree lanes on wind is dependent on the wind direction relative to the street canyon: while tree lanes reduce the velocity of winds perpendicular to the street canyon, they accelerate wind underneath their canopy for winds with a parallel direction (Jeanjean, et al., 2017).

Shelterbelts & Hedges

In the previous chapter shelterbelts and hedges were defined as two distinctive landscape elements. However, hedges have a similar shape to shelterbelts, albeit on a different scale. For that reason, these two landscape elements are expected to have similar microclimatic effects and are discussed in the same paragraph.

The influence of the shelterbelts and hedges on wind patterns depends on several factors, including porosity, shape, height, orientation, width and spacing (Cornelis, & Gabriels, 2005). Amongst these variables, porosity – defined as open barrier area divided by the total barrier area – has the most significant influence on wind patterns (Cornelis, & Gabriels, 2005). While shelterbelts with a low porosity better reduce wind velocity in their wake area, they tend to create more turbulence and their downwind velocity tends to recover more quickly (figure 4.2.2; Sprik, 1974; Cornelis, & Gabriels, 2005).

Due to this trade-off, a barrier porosity of 35% is considered to give optimal shelter over the longest leeward distance (Wu, et al., 2013).

Moreover, shelterbelts and hedges with an evenly distributed porosity create the largest sheltering zone (Cornelis, & Gabriels, 2005). This holds true as wind is channelled towards open areas within barriers, resulting in increased velocities in those places (Sprik, 1974).

The influence of shelterbelts on wind patterns results in two distinctive zones with a unique microclimate: the cavity zone, which on average encompasses 0-8 times the height of the wind barrier downwind, and the wake zone, located on average in-between 8H and 24H downwind (Brandle, et al., 2000).

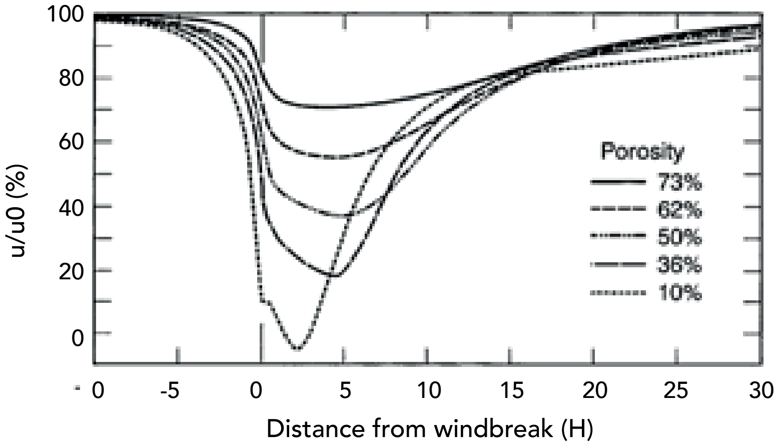

Figure 4.2.2 Relationship between barrier porosity and its effect on wind speed around the wind break (Cleugh, 1998).

While the cavity zone is characterised by limited air exchange (section 2.3.2), heat transfer from the cavity zone will be less efficient than from the wake zone (Cleugh, 1998). During a sunny day this causes near surface air temperatures in the cavity zone to be several degrees higher than upwind air temperatures (Brandle, et al., 2000). For example, Jones, & Oreszczyn (1987) found that the air temperatures in the cavity zone of a shelterbelt in the UK could be around 1°C higher than the air temperature of the upwind area.

Besides the direct influence of shelterbelts and hedges on wind speed, they also reduce the daytime radiant temperature through casting shade (Cleugh, 1998). Yet, in the evening shelterbelts trap longwave radiation which leads to an increase in air temperatures close to the margins of the shelterbelt (Rhee, 1959; Jones, & Oreszczyn, 1987). The effect of longwave radiation trapping can occur up to a distance of 1 time the height of the shelterbelt (Cleugh, 1998). However, limited research has been done to quantify the effects of shelterbelts on radiant temperature.

Green walls

From the historic literature review it appeared that green walls were sometimes created to protect façades from wind. Contemporary scientific literature confirms this historical assumption (Perez, et al., 2011; Perini, et al., 2011). For example, a green wall covered with Hedera helix of approximately 20 cm thick decreased wind speed from 0.51 m/s to 0.08 m/s (Perini, et al., 2011).

Besides their ability to reduce wind speed, green walls also have a direct cooling effect on the wall surface temperature (Alexandri, & Jones, 2008; Cameron, et al., 2014; Hoelscher, et al., 2016). For example, Hoelscher, et al. (2016) found a reduction in surface temperature of 15.5°C for green walls. Indirectly, the reduction in wall surface temperature reduces the ambient air temperature (Cameron, et al., 2014; Djedjig, et al., 2013; Alexandri, & Jones, 2008). To illustrate this, Alexandri and Jones (2008) researched the cooling effect of green walls on air temperature for different cities. Green walls that were located in London, Moscow and Montreal significantly reduced air temperatures with 1.7 to 2.1 °C.

In order to learn more about the relative contribution of evaporative cooling and shading effect of green walls, the cooling effect of both sealed (non-evapotranspirative) and non-sealed plant species was studied in the UK (Cameron, et al., 2014).

They found that all sealed and non-sealed plant species significantly reduced wall and air temperatures, but that non-sealed plants had an additional cooling effect through evaporation. With a similar purpose, Hoelscher, et al. (2016) measured the evaporation and shading effect of green walls in three common climbing plants growing against real facades in a German city (figure 4.2.3).

Finally, while green walls are likely to inhibit longwave radiation from buildings (Cameron, et al., 2014; Hoelscher, et al., 2016) they are not likely to inhibit longwave radiative cooling from the street due to their vertical character along buildings. For that reason, it is understandable that no research has been done on longwave radiation trapping of green walls

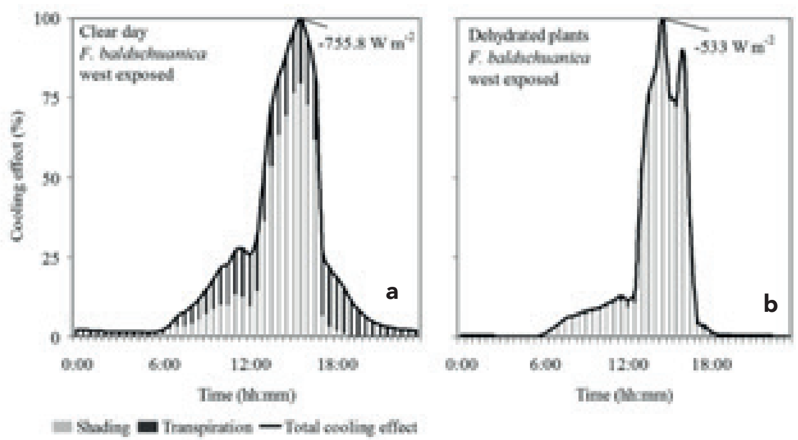

Figure 4.2.3 Effect of shading and transpiration on cooling for hydrated (a) and dehydrated plants (b) (Hoelscher, et al., 2016)

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Summary

The results from the literature review are summarised in figure 4.2.4. It illustratethat the microclimatic effects of tree lanes, green walls and shelterbelts are quantified in scientific literature. More specifically, the third column indicates which microclimatic aspects are researched. For tree lanes and green walls all microclimatic effects that are relevant to thermal comfort are described in scientific literature. However, for shelterbelts and hedges no scientific research has been done to quantify their evaporative cooling potential and longwave radiation effects.

Most importantly, the microclimatic effects of vertically shaped trees, berceaux, umbrella trees and weeping trees are not quantified at all. For that reason, it is necessary to study their microclimatic effects. In the next part of this chapter, a first attempt is made to gain novel knowledge about the microclimatic effects of these so far unresearched landscape elements.

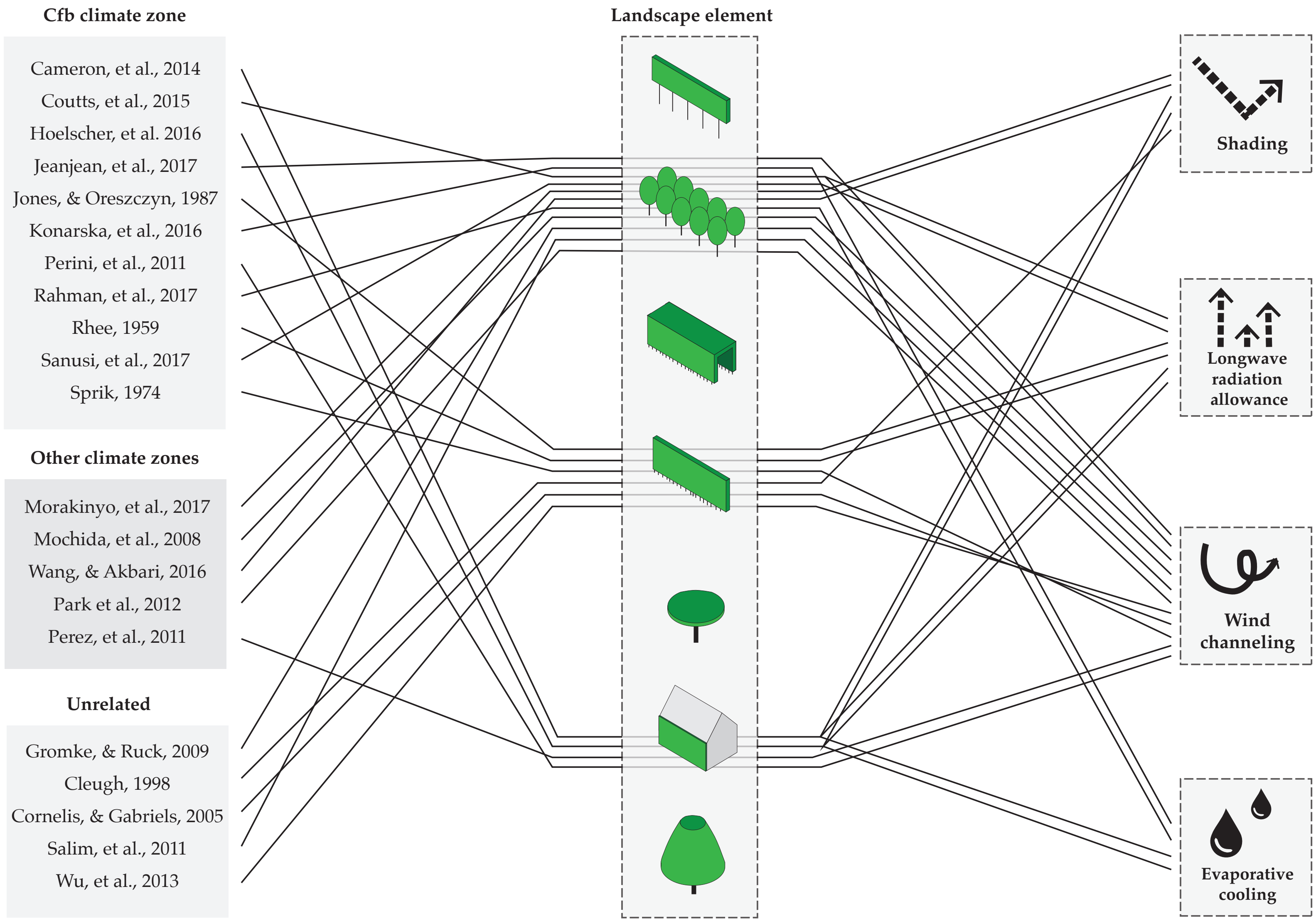


Figure 4.2.4 Overview literature review, indicating which microclimatic aspects of which landscape elements are studied and related to climate zone

4.3 ENVI-met

4.3.1 Method

In order to examine the effects of the berceaux, vertically shaped trees, umbrella trees and weeping trees on the microclimate, microclimate simulations are made in ENVI-met V4. ENVI-met V4 is a three-dimensional model that simulates surface-plant-air interactions in order to assess the urban microclimate. These simulations are based on the fundamental laws of fluid dynamics, including turbulence and airflow, and based on thermodynamics, such as heat exchange and evaporation. This three-dimensional model is coupled with two one-dimensional models: the first of these one-dimensional models extends 2500 m above ground level and simulates atmospheric processes at the boundary level, while the other calculates the heat and water transfer with the soil up to 2m deep.

ENVI-met requires two types of input: climatological and spatial input. The climatological input describes initial climatological conditions such as air temperature, wind speed, humidity and cloud cover. The spatial input contains the three-dimensional representation of the urban area of interest. For the input file it is possible to add buildings, vegetation, soils and surfaces from the database to a rectangular grid. ENVI-met V4 offers the tool Albero, with which it is possible to create customised three-dimensional vegetation with a minimum grid size of 1m. The area input file has a maximum size of 250x250 cells and a resolution of 0.5-10m in space and 10 s in time, which allows modelling small-scale surface-plant-air interactions.

Once the model has finished its simulation, it produces output files that can be visualised in LEONARDO. With this tool it is possible to extract hourly data of all the relevant parameters that influence thermal comfort: radiant temperature, wind speed, relative humidity and air temperature. Finally, based on these four types of output data, the tool Biomet is able to calculate PMV values.

Lately ENVI-met has been applied extensively in thermal comfort and urban design studies (Hagen, 2011; Ali-Toudert, & Mayer, 2007; Barakat, et al., 2017; Skelhorn, et al., 2014). However, limitations of ENVI-met include the assumption of a constant wind speed, wind direction and cloud cover (López-Cabeza, et al., 2018). Next to that, it is a time-consuming activity to run the model (Skelhorn, et al., 2014). Despite these pitfalls, ENVI-met is particularly suitable for the aim of this research due to its high spatial resolution that fits the small scale of the landscape elements. Moreover, the software provides all the output that is relevant to assess the effects of the landscape elements on thermal comfort. On top of that, ENVI-met includes surface- plant-air interactions and has the ability to create uniquely shaped vegetation, which are both required to measure the microclimatic effects of the historical green landscape elements.

Spatial input ENVI-met

Base model

The base model is located in Amsterdam (52°22′ N; 4°53′ E) and created with a grid size of 1 m. This grid size corresponds with the smallest grid size possible to build vegetation in Albero but still allows the small-scale assessment of the microclimate. During the set-up phase it appeared that ENVI-met requires the presence of buildings in the base model to diminish turbulence errors. Therefore, a street canyon with a H/W ratio below 0.3 is created, which ensures that the landscape elements will be exposed to wind (section 2.3.2). In order to allow maximum solar exposure, the street is oriented East-West (Mohajeri, et al., 2019). In the centre of the street canyon a 5-metre-wide strip of lawn is created that allows water uptake by the roots of the landscape elements from the soil. Other than this, the street canyon is entirely paved with a brick road surface. The buildings have a height and depth of 9 m and are placed 31 m from each other, creating a H/W ratio of 0.29. In order to minimise model errors, the buildings are placed with 18 m distance from the edge of the model domain. For the same reason, the model height was assigned an equal distance of 1 m for the first 20 grids, and telescoping was applied with a factor of 2.5% for the remaining 15 grids.

Landscape elements

As stated before, ENVI-met allows the creation of vegetation with the database tool Albero. This requires the definition of a representative model for each landscape element. For the vertically shaped trees, berceaux and umbrella trees this was attempted by estimating the dimensions from pictures and maps of different examples of these landscape elements (Appendix 1). While this method is not very accurate, it suffices for the 1 m grid size of Albero. Eventually the average dimensions for these three landscape elements were determined and used to create a representative model in Albero. Unlike the other three landscape elements, the shape of the weeping tree is not affected by pruning activities and therefore relies mostly on the characteristics of the species. For this reason, representative spatial dimensions were obtained from a tree nursery catalogue (van Ebben, 2019). It was chosen to use the dimensions of a weeping ash (Fraxinus excelsior ‘Pendula’), as this tree species was most represented in historic literature.

Besides modelling the canopy structure, all landscape elements were assigned the same albedo value of 0.60, a C3 CO_2 fixation type, and leaf area index (LAI) of 2 for summer and 1 for autumn. By using similar values for all landscape elements, it is possible to study the influence of the shape of each landscape element on the microclimate.

Umbrella tree
Based on 5 still-existing examples of “etagelindes” in the Netherlands and Belgium (appendix 1), a representative umbrella tree is created. While for the majority of these “etagelindes” only their lowest level sustained time, it was impossible to determine the dimensiosn of their upper two levels. Next to that, it is expected that these two upper levels do not have a significant additional influence on the microclimate. For that reason, I decided to model the “etagelinde” with one level. This representative tree has a total height of 3 m, with a stem of 2 m high and a crown of 1 m thick. The diameter of the crown is assumed to be 13m and the roots are assigned a width of 10 m and depth of 2 m. The “etagelinde” is located in the exact centre of the street canyon (figure 4.3.1).

Berceaux
Based on the dimensions of 10 still existing berceaux, I decided to build the berceau 4 m wide and 4m high (figure 4.3.2). I chose to model a completely covered berceau, as this is expected to have the most significant influence on the microclimate. Unfortunately, it was impossible to create two different trees in Albero on one PC. Therefore, the berceau is modelled as a single tree with one root system of 5 m wide and 1.5 m deep. The berceau is located parallel to the buildings in the exact centre of the street canyon.

Vertically shaped trees
As stated in section 3.2, two types of vertically shaped trees existed: pruned trees and espaliers. I decided to model the microclimatic effects of pruned trees as these generally had larger crowns than espaliers and therefore are likely to have a more significant influence on the microclimate. Based on the estimated dimensions of pruned trees from pictures, I chose to build representative vertically shaped trees with a total height of 4 m and a crown of 2m high and 3 m wide. The roots of the vertically shaped tree are modelled 3 m wide and 1.5 m deep. Similarly, to the berceau, the vertically shaped trees are located in the centre of the street canyon parallel to the buildings (figure 4.3.3)

Weeping tree
According to the nursery catalogue, the weeping ash reaches an average height of 9 m and width of 7 m (van Ebben, nd.-a). The crown was modelled to remain open inside and its branches did extend up to one metre above ground (figure 4.3.4). Based on the crown volume, the roots were estimated to be 2 m deep and 10 m wide. Similar to the umbrella tree, the weeping tree is located in the exact centre of the street.

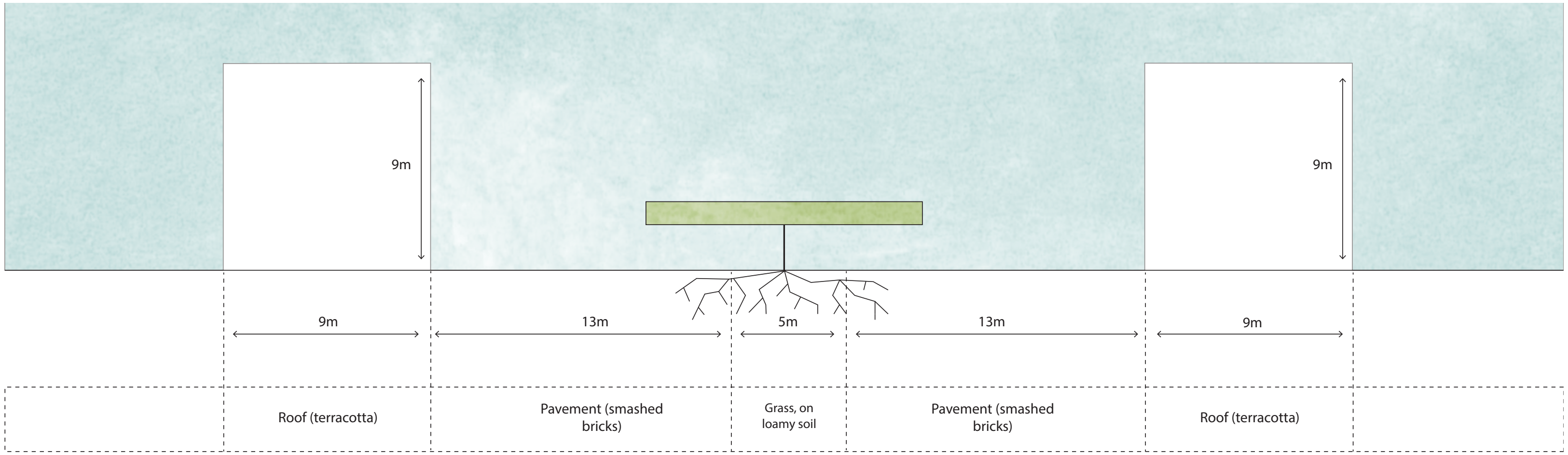


Figure 4.3.1 Section umbrella tree

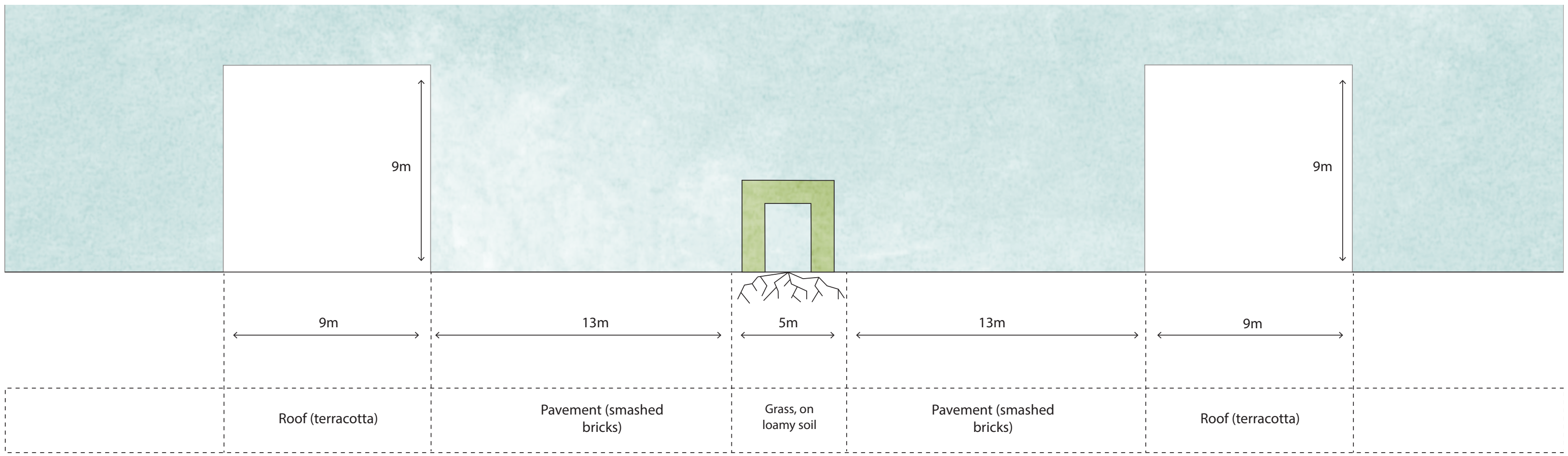


Figure 4.3.2 Section berceaux

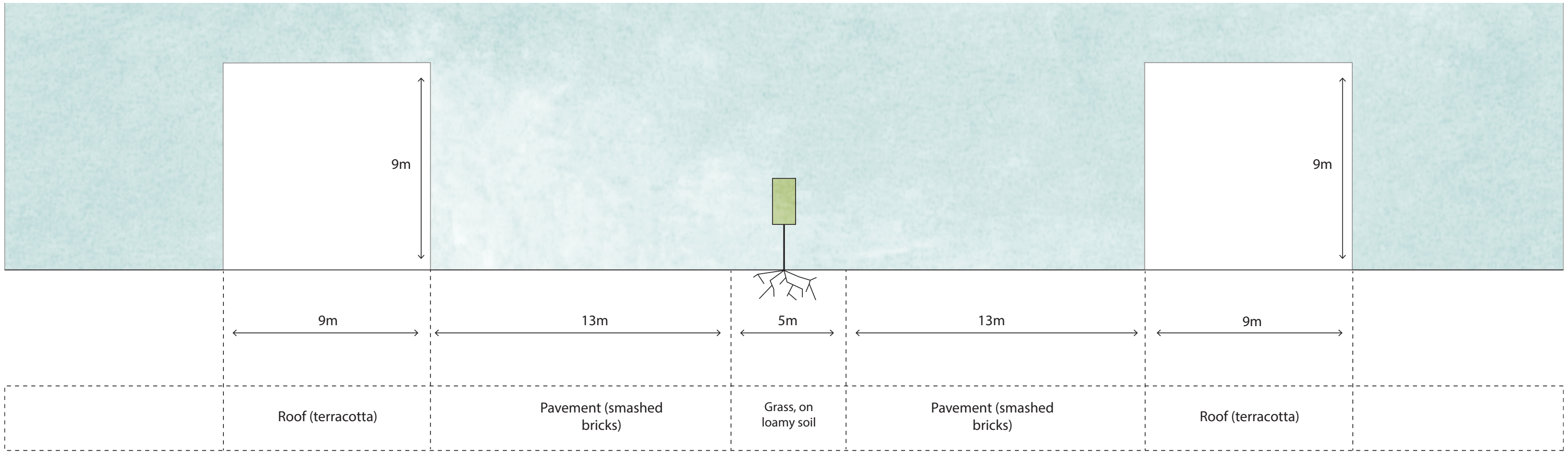


Figure 4.3.3 Section vertically shaped trees

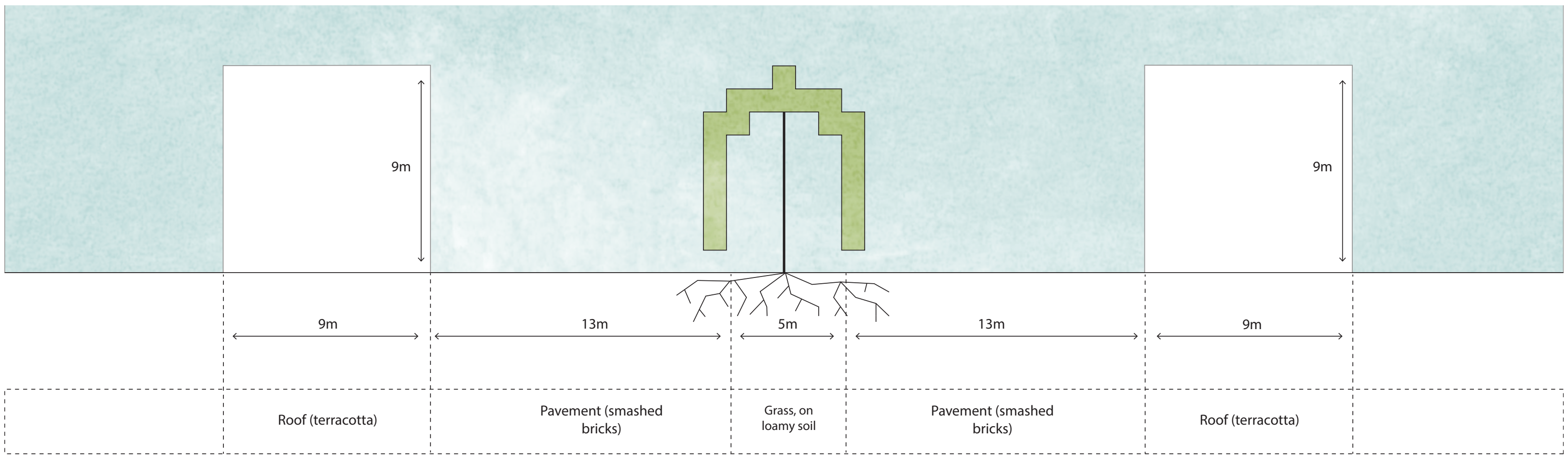


Figure 4.3.4 Section weeping tree

Meteorological input ENVI-met

The influence of the berceaux, vertically shaped trees, weeping trees and umbrella trees on the microclimate is assessed under two different meteorological conditions (table 4.3.1). These two meteorological conditions are defined to assess the ability of each landscape element to reduce cold stress in autumn and heat stress in summer.

The first meteorological condition is defined as a sunny and windy autumn day (AD). For this day air temperatures are below 21°C and wind will reduce thermal comfort (Kleerekoper, 2016). I decided to only include days for which wind speeds exceed 5 m/s, which is the maximum acceptable mean wind speed according to the Dutch standard for wind comfort (Willemsen, & Wisse, 2007). The selection of days with uncomfortable winds together with solar exposure, simultaneously allow the assessment of the deciduous landscape elements on cold stress by their influence on wind and solar exposure.

The second meteorological condition is defined as a hot summer day (HSD). This day with tropical temperatures (> 30° C, KNMI, 2012) has a clear sky and low wind speeds (<3m/s). On such days, heat stress is most severe and cooling from landscape elements is most wanted.

Based on the meteorological criteria as depicted in table 4.3.1, days are selected from the hourly dataset of KNMI station the Bilt. Data is selected from station The Bilt due to its central location in The Netherlands (52.101°N, 5.177°E), which makes it fairly representative of the Dutch climate. Days are selected over a time-period from 1989 to 2018, which is the most recent climatological period. In total, 28 hot summer days and 12 autumn days are selected. While the number of selected autumn days is limited, this is due to the unique combination of windy and sunny conditions. Then, the conditions for hot summer days are expected to increase in future with climate change.

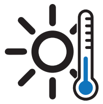
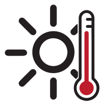
	Icon	Maximum air temperature	Mean wind speed	Mean cloud cover	Season	Indirect assessment
Autumn day (AD)		≤ 21°C	> 5 m/s	≤ 2 octa	Autumn	Ability to reduce cold stress during autumn
Hot summer day (HSD)		≥ 30°C	< 3 m/s	≤ 2 octa	Summer	Ability to reduce heat stress during summer

Table 4.3.1 Meterological selection criteria for two different climatological conditions

For these selected days the average wind speed and cloud cover was calculated (table 4.3.2). While the average cloud cover was both 1.0 octa for both the HSD and AD, the mean wind speeds were 2.3 and 5.7 m/s for the HSD and AD respecitvely. After that, the diurnal variation in air temperature and relative humidity was calculated for these days (figure 4.3.5). From these results, the maximum and minimum values for air temperature and relative humidity were identified in relation to the hour for which they occured (table 4.3.2).

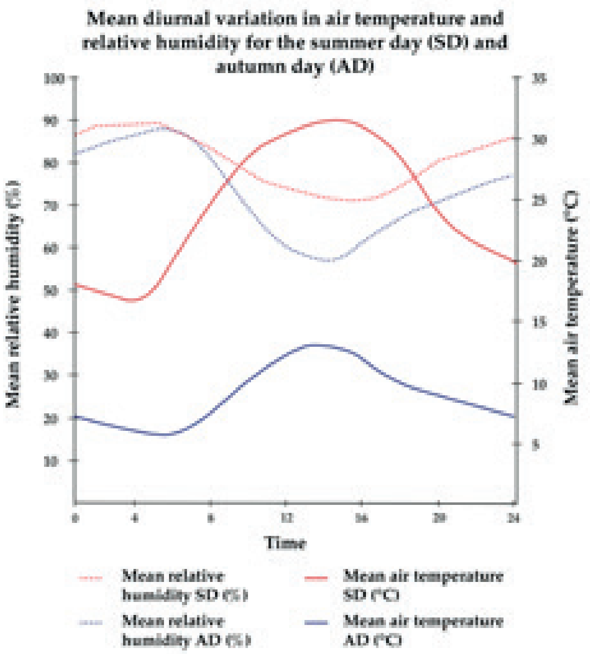


Figure 4.3.5 Mean diurnal variation in air temperature and relative humidity for the two climatlogical conditions

For the meteorological input file, the cloud cover is assumed to have a medium height, the specific humidity at 2500 m is assumed to have the default value of 7 and the roughness level to have the maximum value of 0.1. These assumptions were similar for each representative day. Next to that, each model is tested for both 90- and 0-degrees wind direction relative to the street canyon, as wind patterns in street canyons are inherently different for perpendicular and parallel wind directions (section 2.3.2).

Day	Tmin °C (time UTC+ 2)	Tmax °C (time UTC+ 2)	RHmin % (time UTC + 2)	RHmax % (time UTC + 2)
HSD	16.5 (04.00)	31.4 (15.00)	37.8 (15.00)	87.0 (04.00)
AD	5.5 (06.00)	13.0 (14.00)	56.0 (15.00)	87.8 (06.00)

Table 4.3.2 Mean values of minumum and maximum air tempera ture and relative humidity for the hot summer day (HSD) and autumn day (AD)

Simulation output

The simulation output is visualised with Leonardo on maps at 1.5m height, which approximates the average core height of the human body. These maps are made for wind speed, longwave radiation, shortwave radiation and PMV. All of these maps illustrate the effect of the landscape element on the microclimate. This is achieved by substracting the output of the base model from the output of the model with landscape elements and connoted with the word ‘delta’. To illustrate this, delta wind speed implies the difference in wind speed between the model with and model without landscape element.

Wind

While ENVI-met assumes the incoming wind speed to be constant throughout the day, wind patterns will be similar for each hour. Therefore, 15 UTC+2 was randomly chosen as the time illustrate delta wind speed (figure 4.3.6).

Longwave radiation

Longwave radiation is especially noticeable a few hours after sunset, when the urban surfaces cool down through emitting longwave radiation (Oke, et al., 2015). The influence of each landscape element on this cooling process is shown by visualising the delta mean radiant temperature for the hot summer day at 24 UTC+2 (figure 4.3.7).

Shortwave radiation

In order to illustrate the minimum and maximum amount of shade cast by each landscape element throughout the day, delta mean radiant temperature is visualised for the moments when the sun is at its highest and lowest point in the street canyon (figure 4.3.8; figure 4.3.9). These maps are visualised around 12 and 19 UTC+2 on the 21st of June and 12 and 17 UTC+2 on the 1st of October.

PMV

Hot summer day

On this hot summer day cooling is most wanted when PMV reaches highest values. This occurs at 15 UTC+2 when PMV of the base model exceeds values of 4.5, causing extreme heat stress. Around this time, the cooling potential of each landscape element is visualised (figure 4.3.10).

Autumn day

During this clear autumn day, comfort levels of the base model are below -2 PMV. Throughout the time period for which the sun enters the street canyon, cold stress is most severe around 17 UTC+2. Therefore, the influence of each landscape element on thermal comfort is assessed around this time (figure 4.3.11).

Results

Wind

As stated before, wind is simulated for both a parallel and perpendicular direction relative to the street canyon. As the H/W-ratio of the street canyon is below 0.3, a wake interference flow should occur for crosswinds (section 2.3.2). According to the simulation results, the maximum influence of landscape elements on crosswinds is below 0.4 m/s. For wind with parallel directions maximum wind speed reductions varied between 0.67 and 2.0 m/s. Due to the minimal influence of landscape elements on crosswinds, the influence on wind patterns is only visualised for parallel wind directions.

From these maps it becomes clear that the vertically shaped trees have the smallest effect on the incoming wind (figure 4.3.6). Then, while the umbrella tree and weeping tree both create a similarily shaped wake zone, the weeping tree creates a larger wake zone. Finally, most significant effects on wind speed were found for the berceau, which could reduce wind speed up to 2.45 m/s inside.

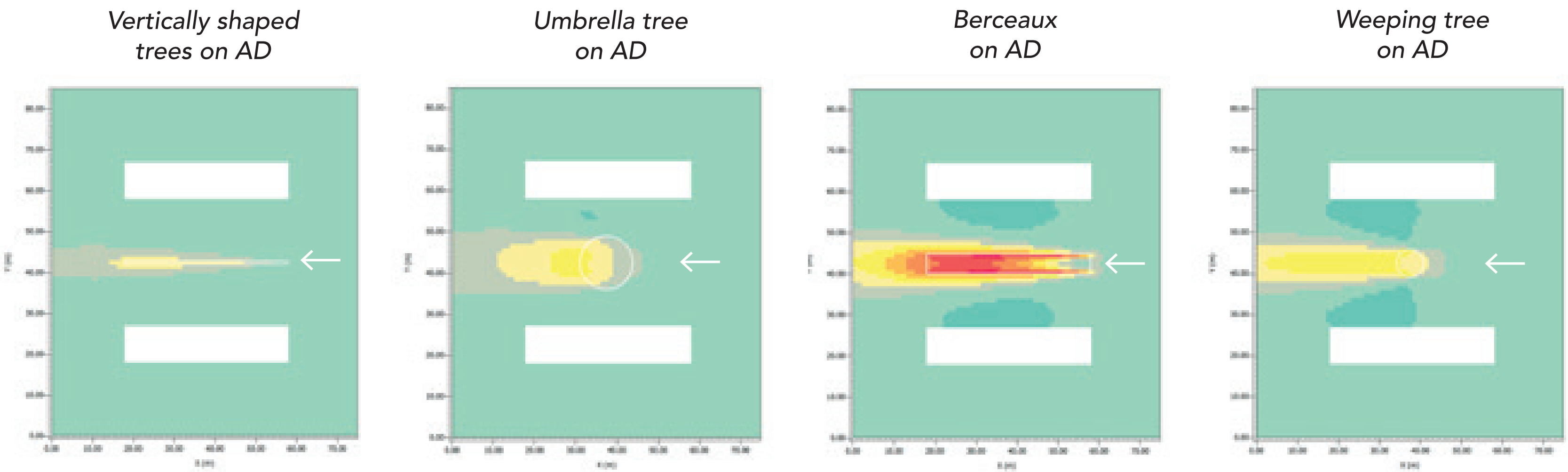
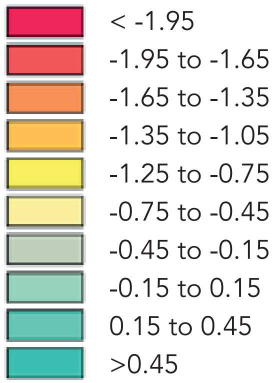


Figure 4.3.6
Difference in wind speed (m/s) between base model and each landscape element at 1.5 m height on WSD and AD at 15 UTC+2



Longwave radiation

The simulation results indicate that the vertically shaped trees trap the least heat, with a maximum effect of 0.9 °C (figure 4.3.7). While it was expected that the weeping tree would trap more longwave radiation than the umbrella tree, results show a similar effect at 1.5m height for both with a maximum increase in mean radiant temperature of 2.9°C. Finally, the berceau traps the highest amount of longwave radiation over a large part of the street, causing an increase up to 3.0 °C.

Vertically shaped trees on HSD | *Umbrella tree on HSD* | *Berceaux on HSD* | *Weeping tree on HSD*

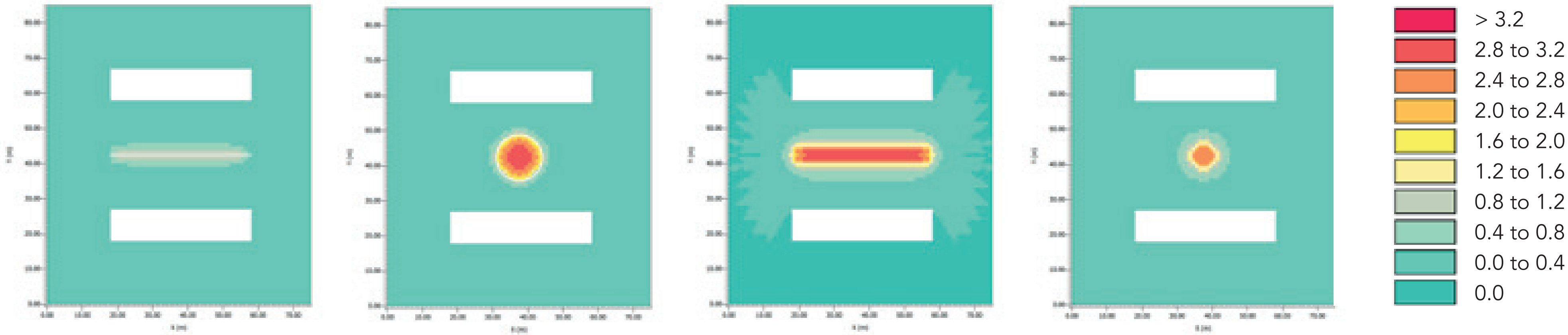


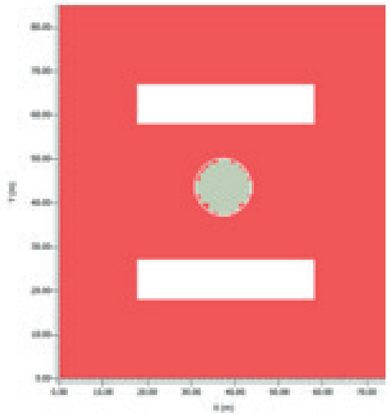
Figure 4.3.7
Difference in mean radiant temperature (°C) between the base model and each landscape element at 1.5m height for the hot summer day (a, b, c, d)

Shortwave radiation

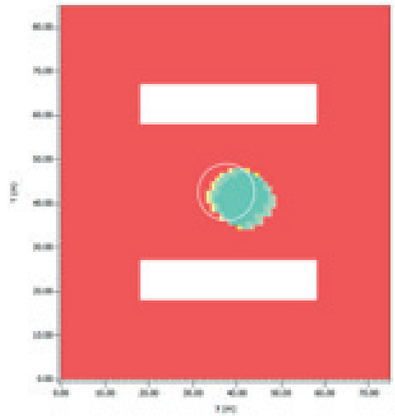
The simulation results around noon on the hot summer day indicate that the vertically shaped trees only cast a narrow strip of shade alongside the buildings, while the berceau casts a wide strip of shade inside its tunnel (figure 4.3.8 and figure 4.3.9). Even though the umbrella tree and weeping tree have a similar shading pattern, it appears that the weeping tree has a higher shading intensity. Around 19 UTC+2, the vertically shaped trees cast more shade, but this remains limited. The difference in shade casted by the berceau between 12 UTC+2 and 19 UTC+2 is rather small as well. However, smallest differences are found for the umbrella tree, which casts almost a similar amount of shade. This is radically different for the weeping tree, which has a large shading pattern around 19 UTC+2.

As the LAI of deciduous landscape elements is smaller in autumn, the shading intensity of the landscape elements is expected to reduce, and more shortwave radiation will enter the street canyon. Despite that, shading areas will be larger in autumn due to the lower solar position. These two effects are visualised at 1.5m height and confirm the hypotheses: all landscape elements have a reduced shading intensity, but a larger shading pattern. Most pronounced differences are found for the weeping tree, which shades an even larger area around 17 UTC+2

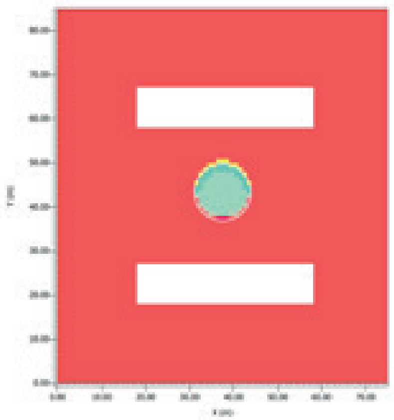
Umbrella tree
on HSD at 12 UTC+2



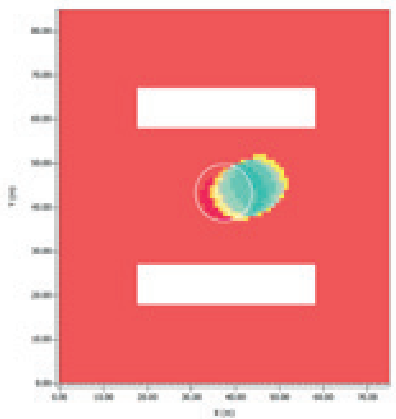
Umbrella tree
on HSD at 19 UTC+2



Umbrella tree
on AD at 12 UTC+2



Umbrella tree
on HSD at 17 UTC+2



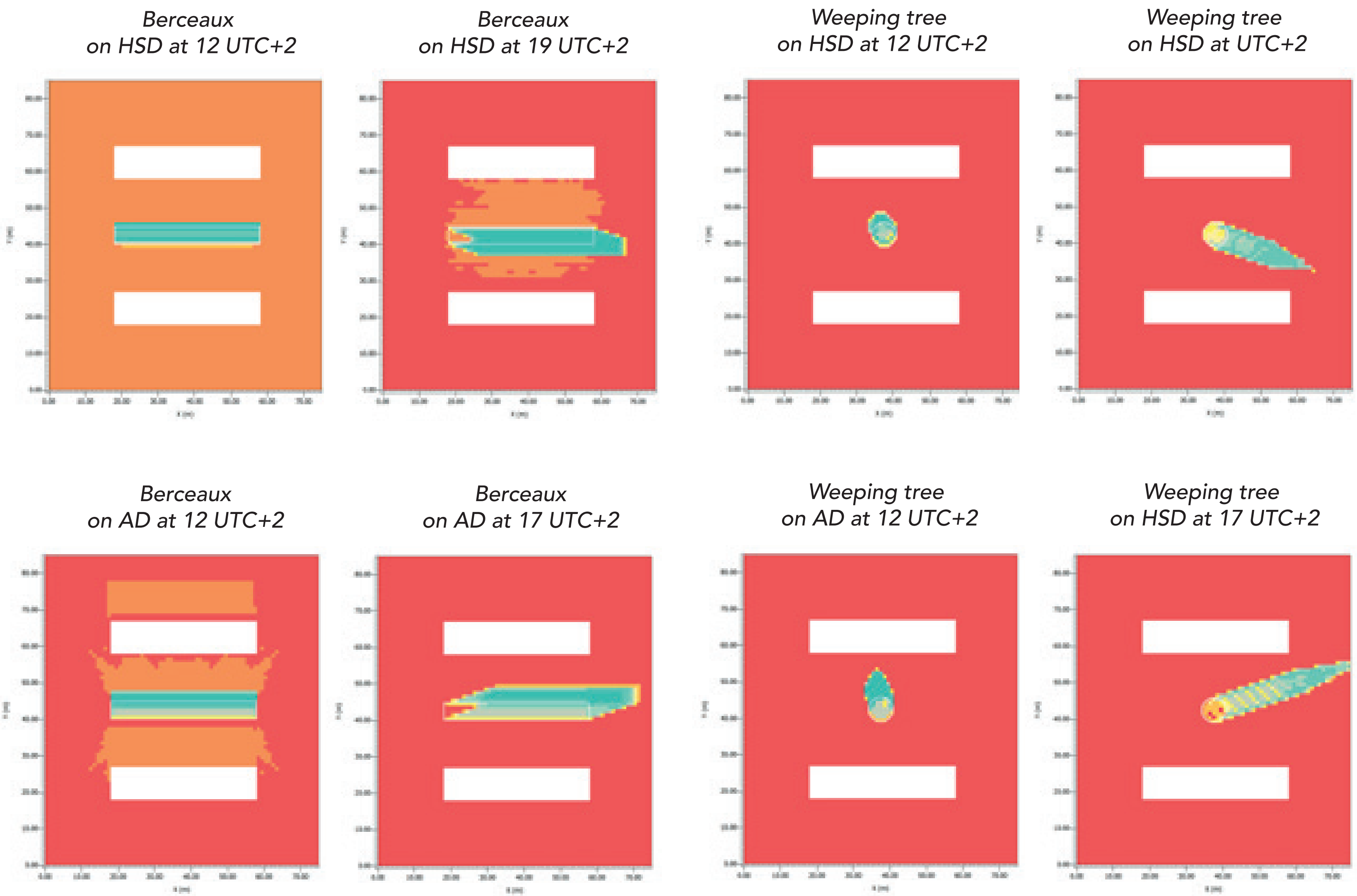


Figure 4.3.8
Difference in mean radiant temperature (°C) between the base model and each landscape element at 1.5 m height for HSD and AD

- 0.0
- -3.0 to 0.0
- -5.5 to -3.0
- -8.0 to -5.5
- -10.5 to -8.0
- -13.0 to -10.5
- -15.5 to -13.0
- -18.0 to -15.5
- < -18.0

Vertically shaped trees on HSD at 12 UTC+2

Vertically shaped trees on HSD at 19 UTC+2

Vertically shaped trees on AD at 12 UTC+2

Vertically shaped trees on AD at 17 UTC+2

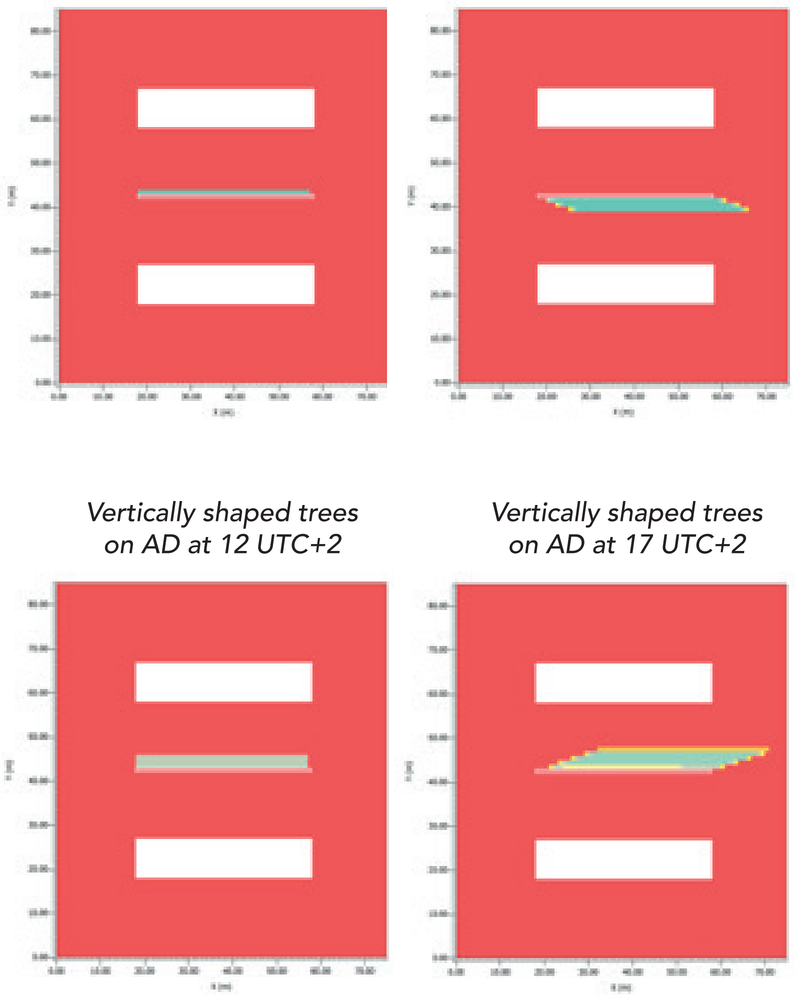


Figure 4.3.9
Difference in mean radiant temperature (°C) between the base model and each landscape element at 1.5 m height for HSD and AD

- 0.0
- -3.0 to 0.0
- -5.5 to -3.0
- -8.0 to -5.5
- -10.5 to -8.0
- -13.0 to -10.5
- -15.5 to -13.0
- -18.0 to -15.5
- < -18.0

PMV

HSD

Amongst all, the berceau most effectively contributes to reducing heat stress in the street canyon. While the weeping tree and umbrella tree both improve thermal comfort below their canopy, the weeping tree has more effect. Finally, the vertically shaped trees have a limited effect on thermal comfort.

AD

On this autumn day, landscape elements either exacerbate cold stress by casting shade or reduce cold stress by channelling wind away from pedestrian levels.

As the weeping tree and berceau reduce wind speed at pedestrian level the best, they improve thermal comfort in their wake areas. However, both landscape elements increase cold stress in those areas where they cast shade, which is most significant for the weeping tree around 17 UTC+2. Finally, while vertically shaped trees have a limited influence on wind speed, they exacerbate cold stress due to their shading effect.

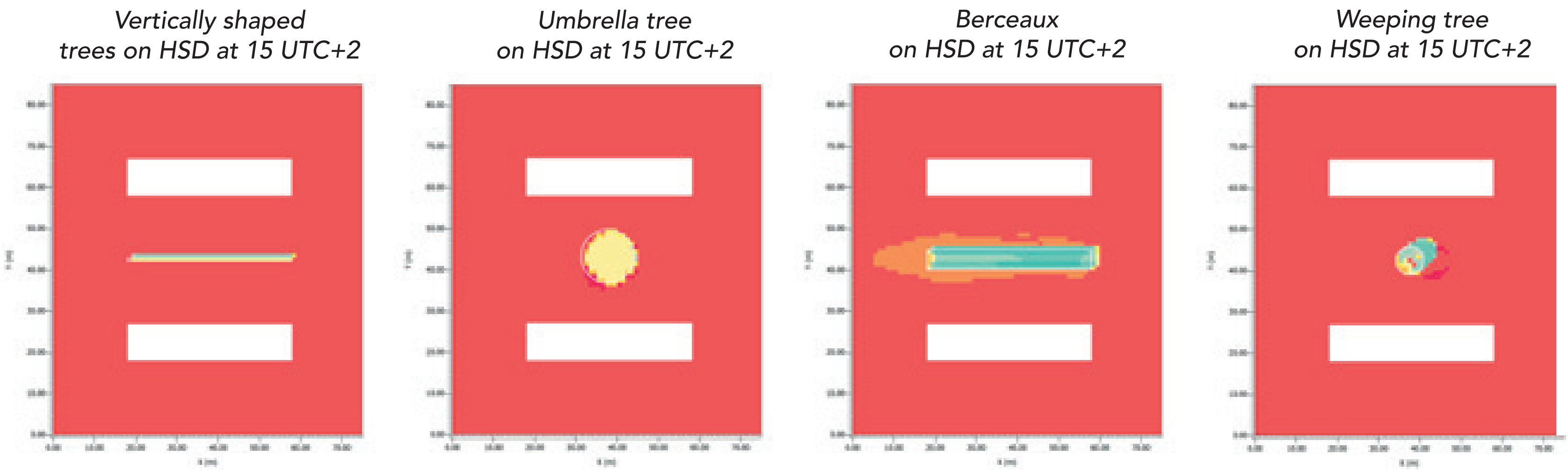


Figure 4.3.10
Difference in PMV between the base model and each landscape element at 1.5 m height for the HSD at 15 UTC+2

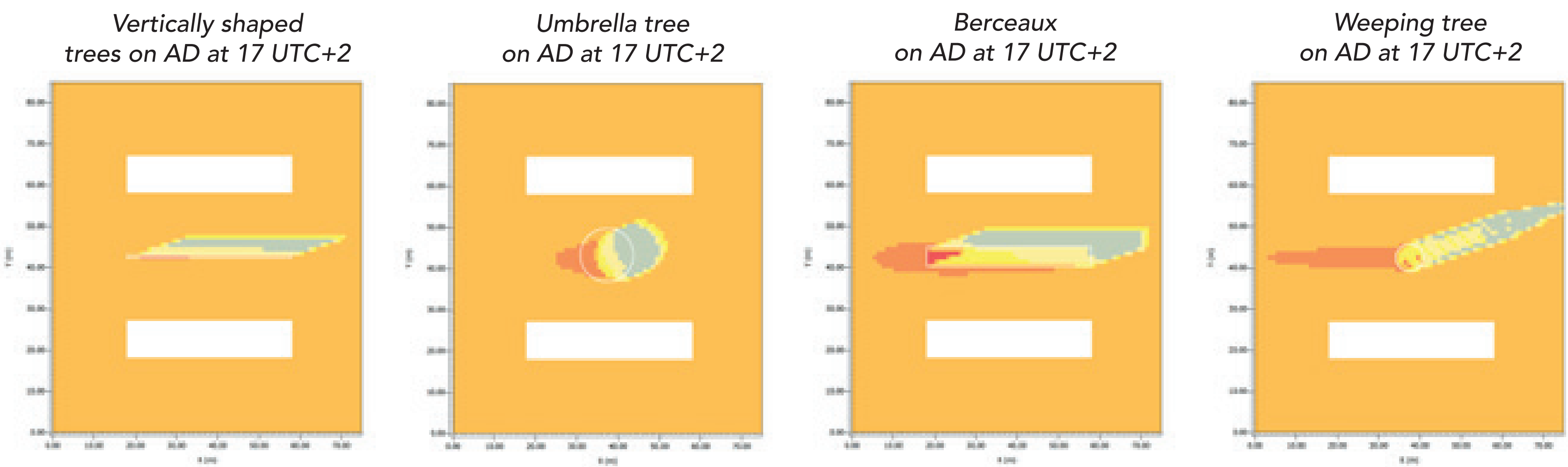


Figure 4.3.11
Difference in PMV between the base model and each landscape element at 1.5 m height for the AD at 17 UTC+2

4.4 Conclusion

Based on the outcomes for the specific climatological conditions, general conclusions are drawn about the influence of the landscape elements on thermal comfort.

First of all, the berceau most effectively reduces shortwave radiation throughout the afternoon, but also blocks potential ventilation. On calm summer days such as the HSD, the berceau most significantly reduces heat stress. However, in autum the berceau continues to cast a significant amount of shade and thereby increases cold stress. At the same time, the berceau reduces wind speed significantly, which reduces cold stress.

The weeping tree is able to reduce heat stress well by casting a significant amount of shade in late afternoon. In autumn, it reduces cold stress on its lee side, but exacerbates cold stress by its large shading pattern.

Next, the umbrella tree reduces heat stress by shading, albeit less signifcant. In autumn, the umbrella tree slightly improves cold stress on its lee side, but potentially worsens cold stress underneath its crown through its shade.

Finally, the vertically shaped trees showed a minimal effect on heat stress. However, this landscape element showed most potential on ventilation and longwave radiation allowance. While this landscape element only had a limited effect on wind, it was unable to reduce cold stress in autumn.

The influence of each landcape element on thermal comfort is represented in a simplified way in figure 4.4.1. Overall, each landscape element has a significant influence (++) on at least one aspect in relation to thermal comfort. While the berceau, weeping tree and umbrella tree significantly modify shortwave radiation and wind, the vertically shaped trees optimally allow ventilation in summer and solar radiation in winter.

Influence on heat stress	Shading	+	++	+++	++
	Ventilation	+++	+	+	++
	Longwave radiation allowance	+++	+	+	++
Influence on cold stress	Solar allowance	+++	+	+	++
	Wind blocking	+	+++	+++	++
	Longwave radiation trapping	+	++	+++	++

Figure 4.4.1 Overview of the microclimatic performance of the landscape elements on heat and cold stress

Figure V
Green walls at huis de Voorst (Schenk, 1700)

Chapter 5

Test bed identification

5.1 Introduction

In the previous chapter the green historical landscape elements have been evaluated for their performance on microclimate control. From this chapter, it appeared that all of the landscape elements have the potential to significantly influence thermal comfort. While most of these landscape elements originally existed in private estate gardens or on the countryside, they have to be redesigned in order to successfully fit into a contemporary urban context. For example, these landscape elements have to allow pedestrian flow, sufficient sight from and onto sidewalks and sufficient daylight intrusion into the buildings.

In order to refit these landscape elements, test beds of streets are defined for which thermal comfort is most problematic. These test beds are generalised abstractions from existing urban streets. Due to their general character, they are representative of and applicable to multiple urban streets. In the following part of this chapter the selection procedure of the test beds is described.

5.2 Test bed identification

For the aim of this thesis the test beds have to be representative of urban streets for which thermal comfort is most crucial. For that reason, urban streets typologies are selected that are used by a high number of people. One example of such streets are shopping streets. In Dutch cities, shopping streets are usally located in the city centre, where retail facilities such as shops, bars and restaurants are clustered. Following from the land use maps of CBS (2012) it appears that the three largest Dutch cities, Amsterdam, Rotterdam and The Hague, have the largest retail area. While these retail areas also have a significant UHI-effect of 2 °C (Klimaateffectatlas, 2017), I decided to define test beds that are representative of shopping streets in these three cities. In addition, these three cities are located nearby KNMI-weather stations that allow the assessment of large scale wind patterns in relation to wind patterns in the street canyons (figure 5.2.1; Lenzholzer, 2015).

The retail areas of these cities are based on the land use map of CBS (2012), which indicates ‘retail and hospitality areas’ amongst other types of land use on a national scale. While this land use map might be slightly outdated, it looks similar to the more recent policy documents of the city of Rotterdam and Amsterdam (Stadsontwikkeling Rotterdam, 2017; Gemeente Amsterdam, 2017). Yet, unlike these policy documents, this map uses a universal definition of retail areas for all three different cities and is therefore most suitable as a selection criterion.

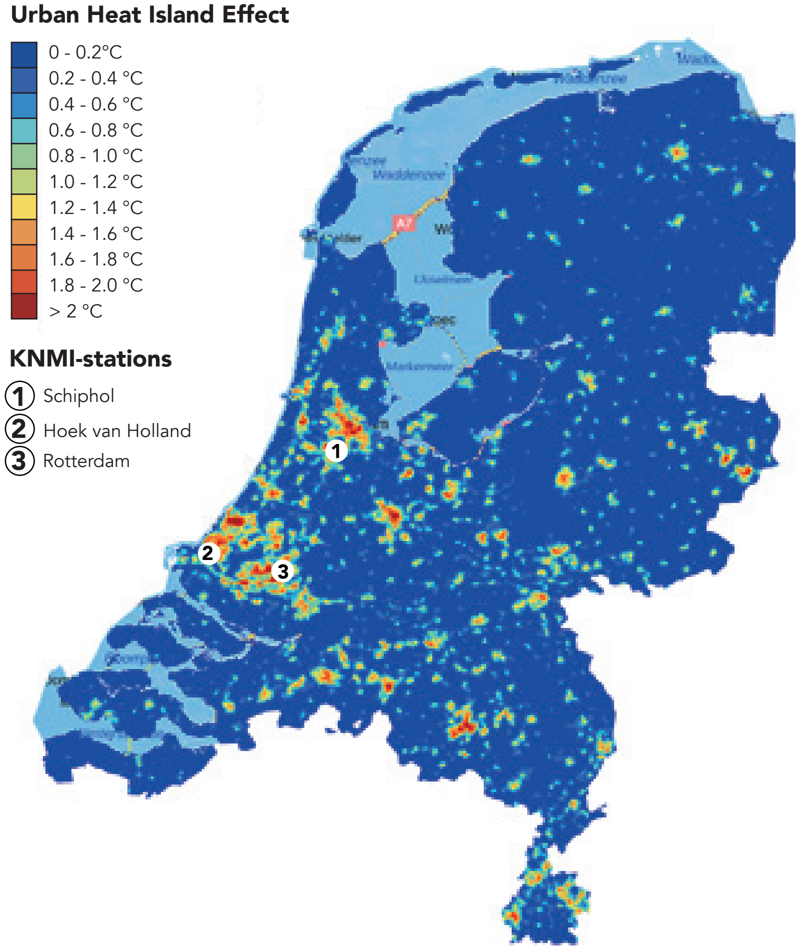


Figure 5.2.1 UHI-map of the Netherlands for 2050 WH climate scenario (Klimaateffectatlas, 2017) and location of KNMI-weather stations closest to Amsterdam, Rotterdam and The Hague

In order to define representative street profiles, a grid of 500 by 500 m is laid on top of the retail area according to CBS (2012) for each city (figure 5.2.2; 5.2.3; 5.2.4). Then, all streets are listed for each grid that covers at least 10 streets from the retail area. In total, this results in 15 grids; 6 for Amsterdam, 5 for Rotterdam and 4 for The Hague. After that, 4 streets are randomly selected from each grid with the ASELECT function in Excel. This random sampling method resulted in the random selection of 60 streets. While the H/W ratio and street orientation significantly influence the microclimate of a street canyon (Shishegar, 2013), these parametres are measured for these 60 streets. Their width is measured with the Google Maps (2019) measurement tool and the average roof height is estimated from the height profile along the roofs made with the section tool in the AHN-viewer (AHN, 2019).

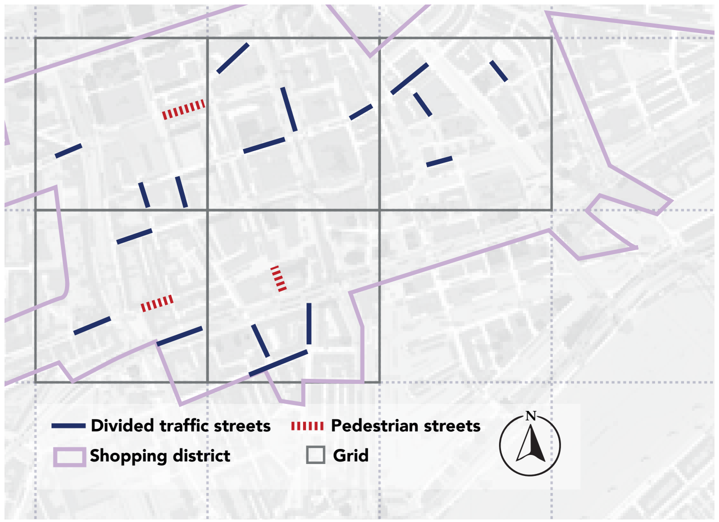


Figure 5.2.2 Selected streets from retail area Rotterdam

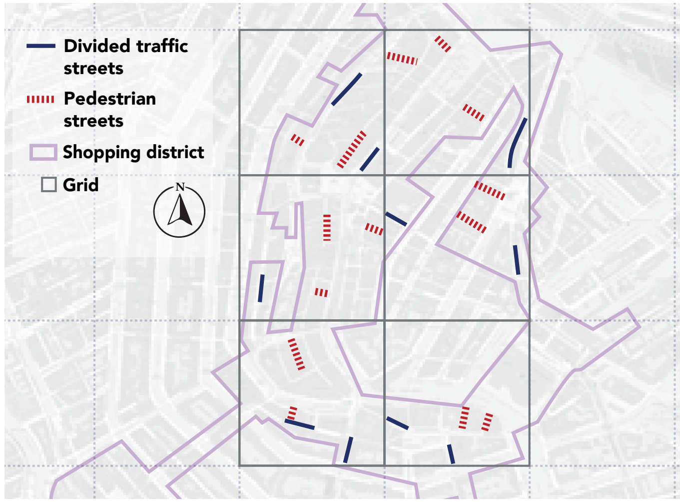


Figure 5.2.3 Selected streets from retail area Amsterdam

Figure 5.2.4 Selected streets from retail area The Hague

From the analysis it appears that street profiles vary significantly in H/W ratio; from 0.42 for the Nieuwezijds Voorburgwal in Amsterdam to 4.5 for the Lange Niezel in Amsterdam. Within this range, two different types of street profiles can be distinguished: pedestrian and divided traffic streets (figure 5.2.5). This typology is based on the position of pedestrians within the street profile, following that thermal comfort is most crucial in those areas that are used by pedestrians. Based on the measurements, pedestrian streets have a mean H/W ratio of 2.5 and divided traffic streets have a mean H/W ratio of 1,0 (figure 5.2.6)

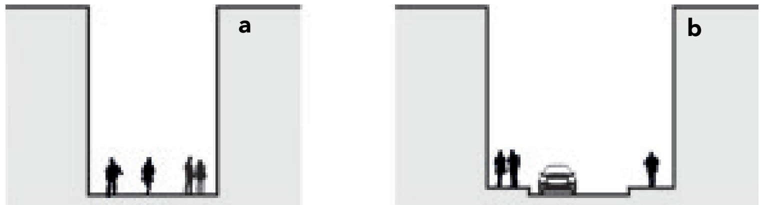


Figure 5.2.5 Typical street profiles of pedestrian (a) and divided traffic (b) streets

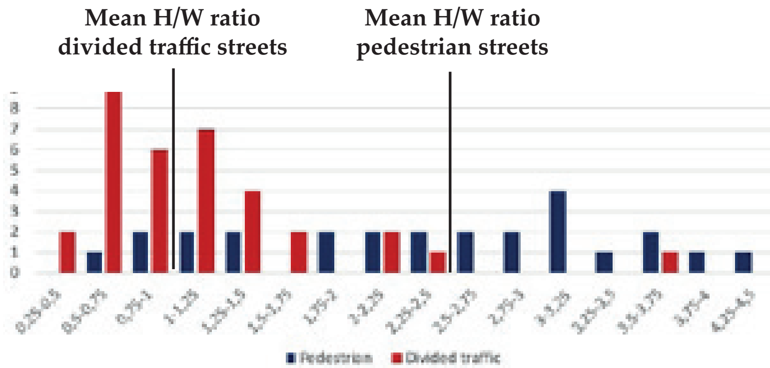


Figure 5.2.6 H/W ratio's of measured street canyons

Microclimate

As mentioned before, the microclimate of a street canyon is mostly the result of the street orientation and H/W ratio. As pedestrian-only streets have a H/W ratio of 2.5, not much solar radiation will access these streets and the influence of shortwave radiation on heat stress will be limited. Consequently, I decided to focus only on divided traffic streets. Next to that, as thermal comfort matters most when most people use the street, I focus only on the microclimate during the afternoon. In the next part of this section, the two most problematic orientations are described in relation to solar exposure and air flow.

Air flow

According to section 2.3.2, a skimming flow will occur for crosswinds as the test beds have a H/W ratio of 1. However, in case of parallel winds, a channelling effect might occur (section 2.3.2), leading to potentially uncomfortable wind speeds

The Dutch standard for wind comfort is a mean wind speed of 5 m/s (Willemsen, & Wisse, 2007). However, the use of mean wind speed as a criteria to define thermal comfort has been questioned by urban meteorologists. Alternatively wind gusts are a better indicator (Stathopoulos, 2009). Therefore, hourly data about wind gusts from KNMI station Schiphol, Rotterdam and Hoek van Holland (figure 5.2.1) for the climatological period 1989 and 2019 are adjusted to pedestrian height in an urban context according to the formula provided in Algeciras & Matzarakis (2016):

$$WS_{1.1} = WS_h * (1.1/\mathrm{h})^{\alpha} \qquad (1) \qquad \alpha = 0.12 * z_0 + 0.18$$

$WS_{1.1}$ wind speed at 1.1 m height (core body height)
WS_h wind speed at measured height KNMI station
h height for which wind speed is measured = 10m (source)
z_0 roughness length = 1.2 (Silva, et al., 2007)

Figure 5.2.7 illustrates the direction of wind gusts above 5 m/s. Around 30% of these uncomfortable wind gusts have a South-Westerly direction.

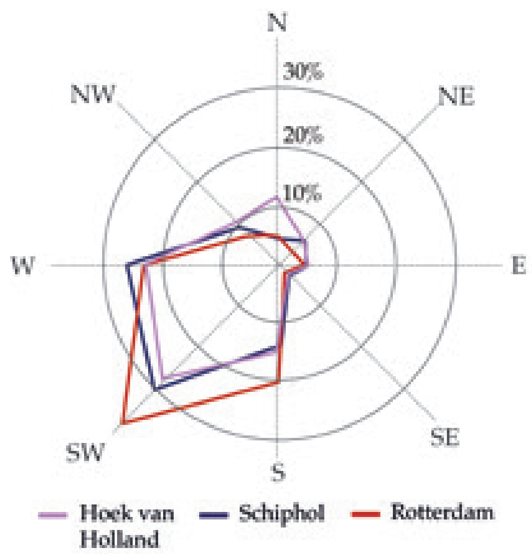


Figure 5.2.7
Wind direction for wind gusts exceeding 5m/s, based on data KNMI station Schiphol, Rotterdam and Hoek van Holland and adjusted to urban wind speed at pedstrian height with formula 1

However, wind has the potential to improve thermal comfort when air temperatures exceed 21°C. In this case, average wind speed is analysed as short-time wind gusts do not help to reduce heat stress for the whole hour. Data about average wind speed for hours with air temperatures above 21°C has been obtained from the same three KNMI stations (figure 5.2.1) over the climatological period between 1989 and 2019. From the wind rose, it becomes clear that cooling winds have no uniform direction for the three different cities (figure 5.2.8). In this case, studying local small-scale air patterns is more useful (Lenzholzer, 2015). However, due to the local character of these air flows, this method does not suit the general character of the test beds.

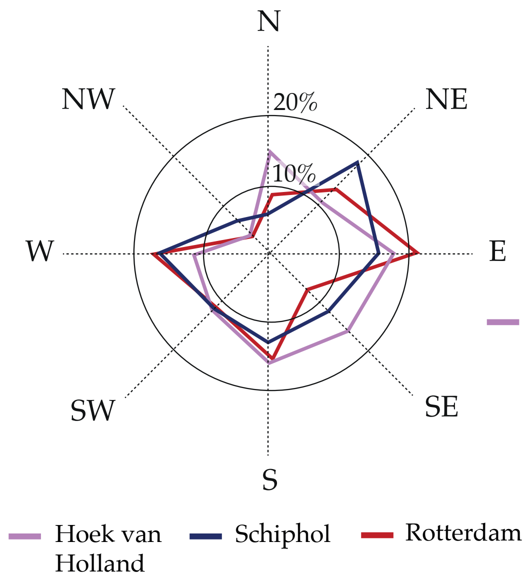


Figure 5.2.8
Wind direction for winds during hours with air temperatures > 21°C, based on data of the Bilt and adjusted with formula 1

Solar exposure

East-West streets (E-W)
While the Northern sidewalk of E-W oriented streets receives solar radiation for the whole afternoon on the 21st of June, no solar radiation enters these streets on the 23rd of September (figure 5.2.9).

Southwest-Northeast (SW-NE)
Different from E-W oriented streets, both sidewalks of SW-NE streets are exposed to the sun on the 21st of June. While the Northern sidewalk is exposed to solar radiation from noon until 16 UTC+2, the Southern sidewalk is exposed to solar radiation from 15.00 UTC+2. On the 23rd of September the Northern and Southern sidewalk still receive solar radiation, albeit for a shorter time period (figure 5.2.10)

Southeast-NorthWest streets (SE-NW)
These streets are only exposed to solar radiation in the afternoon from noon untill 4.45 UTC+2 on the 21st of June. Which is for a shorter time period compared to the aforementioned street orientations. Nevertheless, on the 23rd of September only a limited amount of solar radiation accesses the street during the afternoon (figure 5.2.11).

North-South steets (N-S)
Similarly to SE-NW streets, N-S streets are exposed to solar radiation between noon and 4.45 UTC+2 on the 21st of June. During this afternoon, both sidewalks receive solar radiation for an almost equal amount of time. In autumn these streets still receive a significant amount of solar radiation (figure 5.2.12).

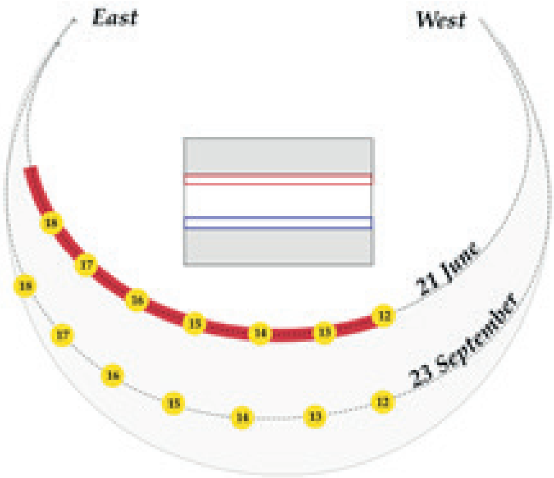


Figure 5.2.9 Exposure of sidewalks in East-West oriented streets in summer and autumn

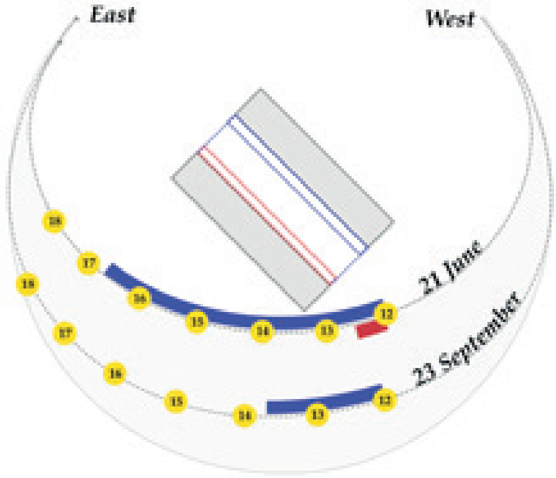


Figure 5.2.11 Exposure of sidewalks in Southeast-Northwest oriented streets in summer and autumn

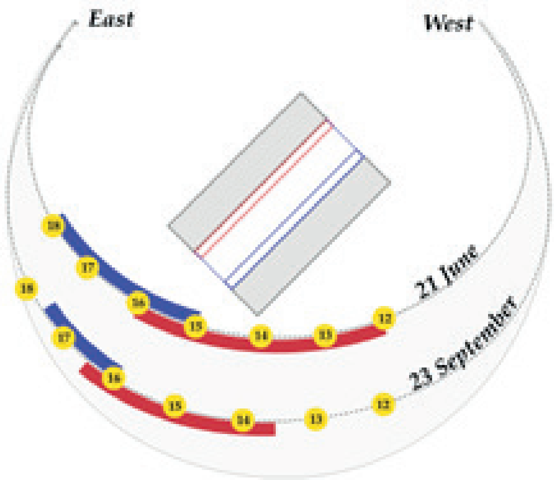


Figure 5.2.10 Exposure of sidewalks in Southwest-Northeast oriented streets in summer and autumn

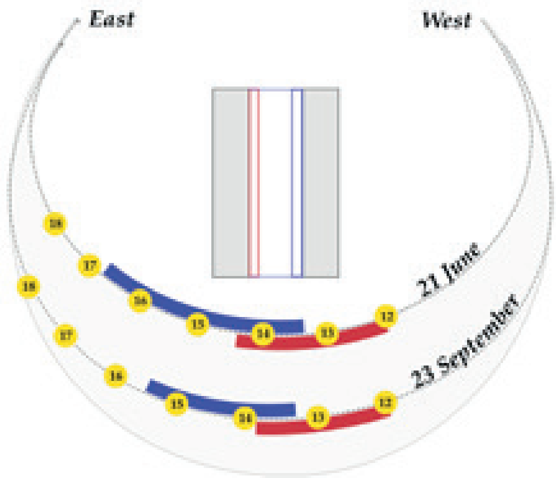


Figure 5.2.12 Exposure of sidewalks in North-South oriented streets in summer and autumn

5.3 Summary

By measuring 60 randomly selected shopping streets in Amsterdam, The Hague and Rotterdam, an average H/W ratio of 1 was found for divided traffic streets. Then the microclimate for different streets orientations was assessed (figure 5.2.13). In summer, SW-NE and E-W streets receive solar radiation during the whole afternoon and are therefore most prone to heat stress. In autumn, E-W and SE-NW street receive least solar radiation and thereby have a high chance of cold stress. For ventilation there was no clear relationship between street orientation and wind direction amongst the three cities. Finally, SW-NE streets most often experience wind nuisance and are therefore prone to cold stress. As SW-NE and E-W streets have potential risks for both heat and cold stress, these two orientations are used to develop the test beds. The shopping streets represented by E-W test beds with a H/W ratio of 1 include De Meent and Kruiskade in Rotterdam and Reguliersdwarsstraat in Amsterdam. Then the shopping streets represented by SW-NE test beds with the H/W ratio of 1 include the Hoogstraat in Rotterdam.

	SW-NE	E-W	SE-NW	N-S
Solar radiation during afternoon on 21 June (hours)	6	6	4 ¾	4 ¾
Solar radiation during afternoon on 23 September (hours)	4	0	1 ¾	3 ½
Ventilation	No clear direction			
Wind gusts > 5m/s	± 30%	20-30%	< 20%	20-30%

Figure 5.2.13 Microclimate for different street orientations of streets with H/W = 1

Figure VI
Berceau at
estate Petersburg
(Stoopendaal,
1718-1719)

Chapter 6

Adapted versions of historical landscape elements

6.1 Introduction

In this chapter I describe how the historical landscape elements are refitted to reduce both heat and cold stress in contemporary cities. In the first phase of this research through design process, each landscape element is adjusted to reduce heat stress. During this iterative process the designed landscape element is repeatedly evaluated and adjusted to optimally reduce heat stress. However, I found that landscape elements that reduce heat stress well often worsen cold stress. For that reason, the five best alternatives for heat stress reduction are selected and redesigned to improve cold stress as well. During this iterative process the design alternatives are evaluated on both heat and cold stress reduction. Finally, the best three alternatives are selected and implemented in a real context. This process, as depicted by figure 6.1.1, is done for both East-West and South West – North East streets.

The designing process has been done with the help of Sketchup, a software in which three dimensional landscapes can be build and is able to simulate shading patterns. Based on these shading patterns, different design alternatives are suggested.

For both heat and cold stress, the solar path in Sketchup has been simulated from noon until early evening, as most people use the shopping district during this time-period. For heat stress reduction, a shadow analysis is done for the 21st of June, when the sun reaches its highest and longest path. Then, for cold stress reduction, the shadow analysis is done for 23rd of September, which is at the beginning of autumn when landscape elements still have some of their leaves.

The evaluation of the landscape elements is based on the factors as described in section 2.4. In summary, green landscape elements can reduce heat stress through shading and evaporation. In doing so, these landscape elements should not obstruct ventilation and longwave radiation.

In autumn landscape elements can reduce cold stress through blocking wind and trapping longwave radiation. In blocking wind and trapping longwave radiation, it is important that these landscape elements do allow maximum solar radiation.

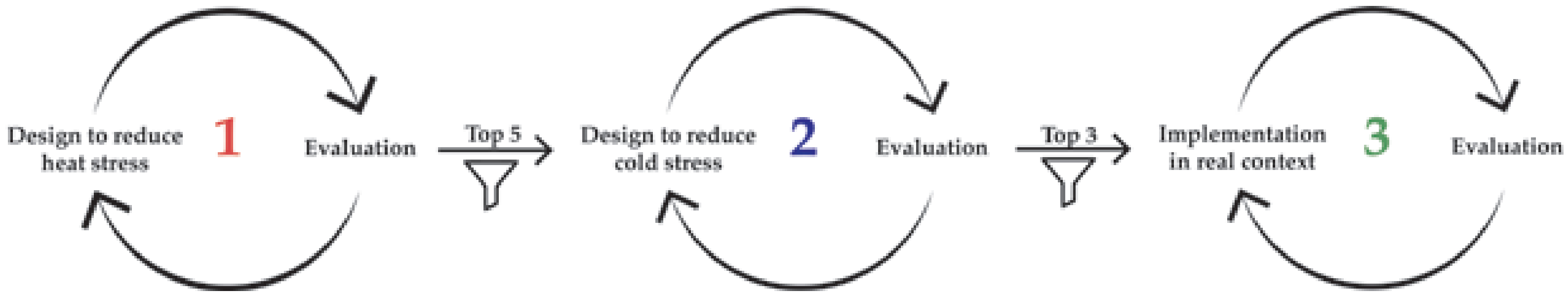


Figure 6.1.1 Research through design process

However, due to the limited amount of solar radiation that accesses E-W oriented streets this potential is not taken into account for E-W oriented streets. Due to the absence of shortwave radiation, longwave radiation in the street canyon will be limited as well (Oke, et al., 2016) and is therefore not considered in the evaluation.

Since the aforementioned factors do not equally contribute to thermal comfort (section 2.4), they are assigned different weighing factors. From high to low, shading/solar exposure has a weight of 3, ventilation/wind blocking a weight of 2 and longwave radiation allowance/trapping and evaporative cooling a weight of 1. For more information see section 2.4.

Together, this results in a simplified evaluation formats for heat stress reduction (figure 6.1.2), and a combined evaluation for heat and cold stress reduction for E-W (figure 6.1.3) and SW-NE oriented streets (figure 6.1.4).

The overall score of each prototype is given by rating each aspect of the evaluation format between 0 and 3 and multiplying this rate with with the weight assigned to this factor. The ratings for solar radiation are based on shade analyses in Sketchup. Ratings for other aspects are based on the expert knowledge I gained from writing the theoretical framework (chapter 2), the literature review and the ENVI-met simulation results (chapter 4).

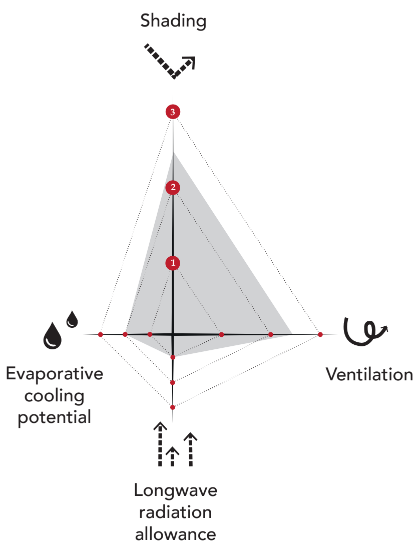


Figure 6.1.2 Evaluation format for heat stress for both street orientations

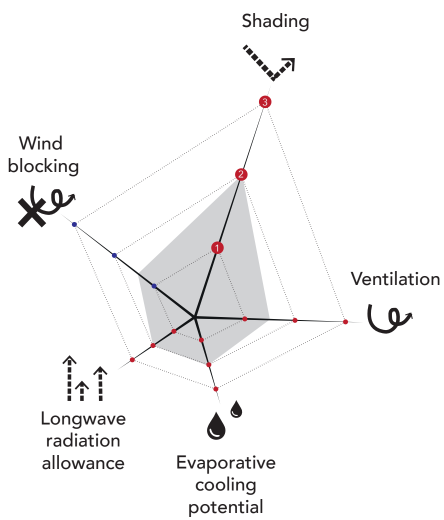


Figure 6.1.3 Evaluation format for heat and cold stress for E-W oriented strees

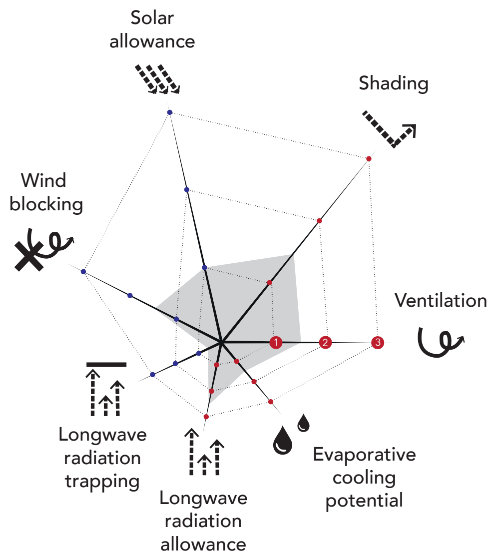
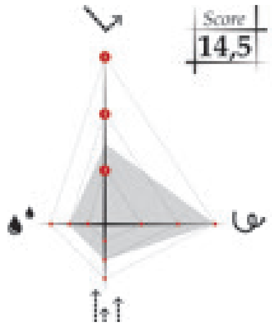


Figure 6.1.4 Evaluation format for heat and cold stress for SW-NE oriented strees

6.2 Heat stress
East-West streets

Figure 6.2.1
Evaluation maxtrix parallel vertically pruned trees



Parallel vertically pruned trees
For the East -West oriented test-beds, vertically pruned trees need to have at least a total height of 5 metres to cast a significant amount of shade on the Northern sidewalk (figure 6.2.2). At the same time, these large crowns have a more significant evaporative cooling potential. If vertically pruned trees are placed parallel to the street, they optimaly allow ventilation and cast shade from twelve until at least mid-afternoon (figure 6.2.1). From then, the sun moves slowly towards a more parallel position relative to the street, and thereby radiates behind the trees.

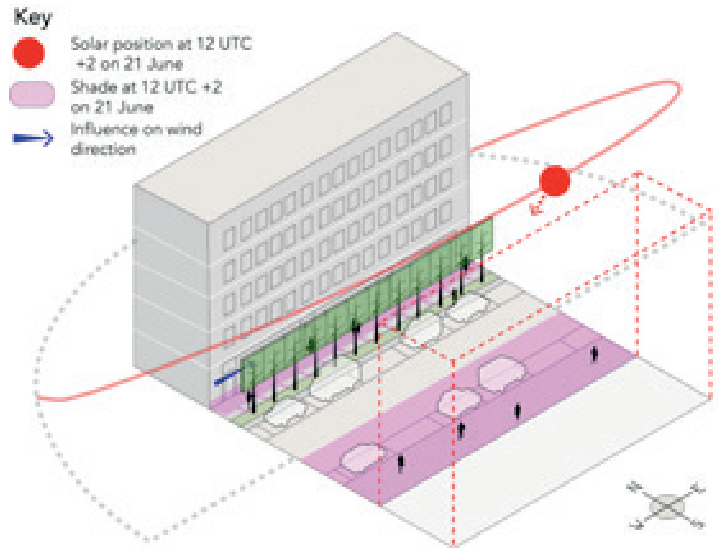
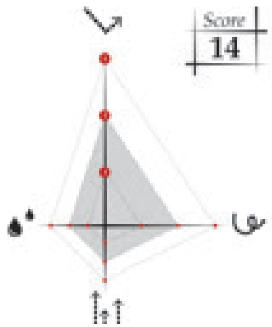


Figure 6.2.2 Parallel vertically pruned trees

Figure 6.2.3
Evaluation matrix diagonal vertically pruned trees



Diagonal vertically pruned trees
Based on a shadow analysis in Sketchup, I found that vertically shaped trees with an orientation of 30 degrees towards the street cast most shade during the afternoon (figure 6.2.3 and 6.2.4). These trees are planted with a distance of 3 metres and their width covers half of the sidewalk. In order to further increase their shade around noon, they could be planted more closely together, but this would reduce longwave radiation allowance. Then, the trees could also be made wider to increase their shading effect around the end of the afternoon, but this would reduce potential ventilation.

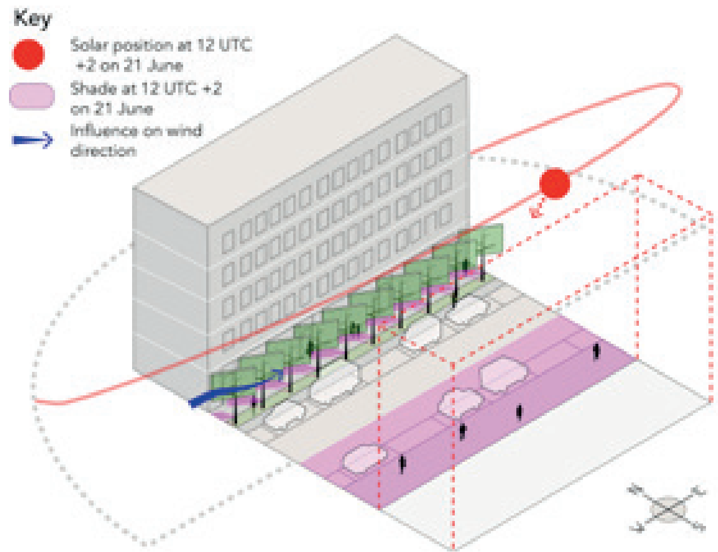


Figure 6.2.4 Diagonal vertically pruned trees

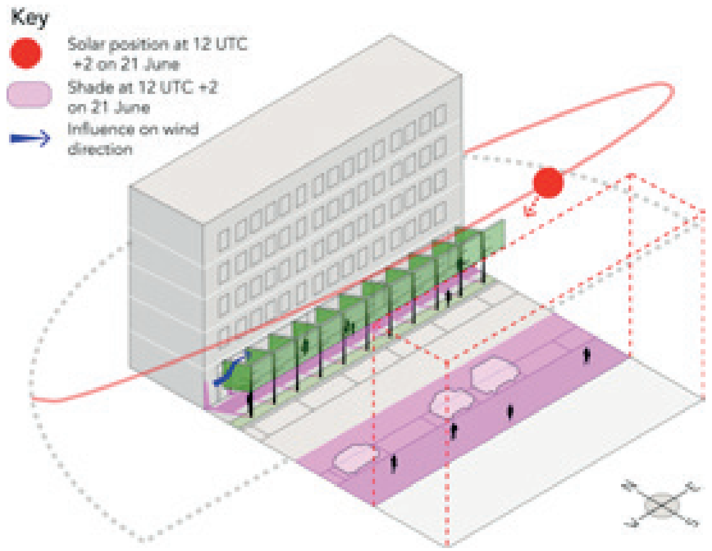
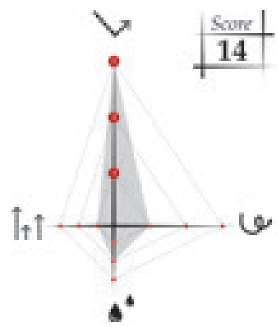


Figure 6.2.5 Mixed vertically pruned trees

Mixed vertically pruned trees

In order to achieve a maximum shading effect, vertically pruned trees with different orientations have to be combined. Optimal shading can be reached with the design as illustrated in figure 6.2.5. The parallel trees cast shade in the early afternoon and the diagonally oriented trees cast shade between mid- and late afternoon. Despite its shading ability, it inhibits potential ventilation and longwave radiation (figure 6.2.6).

Figure 6.2.6
Evaluation matrix mixed vertically pruned trees



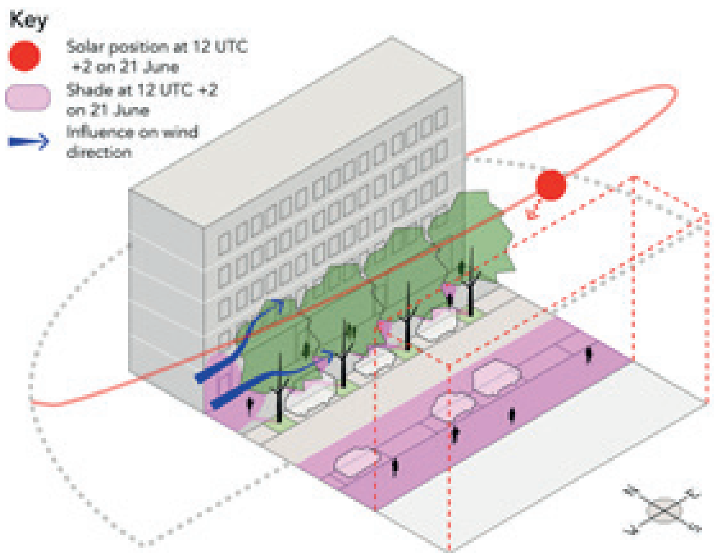


Figure 6.2.7 Tree lane above sidewalk

Tree lane above sidewalk

Tree lanes in general have a large crown volume and thereby a large evaporative cooling potential. This prototype consists of one row of small trees along the Northern sidewalk (figure 6.2.7). As their crowns are located above the sidewalk and close to the buildings, they are able to cast shade from early until late afternoon. For this prototype, the species acer campestre could be used, which will eventually grow 7 metres wide and become 11 m high (van Ebben, n.d.-b). However, while the tree lane is located above the sidewalk, it significantly reduces ventilation. Next to that, the high density of this tree lane causes a significant amount of longwave radiation trapping (figure 6.2.8).

Figure 6.2.8
Evaluation matrix of tree lane above sidewalk

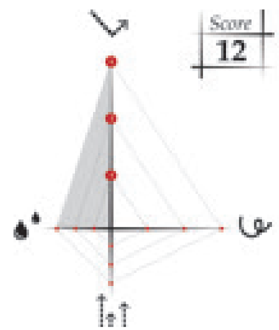
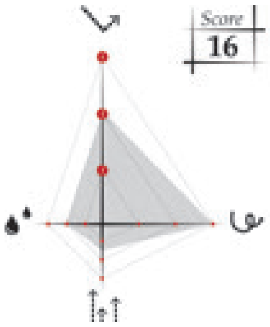


Figure 6.2.9
Evaluation matrix large tree lane



Large tree lane

As shown by figure 6.2.10, a large tree lane is located in the centre of the street canyon. These large trees are well able to shade the Northern sidewalk between early and mid-afternoon. However, later in the afternoon, the sun will radiate behind these trees, reaching the sidewalks. Despite that, this tree lane will channel wind towards the sidewalks and thereby improves ventilation (figure 6.2.9). Furthermore, as the crowns are not located directly above the sidewalk, a smaller amount of longwave radiation will be trapped compared to the previous prototype.

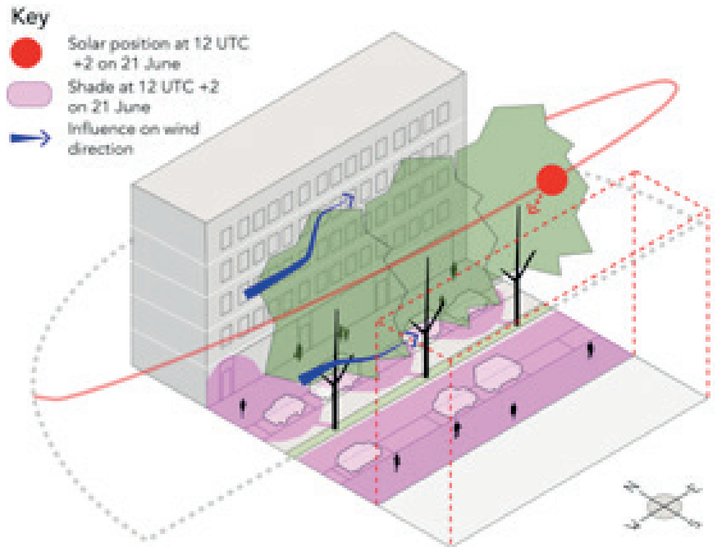
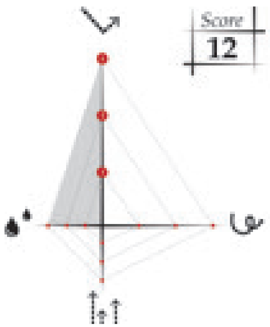


Figure 6.2.10 Grand tree lane

Figure 6.2.11
Evaluation matrix shelterbelts



Shelterbelts & weeping trees

Compared to tree lanes, shelterbelts and weeping trees have the potential to cast additional shade around the end of the afternoon, when the sun reaches its lowest position and might shine underneath the crowns of traditional tree lanes. In the example of the shelterbelt (figure 6.2.12), its hedges are oriented 60 degrees towards the street to cast additional shade on the sidewalk during late afternoon. However, in Sketchup it appeared that shelterbelts were unable to significantly cast shade additional to tree lanes. Similar results were found for weeping trees. Compared to the tree lanes above the sidewalk, these landscape elements reduce ventilation even more (figure 6.2.11), and are therefore not recommended.

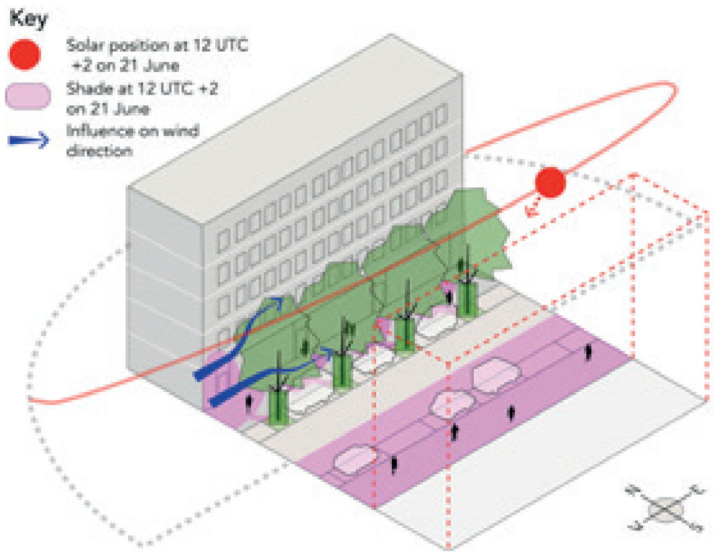


Figure 6.2.12 'Shelterbelts'

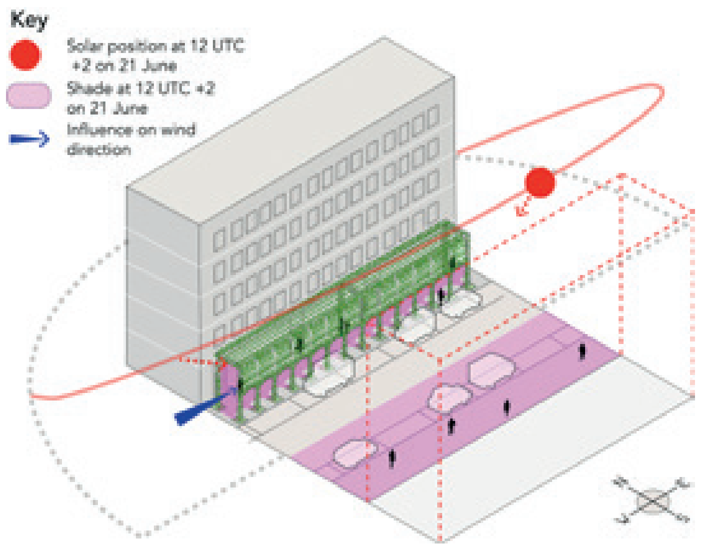


Figure 6.2.13 Semi-closed berceau

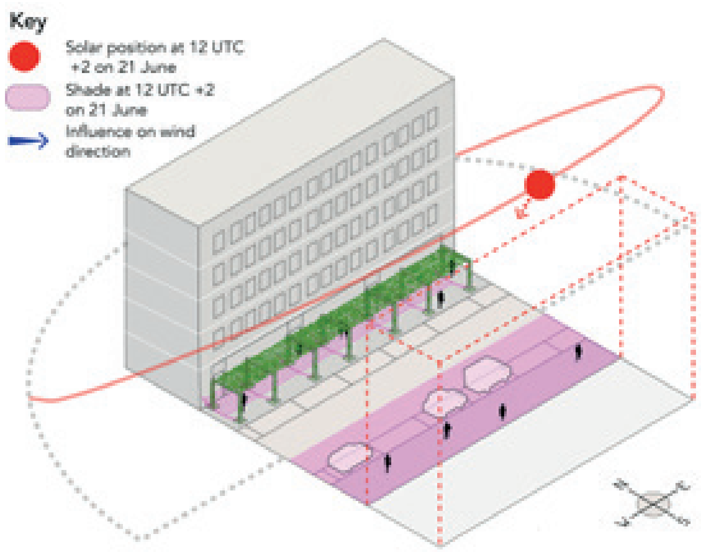
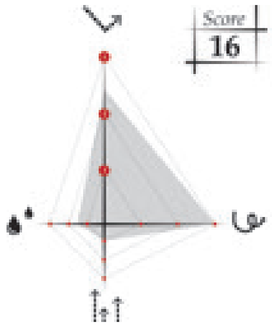


Figure 6.2.15 Roofed berceau

Semi-closed berceau

This prototype looks similar to historical berceaux. However, instead of covering it with shrub species, it is covered with climbing plants that require less maintenance. Due to the height of the berceau, it allows ventilation very well but it has a reduced evaporative cooling potential. While the height requires the top part of its sides to be closed to significantly shade the sidewalk, this prototype also traps a significant amount of longwave radiation (figure 6.2.13 & 6.2.14). Finally, the sun will radiate upon the first part of the sidewalk in late afternoon, when the sun has a low position.

Figure 6.2.14
Evaluation matrix semi-closed berceau



Roofed berceau

In favour of evaporative cooling potential, this berceau has been designed 2.5 metres above the sidewalk. By lowering its roof it is no longer necessary to add sides to the berceau to cast significant shade (figure 6.2.15). However, at the same time this prototype brings about slightly reduced ventilation (figure 6.2.16).

Figure 6.2.16
Evaluation matrix roofed berceau

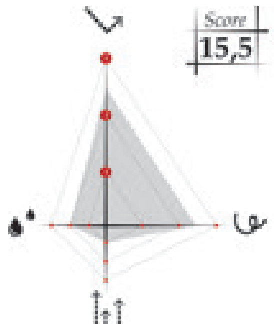
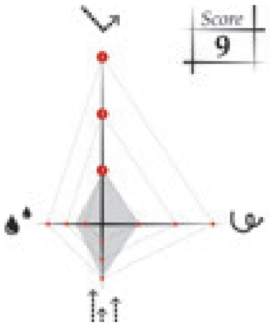


Figure 6.2.17
Evaluation matrix perpendicular hedges



Perpendicular hedges
Due to their restricted height, hedges have most shading potential around the end of the afternoon, when the sun reaches its lowest point. As the sun is positioned parallel towards the street around this time, hedges have to be oriented perpendicular towards the street to cast most shade (figure 6.2.18). While these hedges are 3 metres high, they still cast limited shade (figure 6.2.17). Next to that, these hedges obstruct ventilation and pedestrian flow.

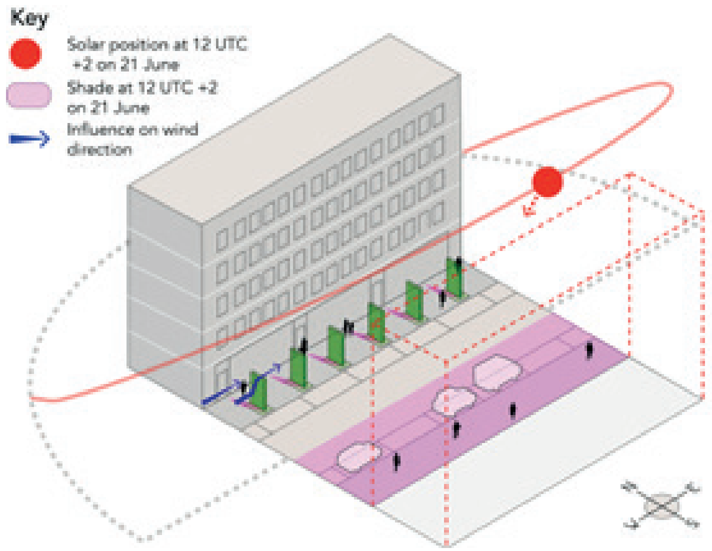
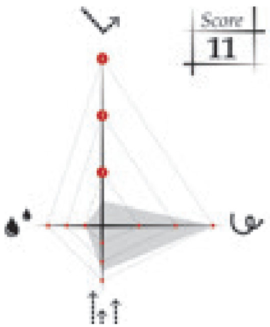


Figure 6.2.18 Perpendicular hedges

Figure 6.2.19
Evaluation matrix parallel hedges



Parallel hedges
If hedges are oriented parallel to the street, they cast a small amount of shade but allow better ventilation and pedestrian flow (figure 6.2.19). Furthermore, these parallel hedges with a height of 3 metre cast shade where pedestrians walk. However, in order to ensure sight from and onto the sidewalk and due to the parking places next to the sidewalk, these hedges should have sufficient openings between them (figure 6.2.20).

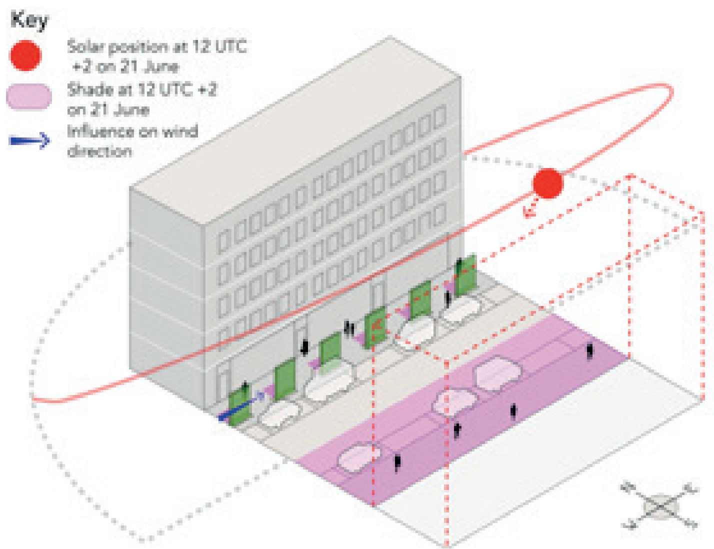


Figure 6.2.20 Parallel hedges

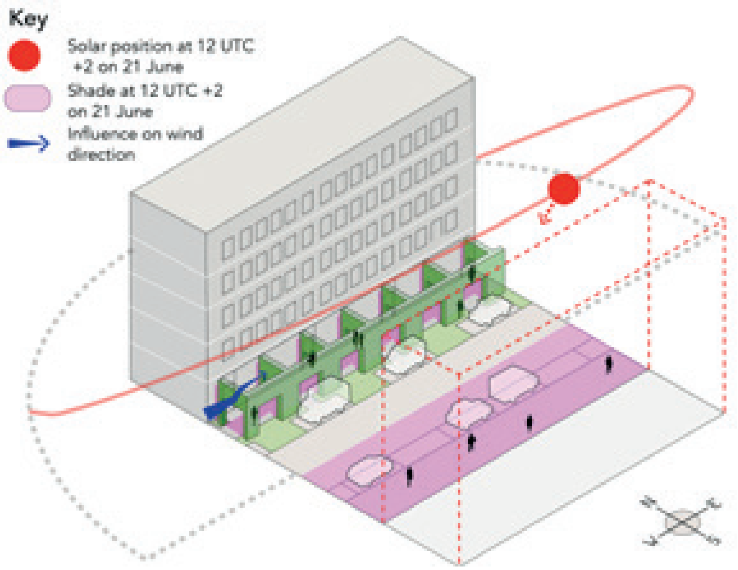
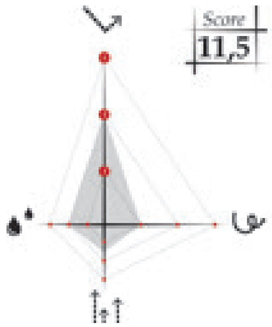


Figure 6.2.21 Hedges as portals

Hedges as portals

For hedges to cast a significant amount of shade, they need to have a greater height. However, this would reduce sight from and onto the sidewalk. For that reason, openings are made in the hedges (figure 6.2.21). Finally, by placing them both parallel and perpendicular to the sidewalk, they cast shade well throughout the afternoon. As a downside, these hedges also obstruct a significant amount of longwave radiation and block potential ventilation (figure 6.22).

Figure 6.2.22
Evaluation matrix of hedges as portals



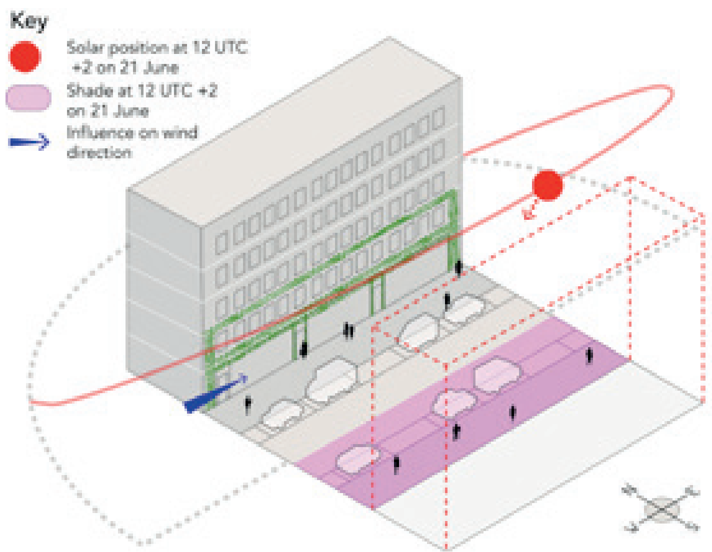


Figure 6.2.23 Green walls

Green walls

As found in scientific literature, green walls have a significant cooling potential through their evaporative cooling effect and by shading the building walls (figure 6.2.23 & 6.2.24). Evergreen green walls are preferred, as these have the additional benefit of insulating the buildings during winter.

Figure 6.2.24
Evaluation matrix green walls

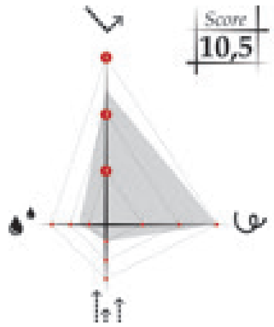
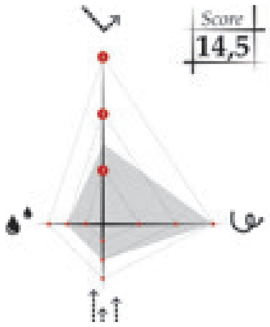


Figure 6.2.25
Evaluation matrix umbrella trees



Umbrella trees
Through the shadow analysis it was found that mainly the lowest level of the "etagelinde" effectively contributed to shade. The additional shading effect that came from higher levels, did not outweigh the maintenance required for these levels. If they are pruned into a square plane instead of a circular plane, they are able to significantly shade the whole sidewalk (figure 6.2.25). If pruned regularly, these trees are able to allow ventilation rather well. However, similar to berceaux their shape signifcantly obstructs longwave radiation cooling (figure 6.2.26).

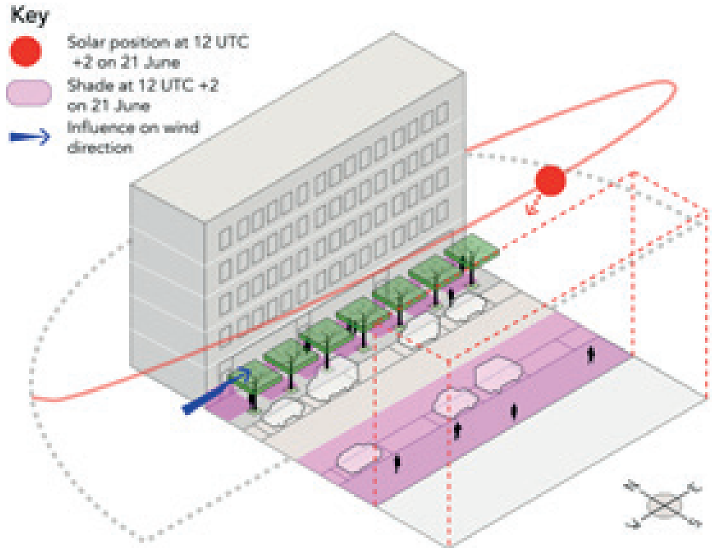


Figure 6.2.26 Umbrella trees

Summary
From the evaluation, the following prototypes scored highest on heat stress reduction: semi-closed berceau (16), roofed berceau (15,5), large tree lane (15.5), parallel horizontal trees (14.5) and umbrella trees (14,5). Next to that, I found that shelterbelts and weeping had no additional benefits to a traditional tree lane along the sidewalk.

6.3 Cold stress
East-West streets

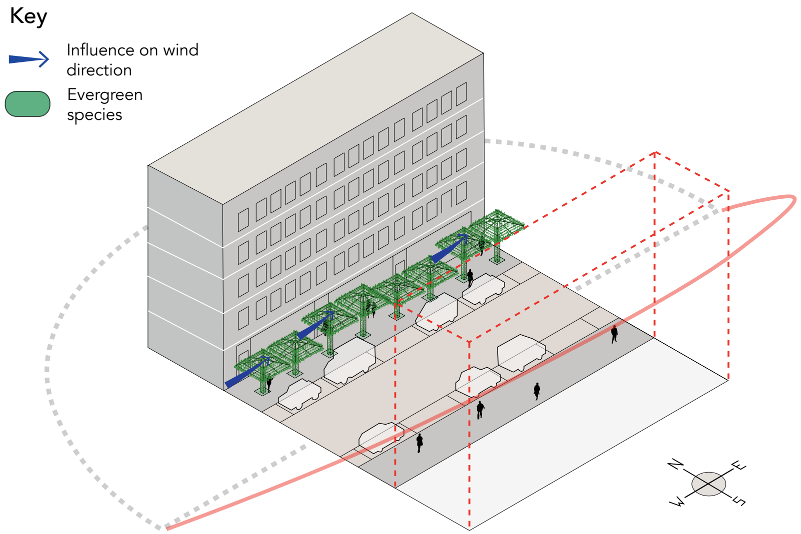
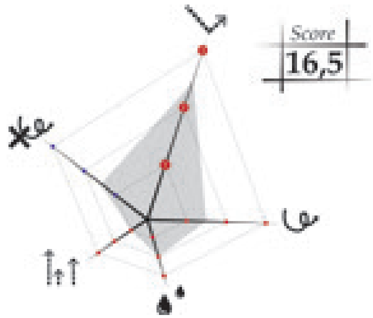


Figure 6.3.1 Umbrella trees of mixed heights

Umbrella trees of mixed heights
Due to their horizontal character, umbrella trees generally have a small influence on wind speed. In order to increase their wind reduction potential, this prototype has umbrella trees with alternating heights and is made of evergreen plants. Instead using evergreen tree species I chose to use evergreen climbing plants which require less maintenance and more easily cover surfaces with these dimensions.

Figure 6.3.2
Evaluation matrix umbrella trees of mixed heights



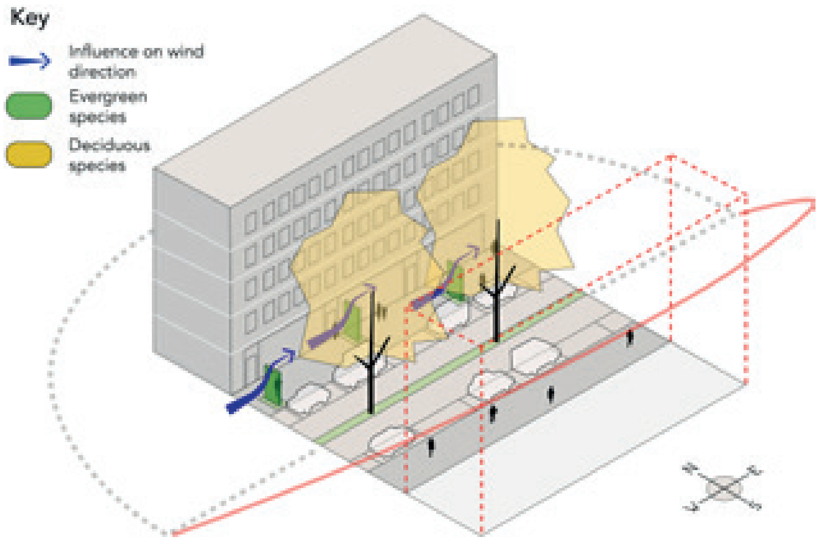


Figure 6.3.3 Large tree lane with hedges

Large tree lane with hedges
As these trees are placed in the middle of the street, they do not have any wind blocking potential, instead their shape channels wind towards the sides of the street. In order to ensure this effect does not occur, deciduous tree species have to be used for this tree lane. In order to further reduce wind speed, evergreen hedges are placed on the sidewalk. While these hedges with a height of 2.5 metre are placed alternately along the façades and parking places, they reduce the wind channelling effect. By pruning the hedges in early summer, more ventilation is allowed, while regrowth until autumn will increase its wind blocking potential.

Figure 6.3.4
Evaluation matrix large tree lane with hedges

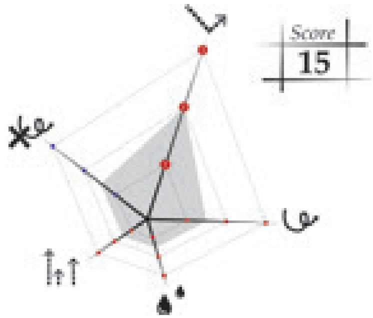
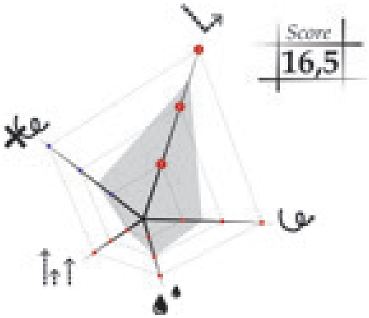


Figure 6.3.5
Evaluation matrix angled berceau



Angled berceau
This roofed berceau is designed to channel wind away from pedestrian levels. This is achieved by designing this evergreen roof of climbing plants in a slightly sloped shape.

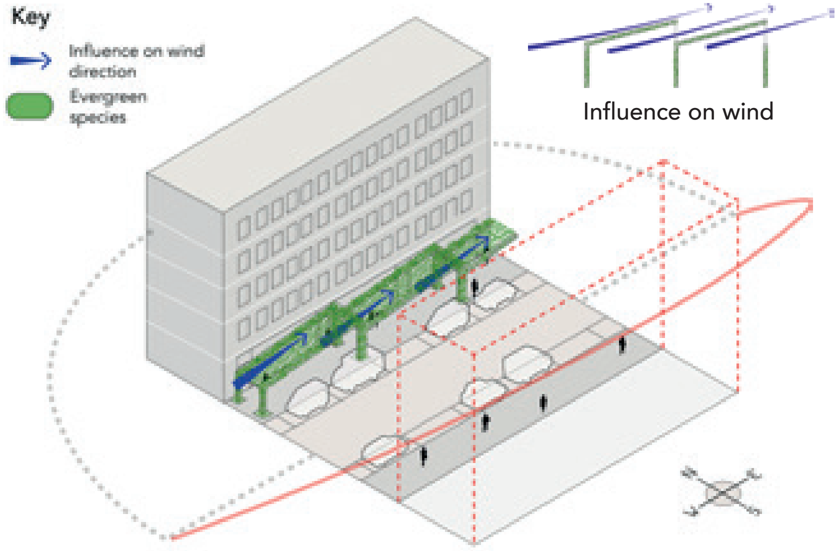
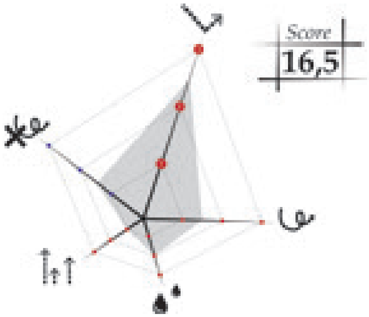


Figure 6.3.6 Angled berceau

Figure 6.3.7
Evaluation matrix berceau with closed front



Berceau with closed front
This berceau with a semi-closed front channels wind above the berceau. Due to its evergreen roof and the presence of cars along its sides the sidewalk will be sheltered from wind.

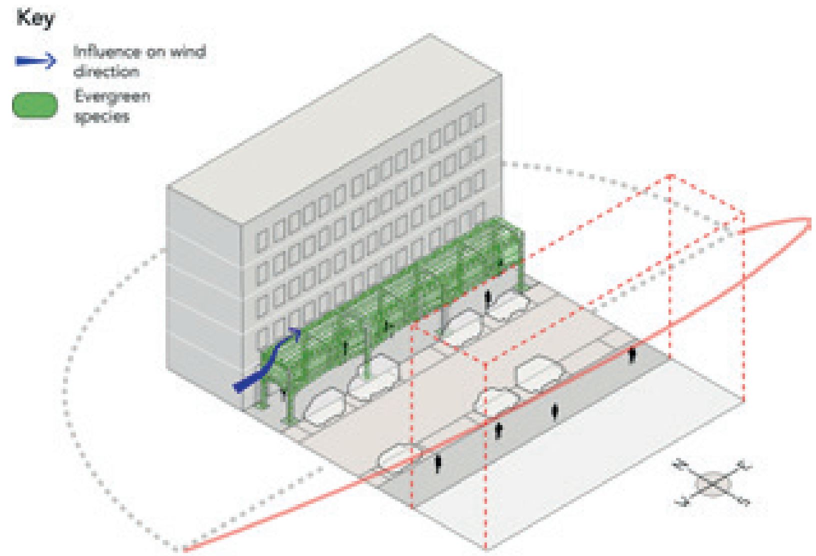


Figure 6.3.8 Berceau with closed front

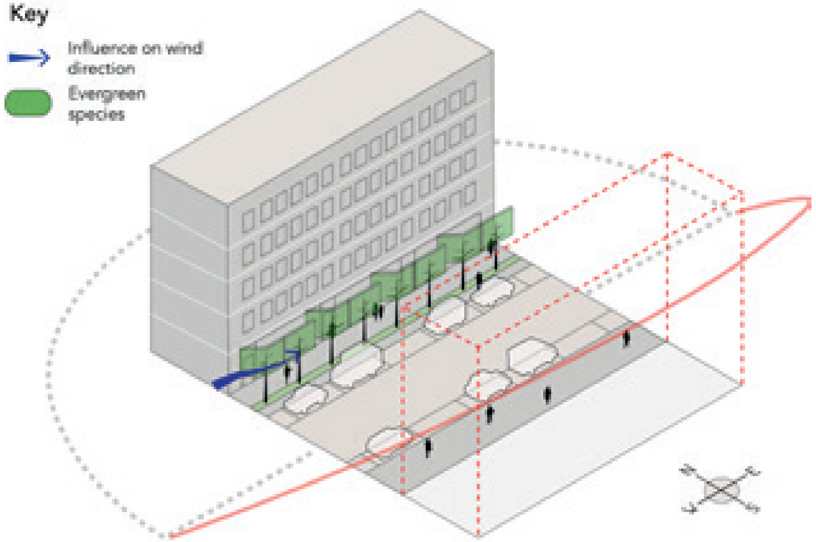
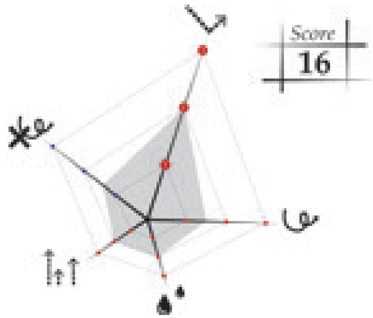


Figure 6.3.9 Mixed vertically shaped trees

Mixed vertically shaped trees
In this prototype some of the vertically shaped trees are bended to guide some wind away from the sidewalk towards the street. These trees are made of evergreen species, for example the coniferous Leyland cypress (Cupressus × leylandii). However, while these trees are able to reduce wind speeds above pedestrian levels, they are less able to reduce wind speeds at pedestrian levels.

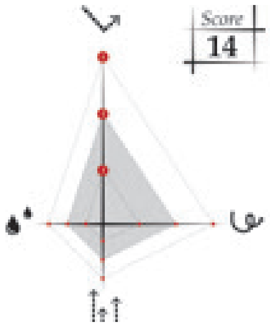
Figure 6.3.10
Evaluation matrix mixed vertically shaped trees



Summary
Amongst these prototypes, the umbrella trees of mixed heights (16.5), the angled berceau (16.5) and the berceau with closed front (16.5) scored highest on both heat and cold stress reduction. In the next section, these prototypes are implemented in a real street. However, as the bereau with closed front looks fairly similair to the angled berceau, I decided to the implement the mixed vertically shaped trees (16) in a real context as alternative to the angled berceau to show more variety in design alternatives.

6.4 Heat stress
Southwest-Northeast streets

Figure 6.4.1
Evaluation matrix diagonal vertically pruned trees



Diagonal vertically pruned trees
Due to the high position of the sun when it radiates upon the Northern sidewalk, vertically pruned trees are unable to shade this sidewalk effectively. Then, for the Southern sidewalk these trees have limited shading potential around 15.30 UTC+2 and around 17.00 UTC+2, when the sun is positioned too high or too low, but cast a significant amount of shade between this time-period. If these trees are oriented 30 degrees towards the street, they cast most shade (figure 6.4.1 and 6.4.2). Its other microclimatic effects are similar to the diagonal vertically pruned trees in section 6.2

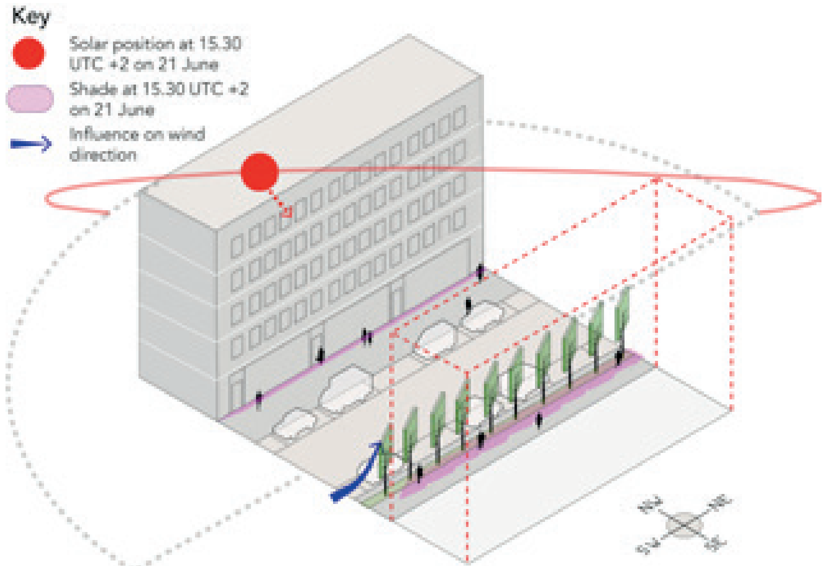
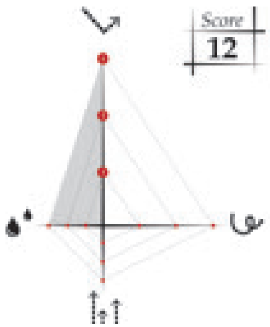


Figure 6.4.2 Diagonal vertically pruned trees

Figure 6.4.3
Evaluation matrix tree lane above sidewalk



Tree lane above sidewalk
From the Sketchup analsys it appears that most shading is casted on both sidewalks when the tree crowns are located directly above the sidewalk. While this prototype shades the sidewalks almost the entire afternoon, the Southern sidewalk receives some shortwave radiation during the last minutes of the afternoon when the sun has a low solar position. Apart from shading this prototype significantly contributes to evaporative cooling, but reduces ventilation and longwave radiation allowance (figure 6.4.3 and 6.4.4)

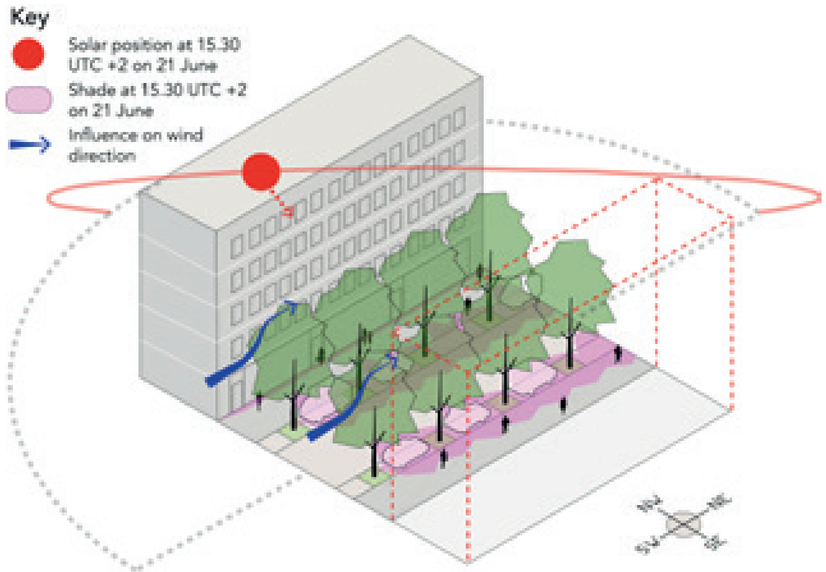


Figure 6.4.4 Tree lane above sidewalk

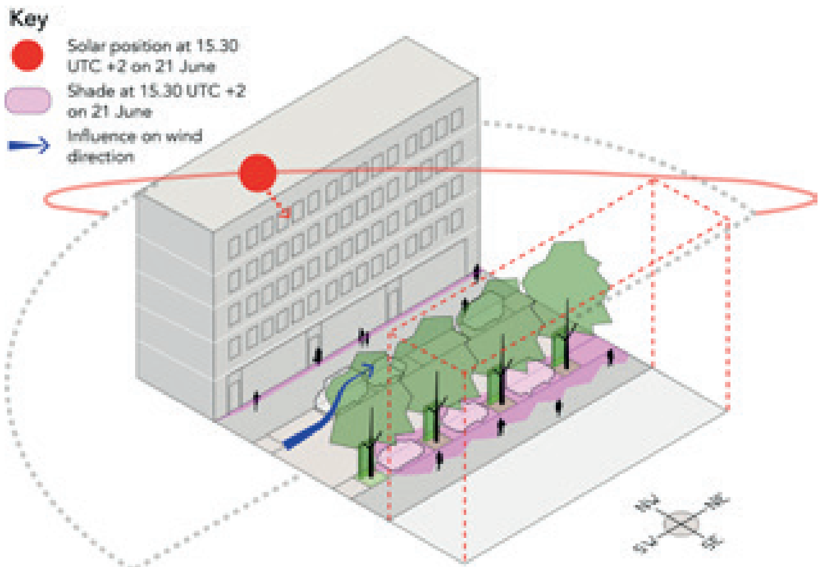
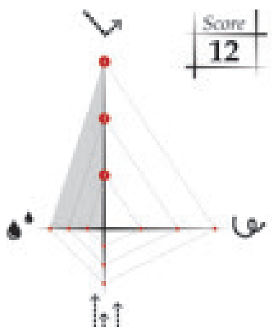


Figure 6.4.5 Shelterbelts

Shelterbelts

As mentioned before, tree lanes above sidewalks are unable to cast shade on the Southern sidewalk during the last minutes of the afternoon. In this prototype hedges are oriented parallel to the street to not further obstruct ventilation and to optimally cast shade in late afternoon, when the sun is located perpendicular to the street (figure 6.4.5). However, due to the distance between the hedges required for parking places, this prototype does not cast a significant amount of shade in addition to tree lanes without hedges (figure 6.4.6)

Figure 6.4.6
Evaluation matrix shelterbelts



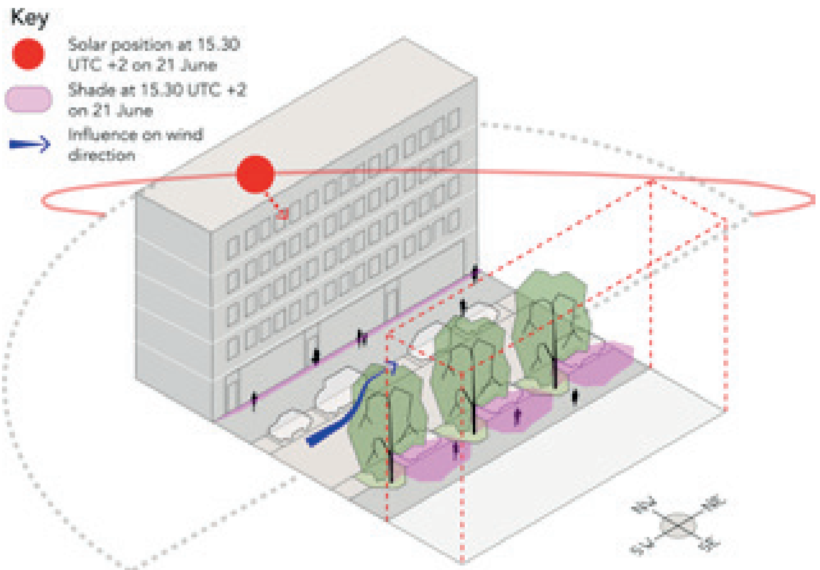


Figure 6.4.7 Weeping trees

Weeping trees

As the branches of weeping trees often reach close to the ground surface, their microclimatic potential is similar to shelterbelts. However, only a few species have sufficient space to grow their branches untill the ground surface. For example, fagus sylvatica 'Black Swan', with an eventual height of 13 m and width of 4 m (van Ebben, n.d.-c). In Sketchup it was found that these weeping trees only cast some additional shade for a few minutes of the afternoon, but poorly allow ventilation and longwave radiation (figure 6.4.8). On top of that, due to their shape they reduce the amount of parking lots (figure 6.4.7).

Figure 6.4.8
Evaluation matrix weeping trees

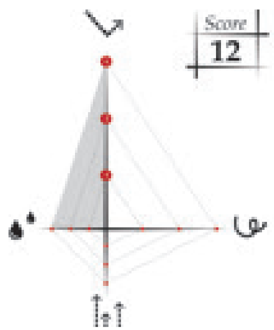
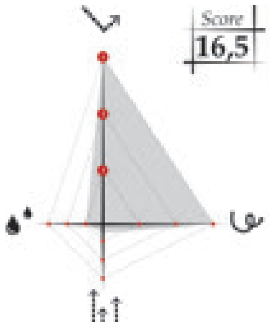


Figure 6.4.9
Evaluation matrix parallel vertically pruned trees



Berceau above parking

Instead of designing a berceau with semi-closed sides to ensure significant shade, this berceau is extended over the parking lots. In additon, this prototypes also shades cars underneath the berceau during mid afternoon, when the sun is oriented more or less parallel to the street. This prototype has a height of 4 metres to allow parking of small delivery trucks as well (figure 6.4.10). At the same time, this height allows optimal ventilation. However, due to its increased width this berceau traps a significant amount of longwave radiation (figure 6.4.9).

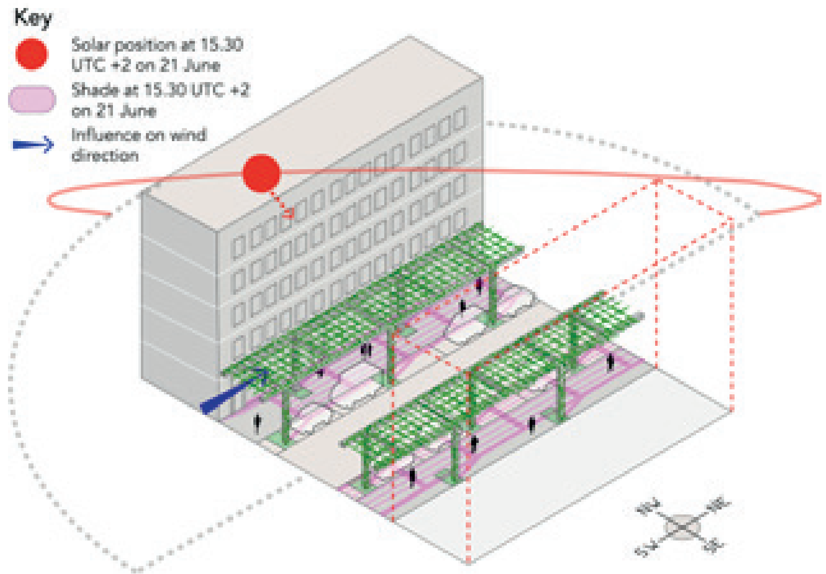
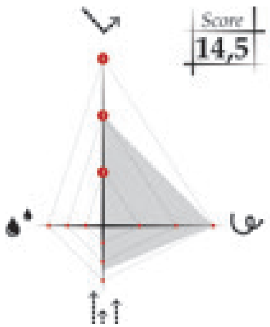


Figure 6.4.10 Berceau above parking

Figure 6.4.11
Evaluation matrix diagonal vertically pruned trees



Elevated berceau

This berceau is connected to the roofs of the buildings and thereby increases the H/W ratio of the street (figure 6.4.12). As a result, the berceau attached to the Southern buildings shades the Northern sidewalk around noon and the berceau attached to the Northern buildings shades the Southern sidewalk at the end of the afternoon. During mid-afternoon, when the sun is more or less oriented parallel to the street, the raised berceaux cast shade on the sidewalks below them. However, due to their height the sun irradiates underneath a part of the berceau upon the sidewalks. Simultaneously, its height allows significant ventilation and longwave radiation, but also diminishes its evaporative cooling potential (figure 6.4.11)

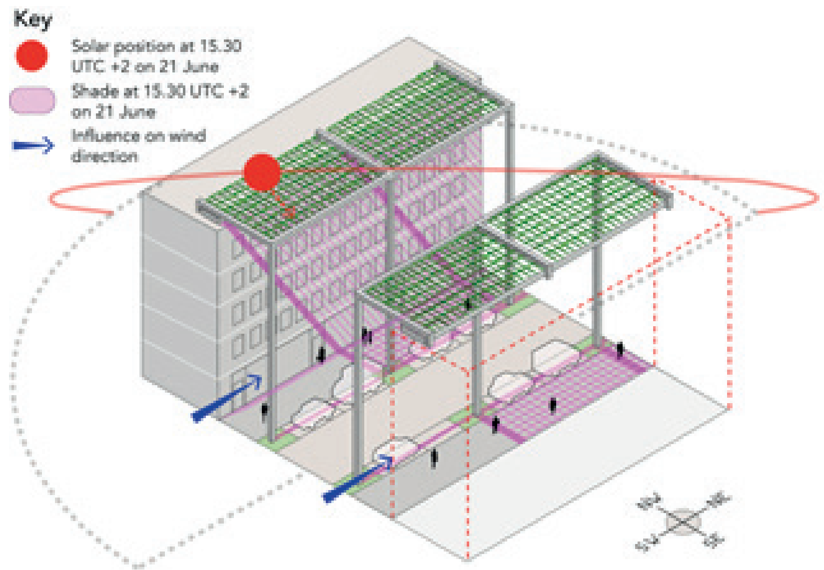


Figure 6.4.12 Elevated berceau

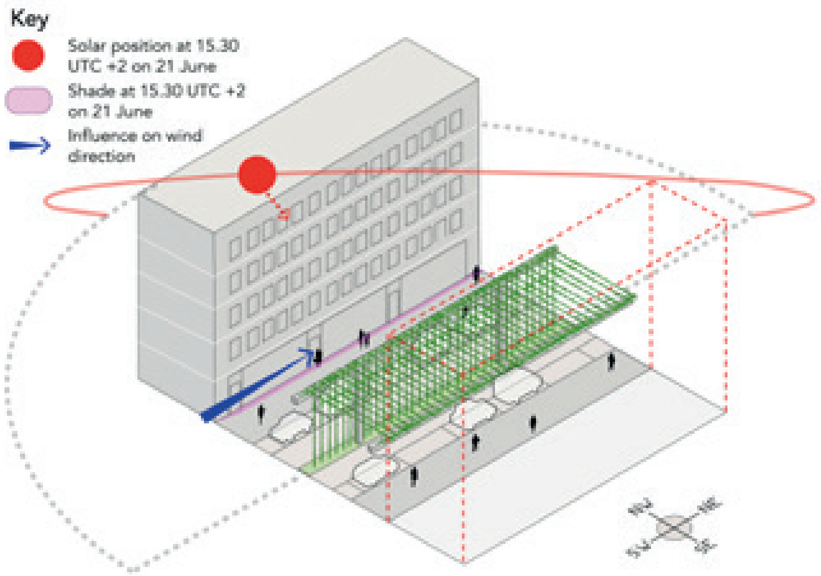
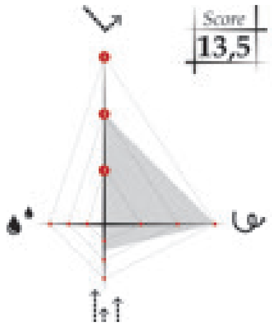


Figure 6.4.13 Closed berceau

Closed berceau

As mentioned before, the sun has a low position at the end of the afternoon, when it radiates upon the Southern sidewalk. For it to cast sufficient shade, the sides of this berceau are completely closed. However, in order to trap no car emissions, this berceau has to be more transparent (figure 6.4.13). While this increases longwave radiation allowance, it reduces its shading and evaporative cooling potential (figure 6.4.14). Next to that, this 7 m high berceau allows ventilation very well.

Figure 6.4.14
Evaluation matrix closed berceau



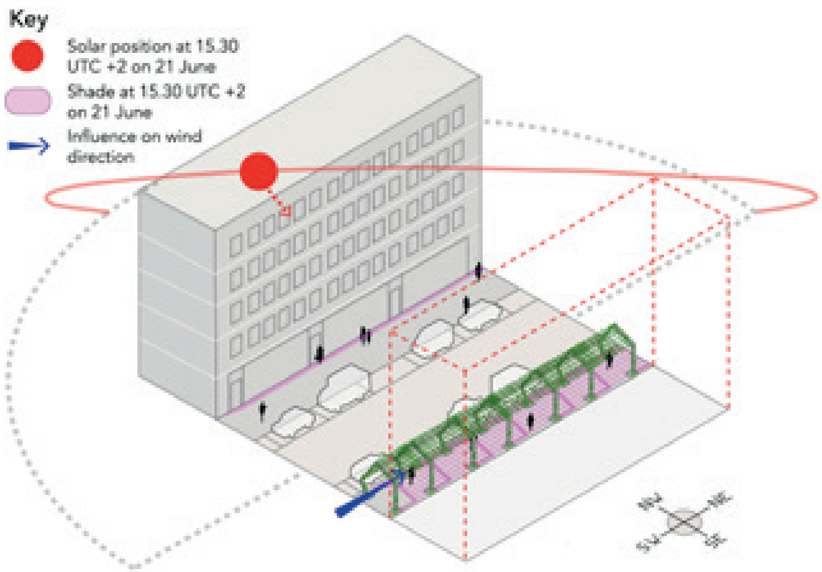


Figure 6.4.15 Tilted berceau

Tilted berceau

Another prototype in response to the low solar position around the end of the afternoon, is the berceau with semi-cloded sides (figure 6.4.15). Compared to the closed berceau this berceau has more evaporative cooling potential. However, due to its restricted height it allows ventilation less well (figure 6.4.16)

Figure 6.4.16
Evaluation matrix tilted berceau

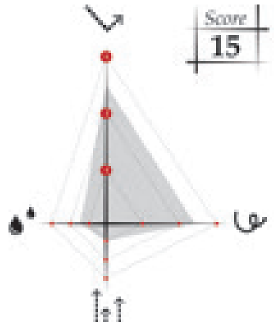
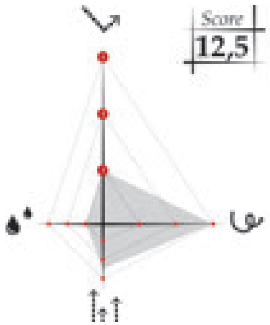


Figure 6.4.17
Evaluation matrix parallel hedges



Parallel hedges
Hedges in this street only effectively cast shade around the end of the afternoon, when the sun has a low position and radiates upon the Southern sidewalk. Again, parallel hedges optimally allow ventilation and cast shade where the pedestrians walk. However, their shading effect is limited by their restricted height.

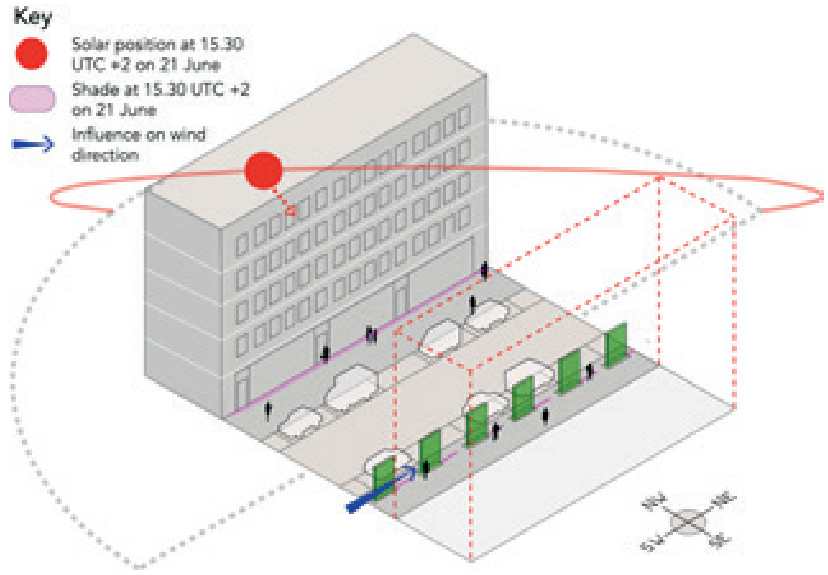
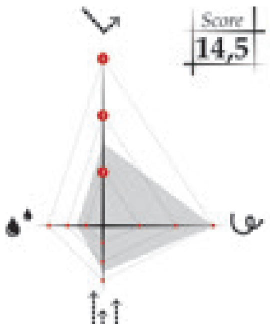


Figure 6.4.18 Parallel hedges

Figure 6.4.19
Evaluation matrix portals



Portals
In order to cast more shade on the Southern sidewalk hedges are designed with a height of 4,5 metre and have openings to allow sight and access from and to the sidewalk (figure 6.4.20). Due to the parallel position of these portals, this prototype allows ventilation rather well (figure 6.4.19).

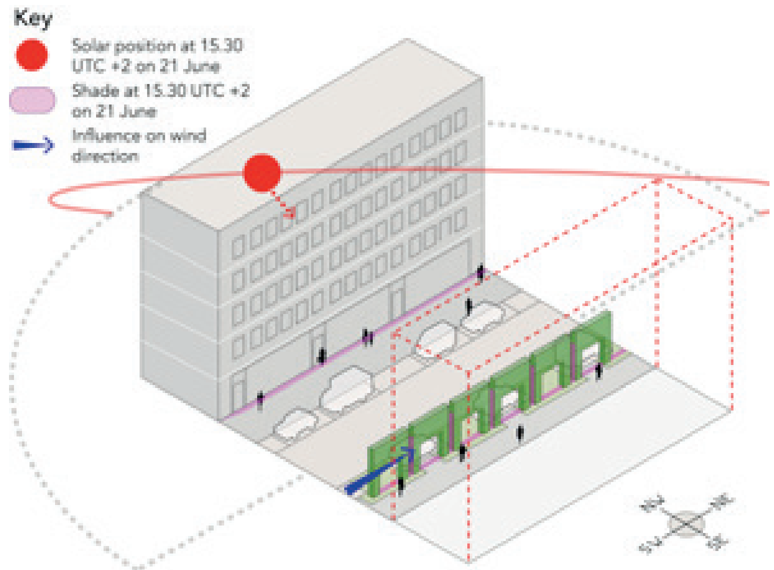


Figure 6.4.20 Portals

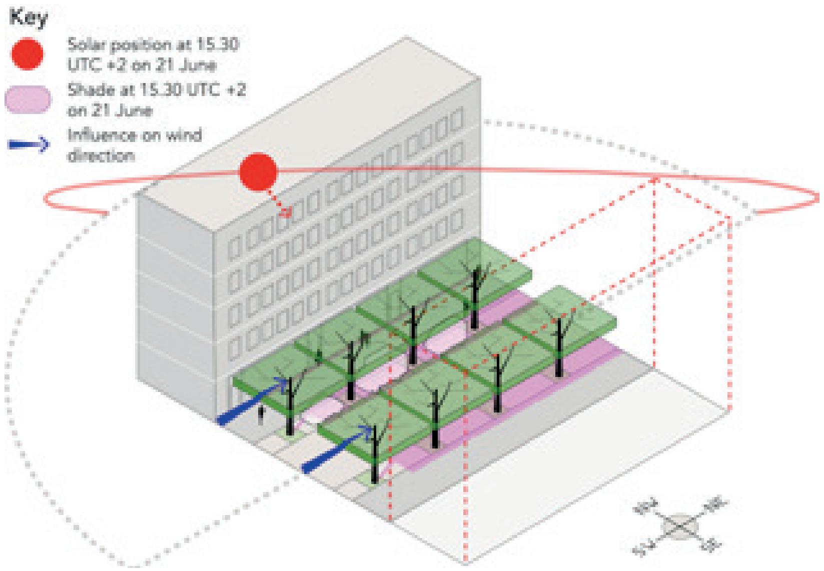
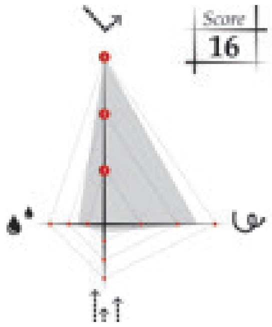


Figure 6.4.21 Parasol trees

Umbrella trees
For the same reason as extending the berceaux above the parking lots (figure 6.4.10), these umbrella trees are extended above the parking places as well (figure 6.4.21). However, this measure would drastically reduce longwave radiation allowance (figure 6.4.22).

Figure 6.4.22
Evaluation matrix parasol trees

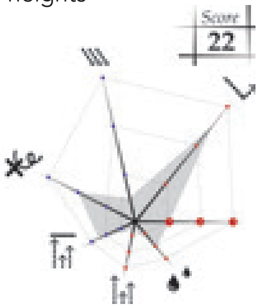


Summary
The following prototypes scored highest on heat stress reduction in SW-NE streets: berceau above parking (16.5), umbrella trees (16), tilted berceau (15), portals (14.5) and elevated berceau (14.5). These prototypes are adapted to reduce cold stress in the next phase. Again, I found that shelterbelts and weeping trees had no additional benefits to a traditional tree lane without hedges along the sidewalk.

6.5 Cold stress

Southwest-Northeast streets

Figure 6.5.1
Evaluation matrix umbrella trees with alternating heights



Umbrella trees with alternating heights

These umbrella trees have different heights to allows the sun to radiate upon the sidewalk during mid-afternoon in autumn (figure 6.5.2). Simultaneously, this prototype casts significant shade in summer due to the higher solar pathway. On top of that, the tree height difference creates additional roughness and thereby reduces the wind channelling effect (figure 6.5.1).

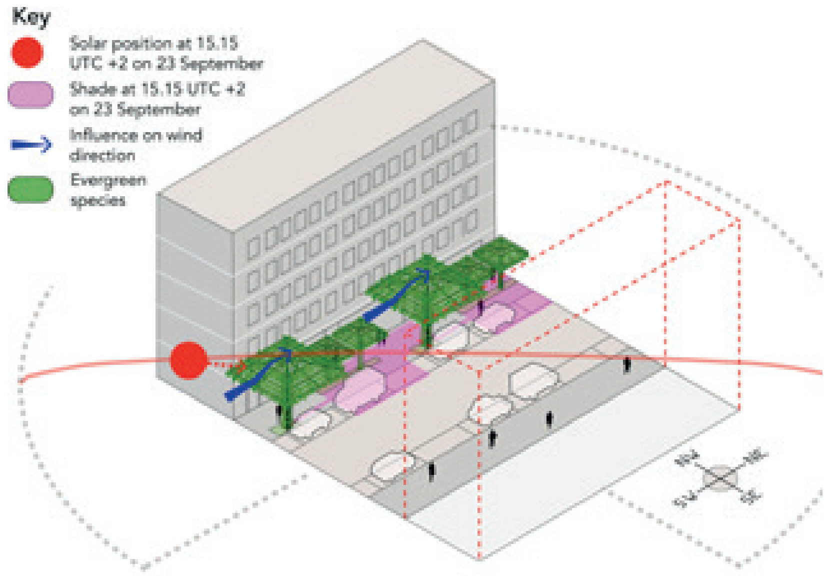
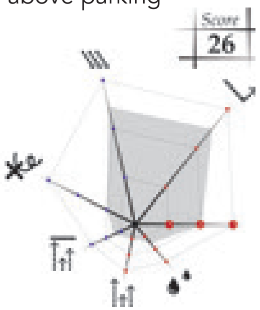


Figure 6.5.2 Umbrella trees with alternating heights

Figure 6.5.3
Evaluation matrix semi-evergreen berceau above parking



Semi-evergreen berceau above parking

This berceau consists of two elements. The Southern part of the berceau is covered with deciduous climbers that allow the lower sun to radiate upon the sidewalk in autumn but cast significant shade in summer. Then, the Northern part of this berceau is covered with evergreen climbers and channels wind away from the sidewalk (figure 6.5.3 and 6.5.4). While the evergreen part of the berceau still casts some shade upon the sidewalk in autumn, sunny and windy conditions hardly occur on the same day. For that reason, the Northern side of the sidewalk is more comfortable during windy and cloudy days and the Southern side of the sidewalk is more comfortable during calm and sunny autumn days.

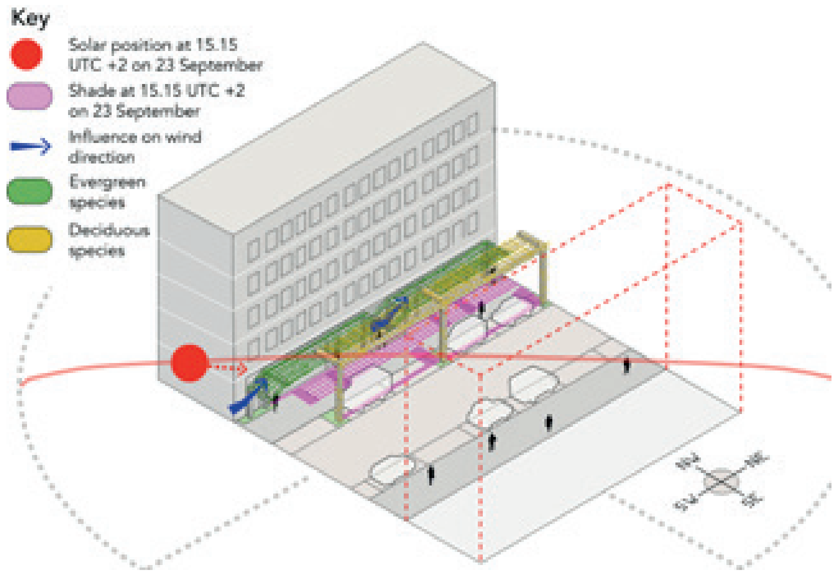


Figure 6.5.4 Semi-evergreen berceau above parking

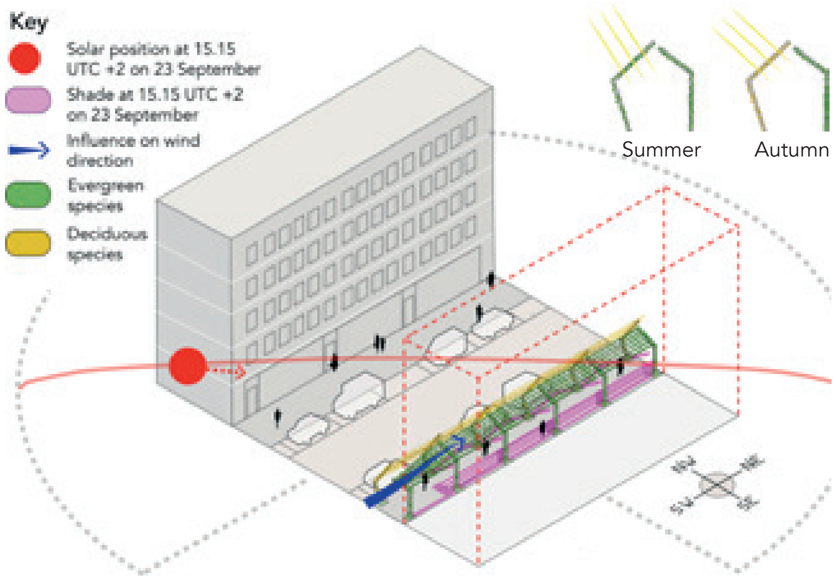
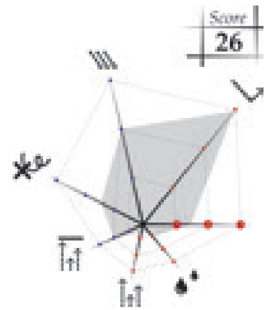


Figure 6.5.5 Semi-evergreen berceau

Semi-evergreen tilted berceau
This prototype is based on the same principle as the previous prototype and consists of two parts. The evergreen part of the berceau channels wind away and the deciduous part casts shade in summer and allows solar exposure in winter (figure 6.5.6). However, unlike the previous prototype the sides of these berceau are tilted. For that reason, it better allows shortwave radiation to access the sidewalk (figure 6.5.5)

Figure 6.5.6
Evaluation matrix of hedges as portals



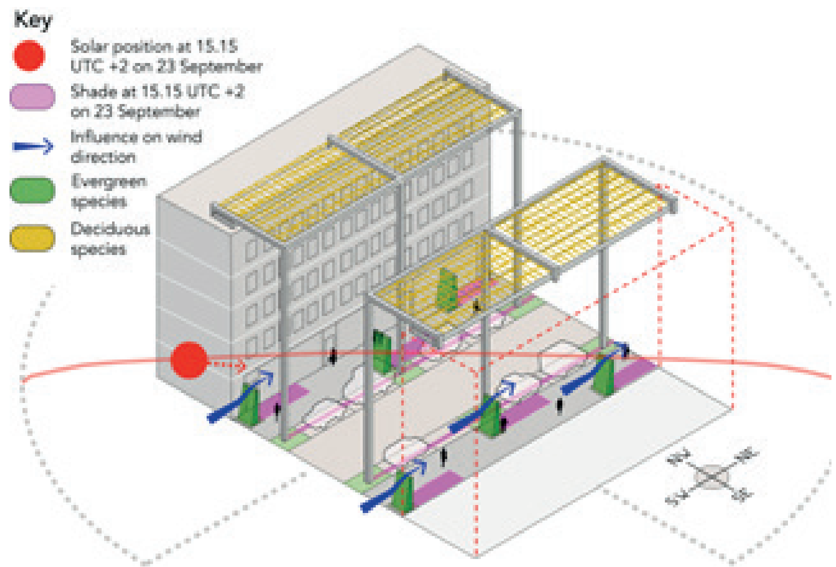


Figure 6.5.7 Elevated berceau with hedges

Elevated berceau with hedges
These elevated berceaux have almost no influence on wind speed at pedestrian levels due to their height (figure 6.5.8). For that reason, they are combined with hedges that provide wind shelter. For this street orientation these hedges are placed on both sides of the sidewalks to create additional roughness (figure 6.5.7). At the same time these hedges cast additional shade and thereby are less favourable in sunny autumn conditions.

Figure 6.5.8
Evaluation matrix green walls

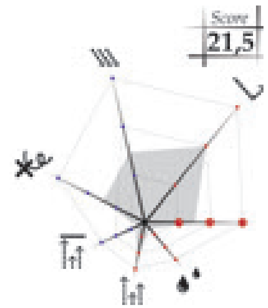
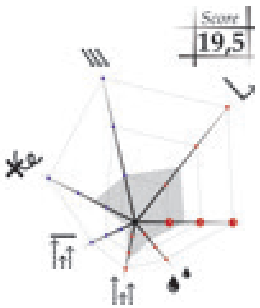


Figure 6.5.9
Evaluation matrix
hedges as portals



Hedges as portals
This prototype scored well in heat stress reduction especially for its ability to allow ventilation. However, in autumn they have to be able to reduce wind speed instead. For that reason, tall hedges were added in combination with the deciduous portals (figure 6.5.10). However, by increasing the wind blocking potential of this prototype, its ability to reduce heat stress decreased significantly as well (figure 6.5.9).

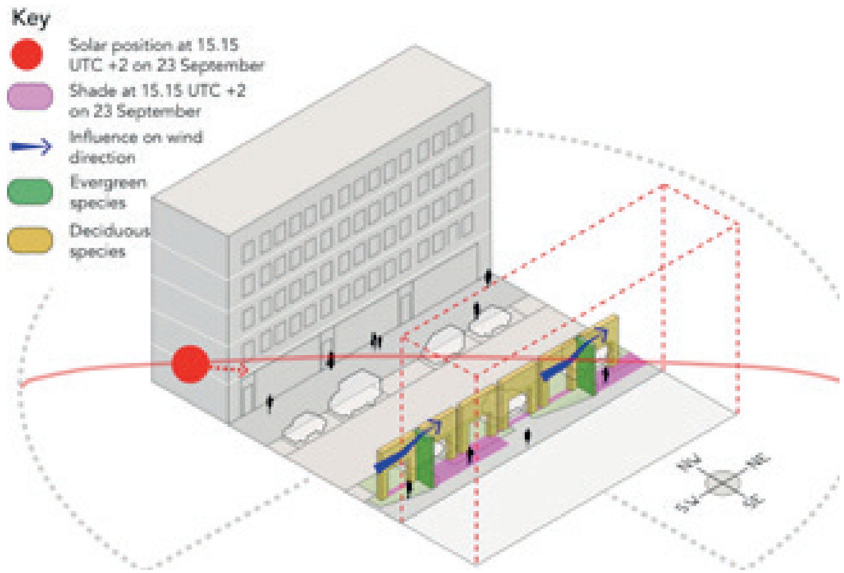


Figure 6.5.10 Hedges as portals

Summary
From the evaluation, the following prototypes scored highest on heat and cold stress reduction in SW-NE streets: the umbrella trees of mixed heights (22), the semi-evergreen berceaux above parking (26) and the semi-evergreen tilted berceau (26). In the final design phase these prototypes will be implemented in a real street.

Conclusion
Prototypes of landscape elements with a restricted cross-sectional crown volume (two-dimensional trees, umbrella trees and berceaux), scored highest on ventilation. Amongst these landscape elements, prototypes with horizontal surfaces above the sidewalks (versions of berceaux and umbrella trees) provided most shade and thereby reduced heat stress most significantly for both street orientations. For E-W streets these prototypes were effectively adjusted to reduce cold stress by alternating the height of umbrella trees to increase wind roughness and by channeling wind over evergreen berceaux. For SW-NE streets, the prototypes that most effectivly allowed solar radiation and reduced wind speed were prototypes of a semi-evergreen berceau and evergreen umbrella trees with alternating heights.

6.6 Implementation

The protypes that scored highest on both heat and cold stress reduction are implemented in a real context in the final phase of the research through design process. During this phase the designs are adjusted to the specific conditions of the respective shopping streets. For each prototype an artistic impression is made that demonstrates the visual effect of the prototypes.

The streets for which the prototypes are adjusted are selected from the dataset of the 60 measured streets. From this dataset the 'Oldebarneveltstraat' and the 'Hoogstraat' are chosen as example of the East-West and Southwest-Northeast test bed respectively (figure 6.6.1).

Van Oldebarneveltstraat
The van Oldebarneveltstraat, as shown by figure 6.6.2, is located between the Mauritsweg on the Western side and the Koopgoot on the Eastern side. This one-way street with parking places along the Southern sidewalk and a tram lane along the Northern sidewalk has a total length of approximately 200 metres. As the Oldebarneveltstraat has a H/W ratio of 0.88, its Northern sidewalk is exposed to the sun for the full afternoon. However, the shrubs along this sidewalk cast insignificant shade. Along the Southern sidewalk a few trees are planted, that partially shade the car road during the afternoon. Finally, the street consists of a high amount of impervious surface, and thereby has a restricted evaporative cooling potential.

Figure 6.6.1 Location streets for implementation

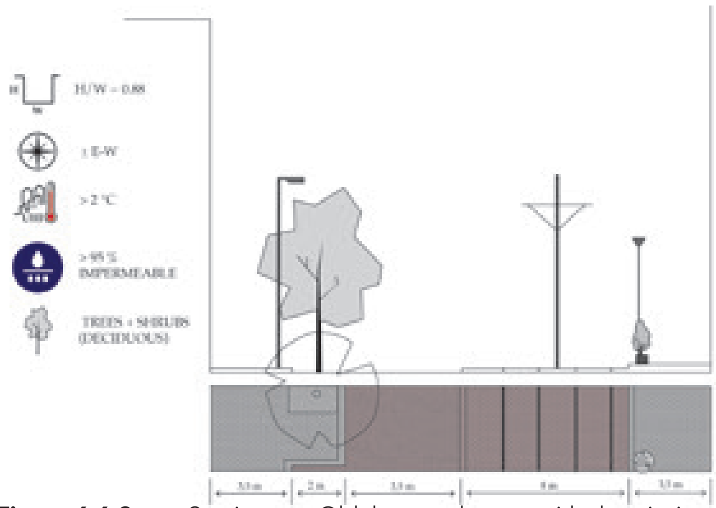


Figure 6.6.2 Section van Oldebarneveltstraat with description of its microclimatic properties

For all three prototypes I chose to transform the impermeable surface underneath the tramline into a grass surface. This measure increases the evaporative cooling potential of the street (Lenzholzer, 2015). On top of that, the grass allows water infiltration and thereby reduces local flood risks during heavy rain periods and supplies the green landscape elements with water. Similarly, the parking spots are designed to have a semi-permeable surface. In all three prototypes the combination of de-paving the surface underneath the tramline and narrowing the northern sidewalks with 0.75 metre created space for plants to grow. Along the southern sidewalk the original deciduous trees - Gleditsia japonica - are maintained which are very drought resistant (Lenzholzer, 2015).

“Umbrella trees” of alternating height

The “stems” of the umbrella trees are designed in a curved shape so that they do not block pedestrian flow (figure 6.6.3). These elements have alternating heights and their ‘canopy’ is slightly sloped as to create more wind roughness. While it is impossible to grow tree species in this particular shape, climbing plants are used that naturally follow the shape of the structure on which they grow. More specifically, evergreen climbing plants are used that maintain their foliage and able to reduce wind speeds in seasons when cold stress is most severe. I chose to use Hedera helix which is a fast-growing climbing plant that easily covers large surfaces and is able to withstand drought, wind and sun (van Ebben, n.d.-d). Finally, while these trees allow sufficient sight on and from the sidewalk, they also provide the van Oldebarneveltstraat with a unique identity.

Mixed vertically shaped trees

These mixed vertically shaped trees consist of two evergreen and deciduous species (figure 6.6.4). The deciduous lime trees (Tilia cordata) have a reasonable drought tolerance (Lenzholzer, 2015) and are planted parallel along the sidewalk to provide shade in summer. These trees also allow some sunlight to access the shops in autumn. Then, half of the canopy of the evergreen vertically shaped trees is angled with 45 degrees to channel wind towards the street. For this purpose I chose to apply the English yew, which is able to withstand sun, shade and droughts (van Ebben, n-d.e). In autumn the yellow leaves of the lime trees will create a visually pleasing contrast with the evergreen English yew.

Berceau with semi-closed front

The structure of this berceau is connected to the buildings along the northern sidewalk (figure 6.6.5). Therefore, less pillars are required for the support of the plants and more space will be available for pedestrians. Again, I used Hedera helix for the aforementioned reasons. While the front of this evergreen berceau is somewhat closed, it brings about slight reductions in wind speed underneath the berceau. If these structures are built from wood from sustainably managed forests they will have a low environmental impact.

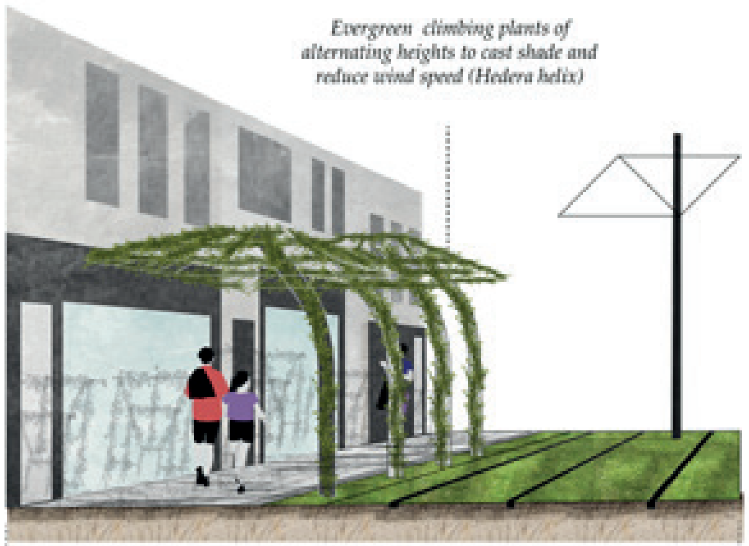


Figure 6.6.4 Umbrella trees with alternating heights implemented in the van Oldebarneveltstraat

Figure 6.6.4 Mixed vertically shaped trees implemented in the van Oldebarneveltstraat

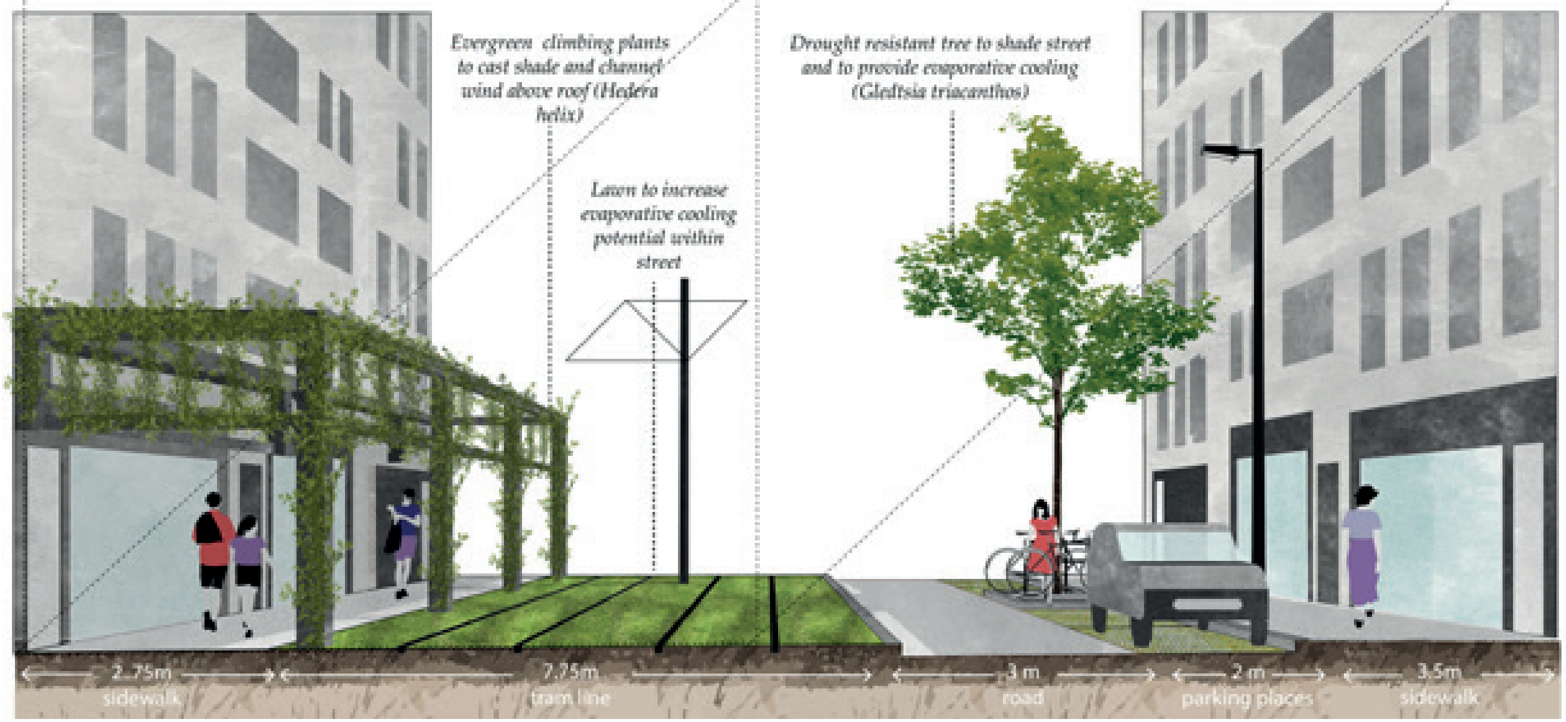


Figure 6.6.5 Berceau with semi-closed front implemented in the van Oldebarneveltstraat

Hoogstraat

The Hoogstraat is oriented East-West and connects the Binnenrotte with the Oostplein. While the H/W ratio of this street is highly variable, the design in this thesis only is applicable to the part of the Hoogstraat between the Kipstraat and Oostplein, which has an average H/W ratio of 0.87. This street has a symmetrical layout with parking lots along both sidewalks (figure 6.6.6). From different google street view records, it appears that the municipality of Rotterdam added temporary trees in planters along the Northern sidewalk after 2015. While these trees still have rather small crowns (< 3m high), it is also expected that their future growth is inhibited by the limited root space available in these planters. Apart from these small trees, the street consists of a high amount of impervious surface and therefore has limited evaporative cooling potential.

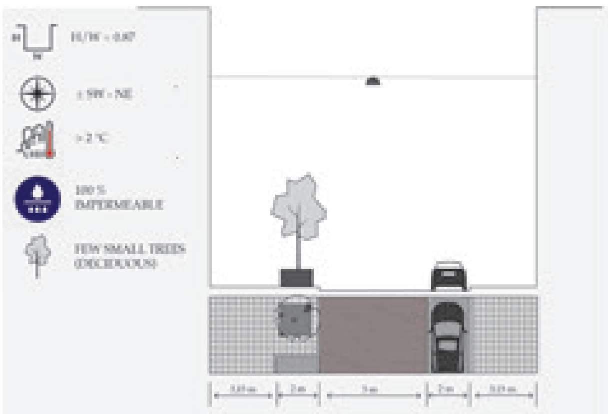


Figure 6.6.6 Section Hoogstraat with description of its microclimatic properties

The design of the umbrella tree and semi-evergreen berceau both are partially positioned on the sidewalk and partially in line with the parking lots. Again, the parking lots are made semi-permeable in order to allow additional evaporative cooling.

Umbrella trees with alternating heights

Again the 'stem' of these umbrella 'trees' is curved to optimally allow pedestrian streams (figure 6.6.7). These umbrella trees are grown with ivy and designed with alternating heights to reduce wind speeds. Unlike the umbrella trees in the E-W oriented streets these landscape elements are placed further apart from each other. While this reduces their shading potential in summer, it allows more solar radiation in autumn.

Semi-evergreen berceau above parking

The semi-evergreen berceau consist of two different plant species. The part of the berceau located along the buildings consists of evergreen climbing plants that are able to reduce wind speed in autumn. Based on the aforementioned reasons, ivy is chosen for this purpose. Then, the side above the parking lots is grown with deciduous climbing plants that cast shade in summer and allow shortwave radiation in autumn. As this berceau covers a large part of the sidewalk, regular street lanterns would not be able to provide sufficient light on the sidewalks. Therefore, I integrated lighting within the construction of the berceau (figure 6.6.8). As a drawback this prototype requires regular maintenance in order to ensure that the evergreen climbing plants do not grow over the berceau above the parking lots.

Figure 6.6.7 "Umbrella trees" with alternating heights implemented in the Hoogstraat

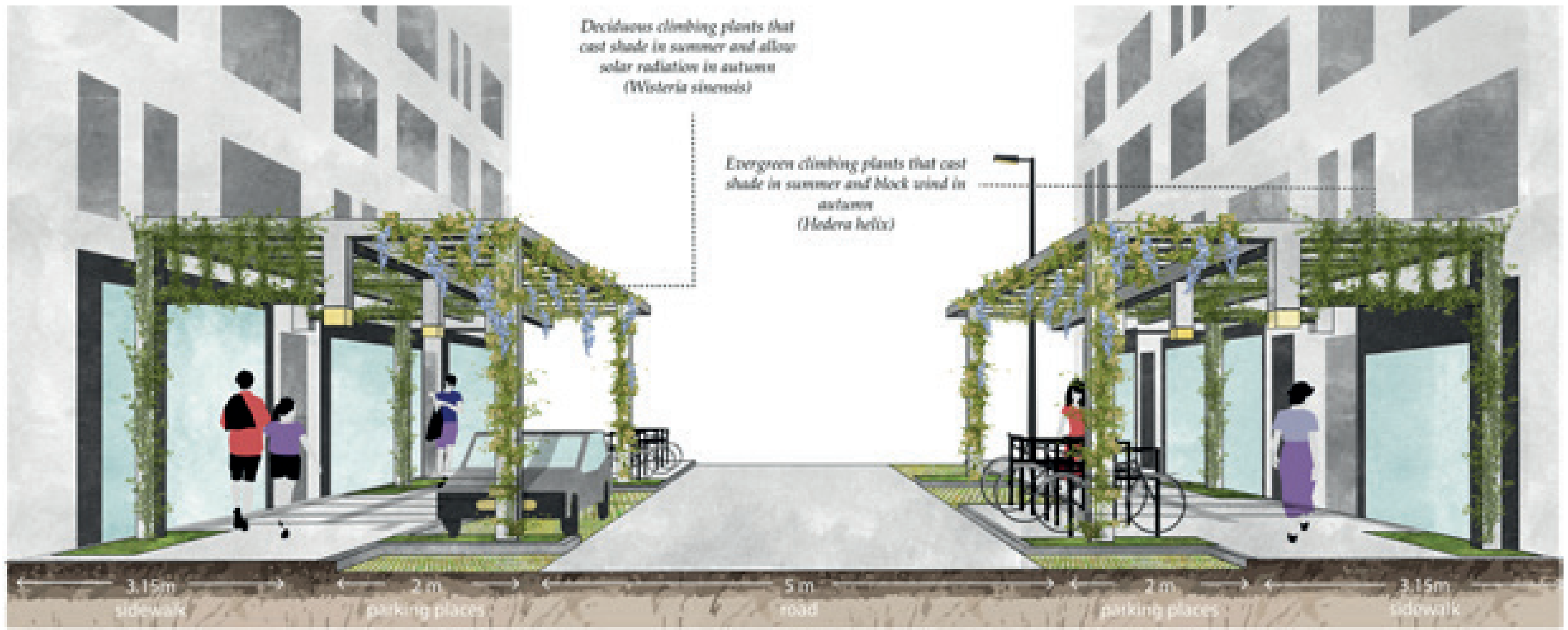


Figure 6.6.8 Semi-evergreen berceaux above parking implemented in the Hoogstraat

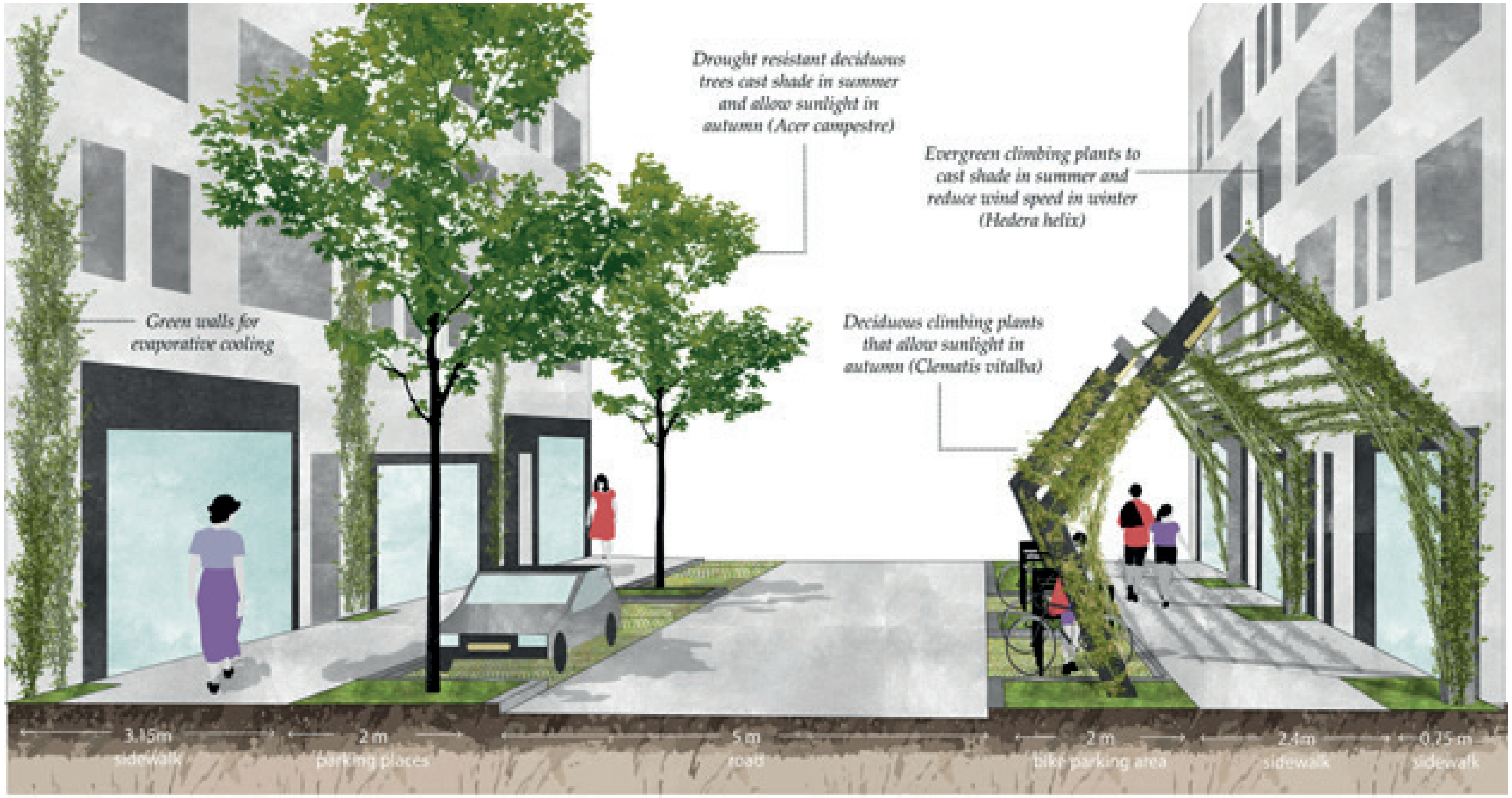


Figure 6.6.9 Semi-evergreen berceau with tiled sides implemented in the Hoogstraat

Semi-evergreen tilted berceau

When the sun radiates upon the Southern sidewalk in late afternoon it tends to have a low position. In order to cast sufficient shade around this time this berceau has semi-closed sides. While these sides only have a height of 2.25 m above the road, I chose to convert this space to parking places for bikes. This berceau is tilted to allow maximum solar radiation in autumn. Similar to the aforementioned berceau, it consists of deciduous and evergreen climbing plants. By means of steal wires along the columns of the berceau, the evergreen climbing plants will provide slight wind roughness.

For the deciduous climbing plants, I used Clematic vitalba that easily covers large surfaces and withstands sun and drought (Appeltern, n.d.)

As this prototype was developed for the Southern sidewalk only. I visualised how deciduous trees along the Northern sidewalk in combination with green walls can further improve thermal comfort of this street.

Summary

The final phase of the research through design process demonstrated how the prototypes can be implemented in real streets. I found that the landscape elements had to be adjusted to allow pedestrian flow, sufficient space for parking lots, sufficient sight from and on the sidewalk and sufficient artificial light during the evening. While the visuals demonstrate how these prototype can be implemented technically, they also show the aesthetic appeal of the prototypes.

Figure VII
Berceau at estate Zeist (Stoopendaal, 1670-1680)

Chapter 7

Discussion and Conclusion

7.1 Discussion

Research methods

SRQ 1

Evidence on the microclimatic purpose of historical landscape elements was mainly found in historical books about the estate garden design. However, for rural landscape elements, such as umbrella trees and shelterbelts, limited literature was found about their microclimatic purpose. Finding more evidence about their microclimatic purpose would require a different research method. For example, searching for toponyms on historical maps could help to reveal additional knowledge about the microclimatic function and spatial characteristics of these rural landscape elements.

SRQ 2

For the microclimate simulations I had to define representative versions of each landscape element. The dimensions of these versions were based on estimations from pictures and measurements on google maps. While this method suffices the accuracy of the 1 metre grid size in Albero (ENVI-met), the number of landscape elements that were measured was limited. More research into the dimensions and varieties within each historical landscape elements is required to understand the representativeness of the models defined in this thesis. Nevertheless, the models used in this thesis provided a first insight into the microclimatic effects of each landscape element.

Next, the climatological data for ENVI-met was obtained from the hourly dataset of KNMI weather station the Bilt. While this station is located in the countryside, data about wind speed from this station is not representative of urban contexts with a higher roughness level. However, this factor was not taken into account in the selection procedure of the climatological days. Despite that, the climatological input for autumn days was given a wind speed of 5.7 m/s, which exceeds the comfort level of 5 m/s and therefore is relevant to assess the influence of these landscape elements on wind speed reduction.

SRQ 3

Due to limited data about H/W ratios of Dutch urban streets, the mean H/W ratio for shopping streets was calculated with the Google Earth measurement tool and the AHN section tool. While these measurements are not very accurate, they also are time precious. Due to the latter, the measurements were limited to 60 shopping streets in Amsterdam, Rotterdam and The Hague. However, in order to learn more about average H/W ratios and due to the general importance of this data in relation to climate sensitive design, further research on typical H/W ratios of urban streets is warranted.

Then, the influence of design interventions on sun-shade patterns were assessed with Sketchup for the June 21st to assess the influence on heat stress and September 23rd to assess the influence on cold stress. I chose to simply the analysis to the 21st of June as this day provides insights into shortest shading patterns and I simplified the analysis to the 23rd of September to assess sun-shade patterns for days when cold stress might occur, but for SW-NE streets still a significant amount of solar radiation accesses the street canyon. Despite that thermal discomfort also occurs in other months when the shading patterns are different, simplifying the sun-shade analysis to these specific days required less time to be spent on analysis and was therefore more easily integrated in the research through design process.

Subsequently, the influence of landscape elements on wind speed was informed by educated guesses, based on the literature provided in this thesis and the outcomes of the ENVI-met simulations. These results were also presented in climatelier sessions with experts on climate-sensitive design. For a more detailed account of wind effects wind simulations could have been made with computational fluid dynamic (CFD) software such as ENVI-met and Fluent. However, compared to CFD software, these educated guesses require less time and are therefore more easily integrated in the research through design process.

The research through design process first evaluated prototypes for heat stress reduction and later adjusted the prototypes that scored highest on heat stress reduction for cold stress reduction as well. Due to this decision, prototypes that scored low on heat stress reduction but have the potential to score high on cold stress reduction are excluded in this process. However, the decision to prioritize heat stress reduction was made as heat stress will become increasingly important with climate change. Next to that, the decision to select prototypes that most effectively improved thermal comfort, resulted in the development of mainly prototypes of the berceaux and umbrella trees. If I had chosen to select the highest scoring prototypes of each landscape element and adjusted those to reduce cold stress, more knowledge about each landscape element would have been generated. Future climate sensitive design research should take these limitations into the research through design process into account. Overall, the selection procedure opted for in this thesis resulted in prototypes that have a significant potential to reduce both heat and cold stress and are therefore relevant for implementation in a real context.

Research outcomes

SRQ 2

In this thesis ENVI-met is used to simulate the microclimatic effects of historical landscape elements. For this model I opted to create a base-model of a street canyon with a H/W ratio below 0.3 in order to allow the assessment of the influence of the landscape elements on both cross- and parallel winds. However, this H/W ratio is not representative of common urban street canyons. Therefore, the outcomes of the ENVI-met simulations are not typical of urban streets. Moreover, no substantial crosswinds were identified in ENVI-met for a H/W ratio of 0.3. This might be due to the influence of building depth and initial wind speed on wind patterns but remains a question for future research.

Next, the climatological criteria defined for the selection of representative days from the KNMI-data set resulted in only a limited number of days over the last thirty years, implying that the outcomes are not representative of common days. However, in relation to criteria for the hot summer days it is expected that these will occur more often in future due to climate change. Then, the conditions for cold stress in autumn were chosen specifically to be sunny and windy to directly assess the influence of the landscape elements on both solar radiation and wind speed. So, while these criteria for autumn conditions were optimal for assessing the influence of the landscape elements on radiation and wind, these specific outcomes would not occur often in reality. Despite this, the nature of the microclimatic effects of the landscape elements on radiant temperature and wind speed shown in this thesis will essentially be similar for other days.

SRQ 3
The actual number of streets represented by the typical test-beds is limited. This is on the one hand due to the limited number of divided traffic streets measured in this thesis and on the other hand due to the unique combination of H/W ratio and street orientation. Nevertheless, the test-beds defined in this thesis are likely to be representative of Dutch shopping streets that have not been measured in this thesis. Moreover, I expect that the average H/W ratio of shopping streets is different amongst cities. Further studies could investigate these differences in H/W ratio between cities to better understand how representative these test-beds are of shopping streets per city.

The prototypes generated in this research through design process are only based on their microclimatic effects. In order to bridge the gap between academia and practice, further research could evaluate the design outcomes in relation to feasibility, maintenance and construction costs. In these evaluations their positive side-effects have to be considered as well.

7.2 Conclusion

Answers to research questions

SRQ 1: What are historical landscape elements for microclimate control in the Netherlands?

Based on the hypothesis that various historical landscape elements had a role in outdoor microclimate control, this thesis first aimed to identify these historical landscape elements. Evidence is found in historical literature about the microclimatic purpose of vertically shaped trees, tree lanes, berceaux, shelterbelts, hedges, green walls, weeping trees and umbrella trees (“etagelindes”).

SRQ 2: How do these historical landscape elements perform on microclimate control?

This question was formulated to quantify the microclimatic influence of the historical landscape elements. Scientific literature showed that green walls, tree lanes, hedges and shelterbelts have the potential to significantly influence thermal comfort. For vertically shaped trees, berceaux, weeping trees and umbrella trees a prominent knowledge gap was identified in relation to their quantitative microclimatic effects. This thesis provided novel knowledge about the microclimatic effects of these landscape elements by means of ENVI-met simulations. The simulation results indicated that the berceau, weeping tree and umbrella tree significantly reduced shortwave radiation and wind speed, while the vertically shaped trees optimally allowed ventilation in summer and solar radiation in winter. Overall, I concluded that each historical landscape elements has the potential to significantly improve thermal comfort and is therefore relevant for microclimate control in contemporary Dutch cities.

SRQ 3: How to implement these historical landscape elements in favour of thermal comfort in contemporary Dutch urban streets?

The final research question aimed to develop new prototypes of historical landscape elements in favour of thermal comfort in contemporary Dutch urban streets. I found shopping streets with a H/W ratio of 1.0 most common and streets with an East-West (E-W) and Southwest-Northeast (SW-NE) orientation most problematic in relation to thermal comfort.

Heat stress

The results from the research through design process showed that hedges were unable to significantly shade the sidewalk and therefore had the least potential in reducing heat stress. Then, tree lanes were able to significantly shade the sidewalk and had a great evaporative cooling potential. Compared to tree lanes without hedges, weeping trees and shelterbelts showed no additional cooling effect. Instead, these two landscape elements further reduced the already poor ventilation potential of tree lanes without hedges. Amongst all landscape elements, landscape elements with a restricted cross-sectional crown volume (two-dimensional trees, umbrella trees and berceaux), scored highest on ventilation. Amongst these landscape elements, prototypes with horizontal surfaces above the sidewalks provided most shade and thereby reduced heat stress most significantly. These prototypes are versions of berceaux and umbrella trees. Unlike traditional versions of the berceau and umbrella tree that consistsed of hedge or tree species, these new prototypes consist of climbing plants that require less maintenance.

The conclusions provided above hold generally truth for both street orientations. The major difference in street orientation is that prototypes along the southern sidewalk of the SW-NE oriented streets scored higher if they had a semi-closed side to reduce shortwave radiation in late afternoon.

Cold stress

The second design loop aimed to adjust the five protypes that reduced heat stress most effecitvely to reduce cold stress as well. As I found that limited solar radiation accesses the E-W streets in autumn, the prototypes of E-W streets were only adjusted to reduce wind nuisance. In doing so, a balance had to be found between wind reduction in autumn and ventilation in summer. Effective strategies are channeling wind over evergreen berceaux, alternating the height of umbrella trees to increase wind roughness, and using hedges as wind screens. For SW-NE streets, the prototypes had to be adjusted to reduce wind nuisance and to allow maximum solar radiation in autumn. Most effective prototypes were a semi-evergreen berceau and evergreen umbrella trees with alternating heights.

Implementation

Apart from their influence on the microclimate, I found that the landscape elements had to be adjusted to allow pedestrian flow, sufficient space for parking lots, sufficient sight from and on the sidewalk and sufficient artificial light during the evening. Implementing these prototypes in streets does contribute to aesthetically appealing and thermally comfortable steets.

GRQ: Which historical landscape elements for microclimate control could be adjusted in favor of thermal comfort in contemporary Dutch urban streets?

This question aimed to generate new prototypes of historical landscape elements for microclimate control in Dutch urban streets. Vertically shaped trees, tree lanes, berceaux, shelterbelts, hedges, green walls, weeping trees and umbrella trees were identified in historical literature as landscape elements for microclimate control in temperate climate zones. Then, a literature review and ENVI-met simulations indicated that all of these historical landscape elements have the potential to improve thermal comfort. Finally, by means of a research through design process, new prototypes of these historical landscape elements were developed in favour of reducing heat and cold stress for two test-beds. Amongst all landscape elements, I conclude that prototypes of the umbrella trees and berceaux are most suitable for improving thermal comfort in Dutch urban streets.

Relevance

Scientific relevance

So far, no scientific research existed about historical landscape elements for microclimate control for temperate climate zones. Thereby, this thesis fills a prominent knowledge gap in historical geography and garden history. Due to the innovative approach of this research, this thesis demonstrated that historical literature found in books on garden design and in poems, is a fruitful source to discover the microclimatic purposes of historical landscape elements. This method is therefore relevant for further (scientific) studies that aim to investigate historical landscape elements for microclimate control.

This thesis generated entirely new scientific knowledge about the microclimatic effects of vertically shaped trees, berceaux, weeping trees and umbrella trees and thereby provides new scientific insights into these microclimate control measures. With these results, it is possible to quantitatively compare these landscape elements with other microclimate control measures. This thesis showed that ENVI-met, with its ability to model uniquely shaped vegetation on a small-scale, is suitable for assessing the microclimatic effects of historical landscape elements.

Next to that, this thesis integrates knowledge from urban meteorology, historical geography and garden history in a research through design process. This novel approach demonstrated how researching historical landscapes could contribute to climate sensitive design and hopefully inspires others to take on a similar approach.

Finally, this thesis reveals the importance of collaborative research between different scientific disciplines to generate novel climate responsive design.

Societal relevance
This thesis contributed new prototypes that broaden the scope of passive low energy microclimate control measures that urban planners and designers can apply to improve thermal comfort of urban streets. As mentioned before, thermal comfort is a critical component of outdoor space quality and will become increasingly important with climate change and continued urbansisation. As the indoor climate is highly affected by the outdoor microclimate, by enhancing outdoor thermal comfort these prototypes have the potential to reduce the energy demand for indoor heating in winter and cooling in summer. This indirectly helps to reduce energy costs and greenhouse gas emissions.

Recommendations
This thesis provided a first overview of historical green landscape elements for microclimate control in temperate climate zones. Future studies could broaden this overview by studying non-green landscape elements for temperate climate zones. For example, future research could investigate the microclimatic aspects of historic fruit walls, that were especially designed to retain heat in favor of fruit ripening. Then, while research about historical landscape elements for microclimate control is limited to one nonscientific book and two scientific studies, and this thesis, it is highly recommended to continue studying historical landscapes elements for other climate zones as well.

While the ENVI-met simulations provided a first indication about the microclimatic effects of the historical landscape elements, the simulated models are highly simplified and not representative of all spatial variations within one landscape element. Further research into different spatial varieties of each landscape elements is warranted to make knowledge about the microclimatic effects of these landscape elements more specific.

Next, since the prototypes in this thesis are largely adjusted based on educated guesses, further research with microclimate simulation software would help to quantify the microclimatic effects of these prototypes more carefully. Finally, the prototypes in this thesis were only adjusted to test beds of common shopping streets, future research is highly desirable to refit these historical landscape elements to other outdoor urban areas as well.

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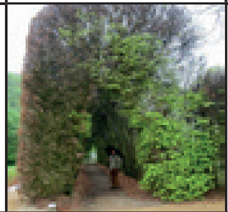
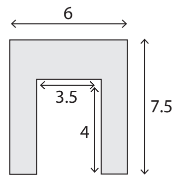
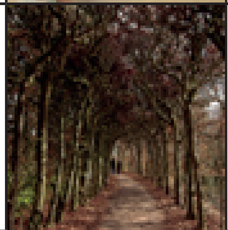
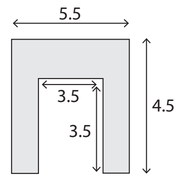
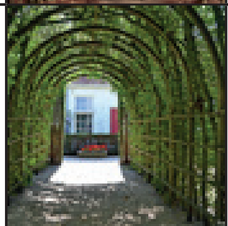
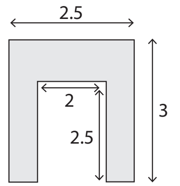
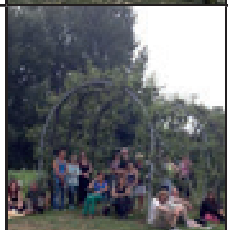
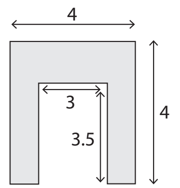
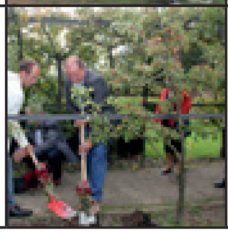
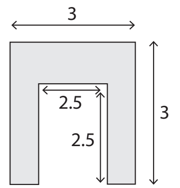
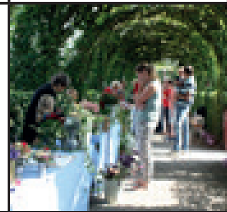
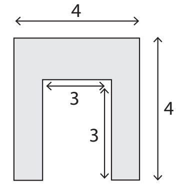
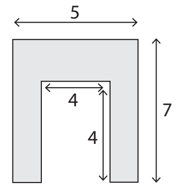
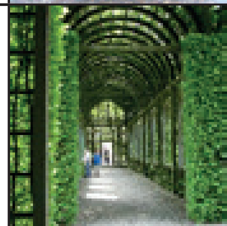
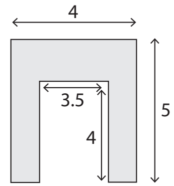
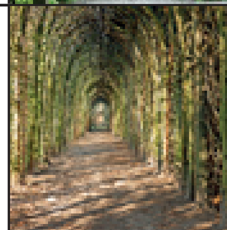
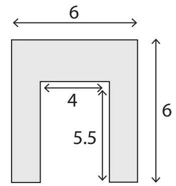
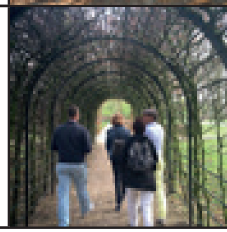
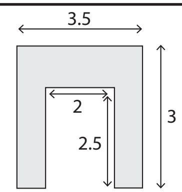
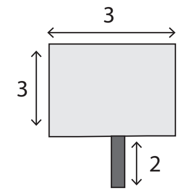
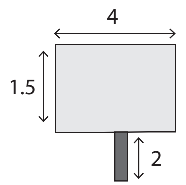
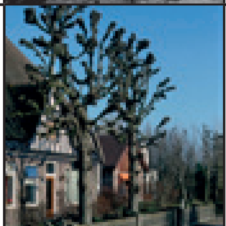
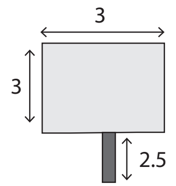
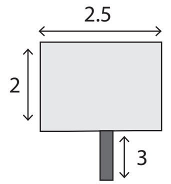
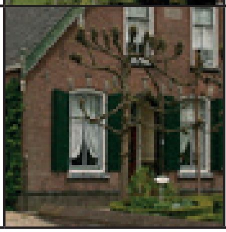
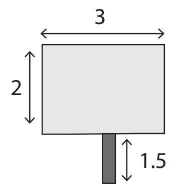
Appendix 1

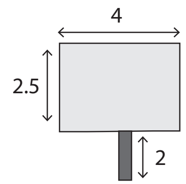
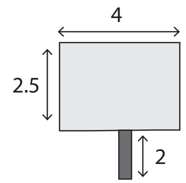
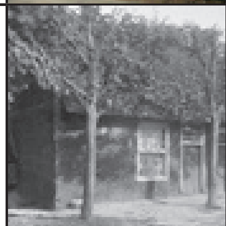
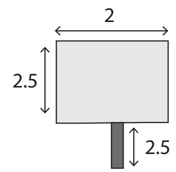
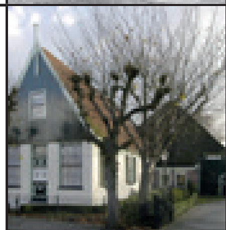
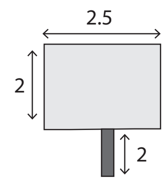
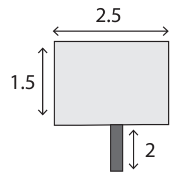
Berceaux: dimensions based on estimations from pictures and Google Earth measurements.

	Picture	Location	Dimensions [m] (not to scale)
[1]		Estate Het Nijenhuis, Wijhe, Overijssel (52°24′57.42″N; 6°12′58.19″ O)	
[2]		De Wildenborch, Vorden, Gelderland (52°07′12.06″N; 6°23′02.95″ O)	
[3]		Prinsenhof, Groningen (53°13′19.56″N; 6°34′08.28″ O)	
[4]		Perenlaantje, Hendrik-Ido Ambacht (51°50′18.62″N; 4°39′09.09″ O)	
[5]		Perenlaantje, Sittard (50°59′58.80″N; 5°52′17.10″ O)	

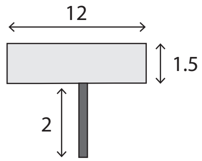
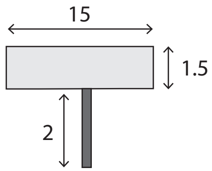
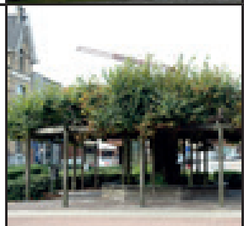
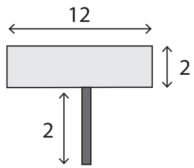
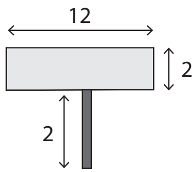
	Picture	Location	Dimensions [m] (not to scale)
[6]		Muiderslot (52°20′02.62″N; 5°04′19.13″ O)	
[7[		De Lind, Oisterwijk (51°34′50.80″N; 5°11′48.86″ O)	
[8]		Paleis het Loo (52°14′00.95″N; 5°56′48.26″ O)	
[9]		Kasteel Weldom (52°12′59.64″N; 6°34′54.95″ O)	
[10]		Beeckestijn (52°27′06.74″N; 4°39′09.37″ O)	

Vertically shaped trees: dimensions based on estimations from pictures

	Picture	Dimensions [m] (not to scale)
[11]		
[12]		
[13]		
[14]		
[15]		

	Picture	Dimensions [m] (not to scale)
[16]		
[17]		
[18]		
[19]		
[20]		

Umbrella trees: dimensions based on estimations from pictures and Google Earth measurements.

	Picture	Location	Dimensions [m] (not to scale)
[21]		Nuenen (51°28′38.84″N; 5°33′05.56″ O)	
[22]		Westerlo (51°05′11.72″N; 4°55′00.43″ O)	
[23]		Retie (51°16′00.89″N; 5°05′04.56″ O)	
[24]		Oisterwijk (51°34′51.87″N; 5°11′54.27″ O)	

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