The effect of different tree configurations on heat stress in courtyards

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The effect of different tree configurations on heat stress in courtyards

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This thesis was conducted as part of the Urban Comfort Lab, a research project together with the TU Delft, Municipality of Haarlemmermeer, Ministry of Interior and Kingdom Relations, Ministry of Infrastructure and Water Management and Stichting Leefomgeving Schiphol. The research is led by Dr. ir. Martijn Lugten together with Dr. ir. Zhikai Peng and ir. Gustaf Wuite.

Abstract

Among the major urban cooling strategies, urban morphological changes and increasing greenery coverage have proven effective in mitigating heat stress. One building type that has been used for centuries in hot and arid climates is the courtyard typology as it can create comfortable thermal conditions. However, little is known about the climate performance of different tree planting patterns in these courtyards. This study aimed to assess the effectiveness of different tree configurations in courtyards with a specific focus on the Amsterdam Metropolitan Area. First, a literature review of the existing studies on the effectiveness of tree planting patterns to reduce heat stress was conducted. Next, 34 historic courtyards in Amsterdam (*hofjes*) and their tree planting patterns were analysed both qualitatively and quantitatively. Through this analysis, prevalent tree planting patterns and general guidelines for tree planting patterns were derived. Based on the literature review and hofjes analysis, six different tree planting patterns have been established. These were: the Cornered pattern with trees in the south facing corner, the Perimeter pattern with a line of trees along the perimeter, the Dispersed patterns with evenly dispersed trees, the Double Row pattern with two rows of trees, the Two Sided Double Row pattern with two double rows of trees on either side of the courtyard, and the Clustered Double Row pattern with two rows of trees clustered in the centre. These tree configurations were modelled in a courtyard to determine their effect on the Physiological Equivalent Temperature (PET) levels using ENVI-met 5, a 3D model simulation software. The courtyard used in this study is located at the Urban Comfort Lab, which is an experimental testing facility in Hoofddorp, The Netherlands. Simulations were carried out for two hot days in 2022, July 17th to 19th, during which temperatures reached up to 35.4 °C. Results showed that during the morning and late afternoon, the the Double Row and Clustered Double Row patterns were most effective in reducing the share of maximum PET values experienced in the courtyard. In the afternoon, during the hottest part of the day, the Dispersed pattern was the most effective in reducing the share of extreme PET values in the courtyard, with PET reductions of up to 7 K. Despite this reduction, it is important to note that PET levels inside the courtyard remained above 41 °C for the majority of the day, indicating the persistence of extreme heat stress conditions. The different mean radiant temperature values of the patterns exerted the largest influence on variations in PET, as wind speed, relative humidity and air temperature showed little variations among patterns. The findings of this research can help architects, urban designers and municipalities in creating more liveable and climate resilient cities in the face of rising temperatures. Additionally, this research contributes to the limited existing literature on the effect of tree planting patterns on heat stress in courtyards and offers a methodology for analysing existing tree configurations in courtyards.

Acknowledgments

I would like to express my sincerest gratitude to my two supervisors Daniela Maiullari and Zhikai Peng for their guidance and critical feedback throughout this process. Coming from an economics background, the research methodologies and topics were fairly new to me. They have gone beyond their requirements as supervisors to help me get acquainted with this research field and for that I am very grateful. Also, a special thanks to Gustaf for introducing me to the Urban Comfort Lab project and being open to answer all sorts of questions throughout the process.

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Lastly, I would like to thank my mother, sisters and of course my father, who unfortunately is not here anymore. It would have not been the same without their continuous support throughout my studies and life in general. Staying within the realms of family, I would like to thank my uncle for being the most flexible employer this past period and lending me a laptop without which I would have not been able to do a substantial part of this thesis.

Thank you all,

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List of Abbreviations and Acronyms

Abbreviation/Acronym	Definition
PET	Physiological equivalent temperature (°C)
MRT	Mean radiant temperature (°C)
UBL	Urban boundary layer
UCL	Urban canopy layer
RSL	Roughness layer
Urban Comfort Lab	The testing facility that was modelled
Lab	Abbreviation of the Urban Comfort Lab
SD	Standard deviation
M	Mean
UHI	Urban heat island
H/W ratio	Height to width ratio, also referred to as the aspect
W/L ratio	Width to length ratio
SVF	Sky view factor
ds	The mean distance between the trunk of the tree and the short side of the courtyard (m)
DS	Half the length of the courtyard (m)
dl	The mean distance between the trunk of the tree and the long side of the courtyard (m)
DL	Half the width of the courtyard (m)
ART	Height to distance ratio between two trees, also referred to as the aspect ratio of a tree

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1. Introduction

1.1 Climate change and heat stress in cities

With the most recent IPCC report stating that there is a 50% chance that the rise in global temperatures surpasses the 1.5 °C threshold in the coming decades, global temperatures are expected to increase (IPCC, 2023). This increase in temperatures is exacerbated in cities as they are generally warmer compared to the surrounding rural environment. This effect originates from the different radiative and thermal properties of the urban fabric, a phenomenon known as the Urban Heat Island (UHI) effect (Oke, 1982). In The Netherlands alone, temperature differences between cities and the surrounding environment are already reaching up to 7 °C (KNMI, 2021), with larger differences becoming more prevalent (van Hove et al., 2011). The increasing frequency and duration of high temperatures can lead to heat stress in humans, posing significant health concerns (Field et al., 2012; Li & Bou-Zeid, 2013). These health concerns range from lower overall well-being and lower productivity levels at work to cardiovascular problems. Moreover, heat stress is recognised as a leading cause of weather-related fatalities in certain parts of the world (Oke et al., 2017; Zander et al., 2018). In addition to health concerns, rising urban temperatures increase the demand for active cooling systems, such as air conditioning, and the energy consumption associated with these appliances (Pataki et al., 2011). Cities are already estimated to be accountable for the consumption of 67-76% of global energy (Seto et al., 2014). As temperatures rise, the energy required for cooling purposes grows accordingly. A review of studies showed that with every 1 °C increase in temperature, peak electricity load of buildings increases up to 4.6% and total energy demand of buildings increases up to 8.5% in different parts of the world (Santamouris et al, 2015) driving urban energy consumption up even higher.

The design of our cities can significantly impact the UHI effect and, consequently, the thermal comfort of humans (van Hove et al., 2011). When considering an urban climate, the city can be looked at from different scales and related mechanisms. These scales range from the microscale, which considers local climates on a building or street scale, to local scales focusing on neighbourhood level, meso scale focusing on the city as a whole and macro scale focusing on the whole urban region (Oke, 2017). In considering the influence of individual buildings on heat stress, courtyards have been adopted throughout history in different climate regions to create comfortable microclimates. Next to creating comfortable microclimates, courtyards can also be of great potential to facilitate outdoor interaction as they frequently function as the main outdoor area for recreational activities

(Darvish et al., 2022; Li et al., 2019). Different researchers have shown the importance of comfortable public spaces in drawing people outside and fortifying social interaction, human connections and overall quality of life (Chen & Ng, 2012; Weijs-Perrée et al., 2019). This potential for courtyards has also been explored to a limited extent in the Dutch context, as a research by Taleghani et al. (2014) showed that the courtyard typology can result in the optimal microclimate in the Netherlands as compared to other urban forms. Many design factors can affect the impact of the microclimates of courtyards, such as alignment to the sun path (Ghaffarianhoseini et al., 2015), height and width ratios (Al-Hafith et al., 2017), opening characteristics and geometry (Chatzidimitriou & Yannas, 2016) and components as shading devices and water features (Zamani et al., 2018). Another important influencing factor for the microclimate of courtyards is vegetation, such as trees, shrubs, and vegetative surfaces (Darvish et al., 2022; Li et al., 2019). Among them, trees play the most important role in regulating microclimates through evapotranspiration and shading (Dimoudi & Nikolopoulou, 2003).

1.2 Problem statement

Cities worldwide are adopting increased tree coverage as a recognised natural solution to combat urban heat and mitigate the UHI effect (Rahman et al., 2020). Both the presence of greenery and its configuration have become a topic of increasing interest in the past decade. The vast majority of this research on tree planting patterns in general urban settings is focused on sub- and humid-tropical and temperate oceanic climates (Fu et al., 2022). However, research on tree configurations in courtyards specifically is scarce and primarily focused on hot and arid climates (Darvish et al., 2022; El-Bardisy et al., 2016; Li et al., 2019). Considering research on different tree planting configurations and their effect on heat stress and general research into courtyards, little to nothing is known in the Dutch context (Fu et al., 2022; Taleghani et al., 2014; Taleghani et al., 2015). With the expected increase in (urban) temperatures in the Netherlands, along with the related health and environmental concerns, it becomes increasingly important to understand how outdoor spaces can perform thermally. This understanding is needed to provide comfortable social environments and to ensure the well-being of citizens in the face of climate challenges.

1.3 Research objectives and questions

The main objective of this thesis is to research the effect of different tree configurations on reducing heat stress in a courtyard setting in the Amsterdam Metropolitan Area. Because of the limited existing knowledge on this topic, the first sub objective is to research existing literature to discover which tree planting patterns are most effective in reducing heat stress in different urban settings, including courtyards. In addition, the second sub objective is to analyse the courtyards in the Amsterdam Metropolitan area and to determine which tree planting patterns are prevalent in these courtyards. From this analysis, input for tree configurations to be tested in this study is to be derived as well. As a focus for the type of courtyards, the historic courtyards in Amsterdam called hofjes are chosen. The third sub objective, finally, is to understand the climate performance and the related comfort level of the different established configurations through modelling. By addressing these three objectives the thesis aims to produce knowledge that can be used by municipalities, city planners and architects to make more informed decisions on tree planting patterns in courtyards to reduce heat stress. Additionally, the findings of this research can add to the scant literature that is currently available on these topics.

Based on these different research objectives, the following main and sub research questions are formulated:

Main research question: “What configuration of trees is most effective in reducing heat stress in courtyards in the Amsterdam Metropolitan Area?”.

Sub question 1: What are optimal configurations of trees to reduce heat stress in a courtyard setting according to existing literature?

Sub question 2: What are prevalent tree configurations that can be derived from historic courtyards (*hofjes*) in Amsterdam?

Sub question 3: What is the modelled effect of the different configurations of trees on reducing heat stress in the courtyard of the Urban Comfort Lab?

1.4 Case study

The courtyard of this study is located in Hoofddorp, The Netherlands where a testing facility of three courtyards made of shipping containers is built as part of a larger research for the Urban Comfort Lab (also referred to as The Lab). The Lab focuses on exploring various design choices and vegetational types within courtyards to understand their impact on noise abatement and thermal comfort (AMS Institute, 2023). The vegetational types considered within the three different courtyards in the Lab are grass, green walls and trees, with this study focusing on trees. Figure 1 shows a photograph taken from the courtyard in the Lab. To determine the effectiveness of different tree planting patterns on local thermal conditions within The Lab, ENVI-met 5 is used. ENVI-met is a computational fluid dynamic cased model and is one of the most commonly used programs for researching the microclimatic effect of different greenery configurations (Fu et al., 2022; Liu et al., 2021). The validation results of ENVI-met against the measurement data at The Lab have not been included in this thesis due to time constraints. However, they are planned for future study, as the measurement campaign has been scheduled for July 2023, which falls beyond the completion date of this thesis.

1.5 Outline

This thesis starts off with an overview of the most important theories and concepts related to this research in the theoretical framework. Afterward, the different methods used for the aforementioned sub questions are explained in depth as well as all the input and set up of the model. After the methodology section, the different sub questions are subsequently answered in Chapters 4, 5 and 6. These chapters are followed by a discussion and conclusion in which the limitations and scientific and societal are discussed. Also, this chapter addresses the main research question. This thesis ends with suggestions for future research and references.

Figure 1. A photograph taken by the author from within the courtyard of the Urban Comfort Lab

2. Theoretical Framework

2.1 The urban climate

This thesis draws upon a few concepts derived from climatological literature. The first concept discussed is the UHI followed by an explanation of the different vertical scales related to the urban (micro)climate. Additionally, the different horizontal scales through which the urban area can be analysed are explained.

The UHI effect is a phenomenon that is characterised by temperatures that are considerably higher than the surrounding natural and rural areas (Oke, 1982). These higher temperatures in cities result from factors such as reduced natural vegetation and evapotranspiration, extensive paved areas with a low albedo level that absorb heat, reduced wind speeds and anthropogenic heat generated from human activities (Mohajerani et al., 2017; Oke, 2017; Pijpers-van Esch, 2015). Figure 2 gives an overview of these causes. The UHI effect can be categorised into surface and atmospheric effects. The surface UHI effect refers to the surface temperature difference between urban areas and the surrounding environment. They are present throughout the day and night, with the most

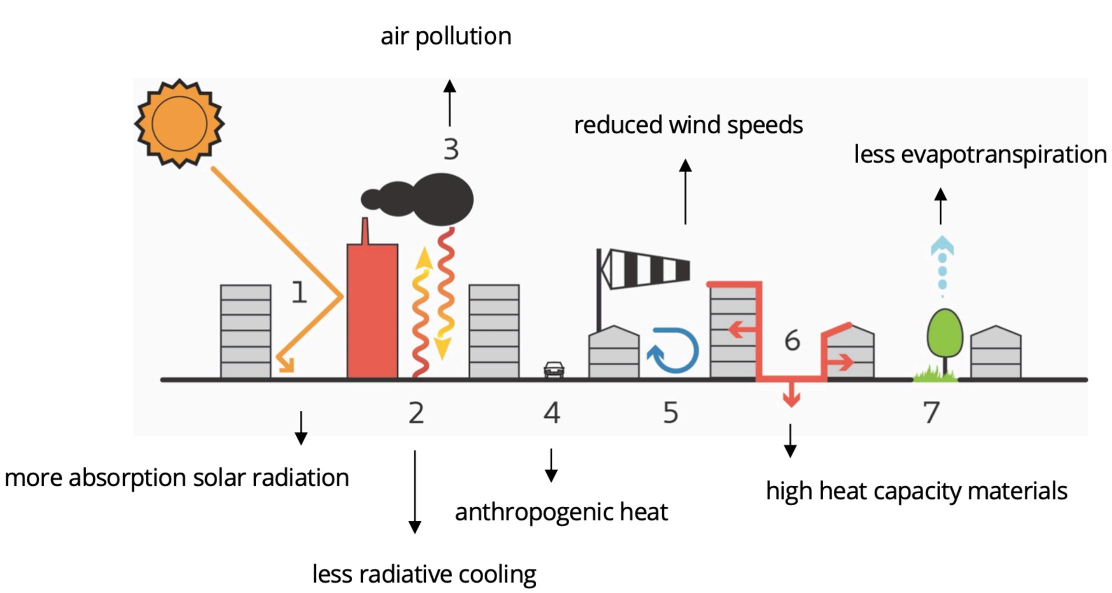


Figure 2. Different causes of the UHI effect (Pijpers-van Esch, 2015)

significant impact during sunny periods. The atmospheric UHI refers to the difference in air temperature between the urban and the surrounding environment and is the most researched component of the UHI effect (van Hove et al., 2011). Figure 3 illustrates the surface and atmospheric UHI effects. These higher temperatures because of the UHI are somewhat homogeneously spread in the atmosphere above the city, called the urban atmosphere. The urban atmosphere is influenced by both the urban form, which refers to the different surface properties, as well as the urban function, which refers to anthropogenic emissions. Both the urban form and function are important contributors to the UHI effect together with the influence of the buildings on wind speed (Pijpers-van Esch, 2015).

Within the urban atmosphere, various urban climate phenomena occur at different scales. From the viewpoint of the vertical plane, the largest vertical scale entails the whole urban atmosphere and is called the Urban Boundary Layer (UBL) (Oke, 2017). The UBL layer is again divided into different sublayers, of which the urban canopy layer (UCL) is the part of the atmosphere from ground level to the mean height of buildings and trees. This layer is followed by roughness sublayer (RSL), which is the part of the atmosphere from the ground layer to two to five times the height of buildings and trees, and includes the UCL. The UCL and RSL both have a vertical dimension of tens of metres. The other parts of the UBL are the inertial sublayer (with a vertical dimension between 25 and 250 metres), and the mixed layer (with a vertical dimension between 250 and 2500 metres). All layers from the ground up to the inertial sublayer are together called the surface layer. Considering these different layers and their effect on the (micro)climate of cities, the UBL and UCL are particularly important (Oke 1982; Oke, 1987). The climate in the UBL is somewhat homogeneous over the city whereas the UCL can differ considerably on a distance of metres. This higher variability in microclimates in the UCL is driven by the high variability in surfaces with different surfaces properties (Oke, 2017; Pijpers-van Esch, 2015).

From a horizontal perspective, the urban environment can be examined at various scales. These scales are the micro, local, meso and macro scales (Oke, 2017). The micro scale refers to the scale of built features such as buildings and canyons and streets, and greenery features such as trees and gardens. The next horizontal scale is the local scale, which includes built features such as city blocks or neighbourhoods and greenery

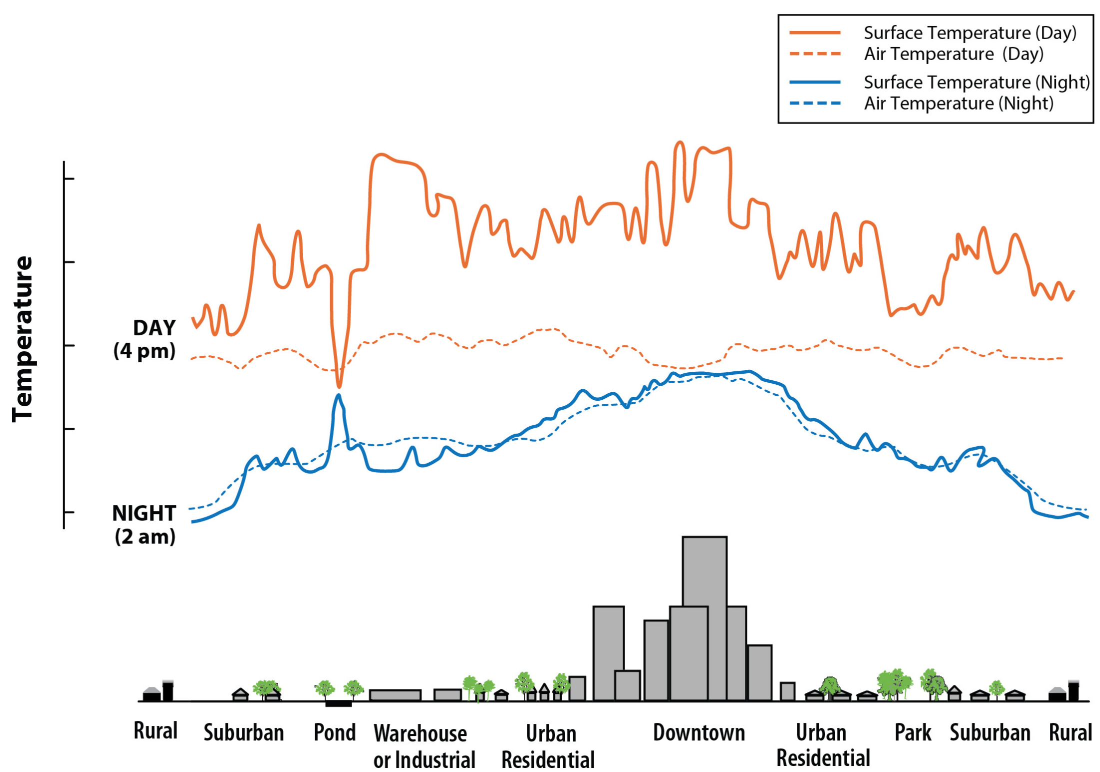


Figure 3. Variations in surface and atmospheric temperatures as a result of the UHI effect (USGS, 2019)

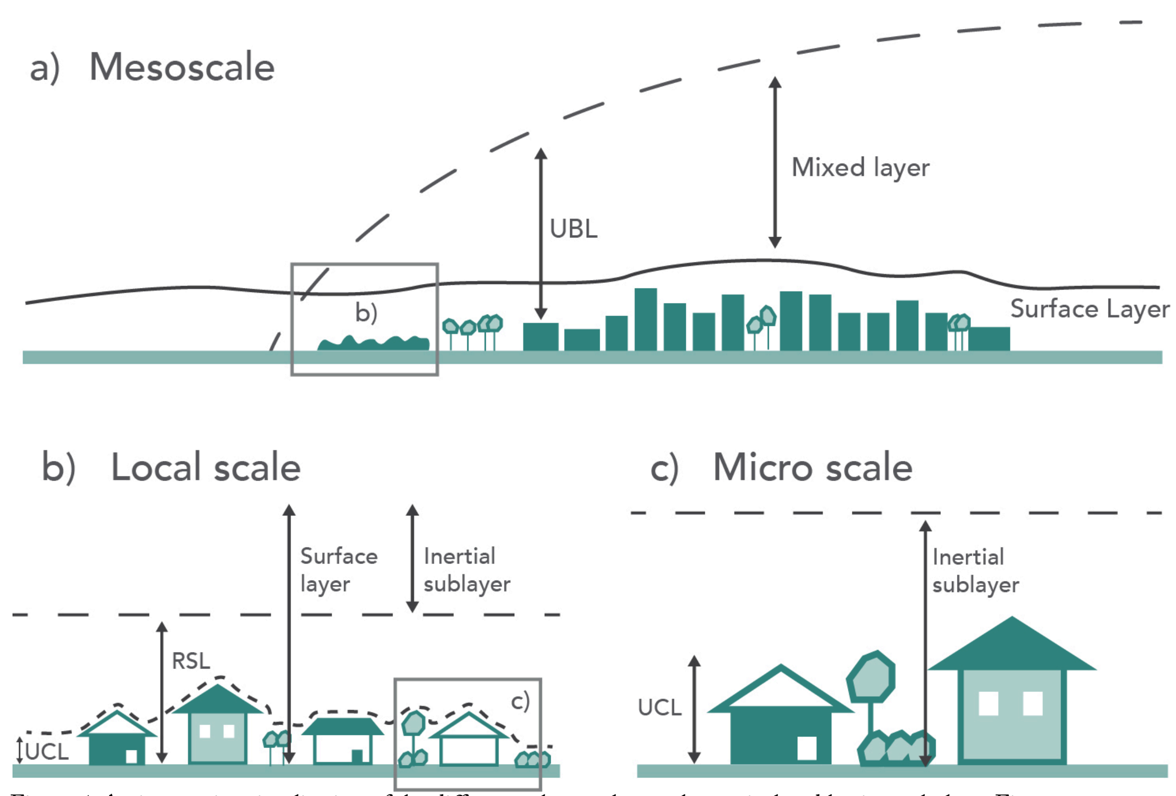


Figure 4. An integrative visualisation of the different urban scales on the vertical and horizontal plane. Figure was adapted by author based on Oke (1997)

features such as parks. The other scales are the meso scales which consider the city as a whole or the macro scale which looks at the city including the surrounding area. Oke (2017) refers to courtyards as part of a neighbourhood block and therefore the local scale with dimensions of 500 m x 500 m. In this research however, a courtyard is considered on the micro scale as the dimensions of the courtyard in the Lab (36 m x 18 m) fall within the typical range specified for the microscale by Oke (2017) (between 10 m and 200 m in width or length). Figure 4 gives an integrated overview of the different scales, both on the horizontal as well as the vertical plane.

Within this research, the focus is on the UCL considering the vertical plane. On a horizontal plane, this research considers the microscale (part c of Figure 4). The influence on heat stress, related to the UHI effect, is measured by considering the influence of the urban form and not function, as anthropogenic heat is not modelled in ENVI-met 5. How heat stress is measured is explained in the next section.

2.2 Measuring heat stress

Since this thesis focuses on reducing heat stress experienced in courtyards, it is important to understand the basics of human thermal stress and how it is measured. One of the most commonly used indices to measure heat stress in the urban environment is the physiological equivalent temperature (PET) (Potchter et al., 2018). PET was first coined by Höppe and Mayer (1987) and is defined to be 'equivalent to the air temperature that is required to reproduce in a standardised indoor setting and for a standardised person the core and skin temperatures that are observed under the conditions being assessed' (Matzarakis & Amelung, 2008, p.165). PET is based on the MEMI model, which is a steady state two-node model (Höppe, 1984). This model assumes a two-node structure of the body: the core and the surface of the skin. The MEMI model includes three equations: the energy balance equation of the total body, the heat flux from the body core to the skin, and the heat flux from the skin through the clothing layer to the surrounding area.

The energy balance equation of the human body is (Höppe, 1999):

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

M refers to the metabolic rate, W is the physical work output, R is the net radiation of the body, C is the convective heat flow, E_D is the latent heat flow to evaporate water into water vapour diffusing through the skin, E_{Re} is the sum of heat flows for heating and humidifying the inspired air, E_{Sw} is the heat flow due to evaporation of sweat, S is the storage heat flow for heating or cooling the body mass. All heat flows are expressed in watts. These individual heat flows are influenced by different meteorological parameters:

Air temperature influences C and E_{Re}
Air humidity influences E_D, E_{Re}, E_{Sw}
Air velocity influences C and E_{Sw}
Mean Radiant temperature (MRT) influences R

The other thermo-physiological parameters that are needed for calculating PET are the heat resistance of clothing (clo units) and activity of humans (W).

Air temperature, air humidity, air velocity and MRT are therefore important meteorological parameters which are also all in way interrelated. The human body does not have separate sensors for these climatological parameters. Therefore, their individual influences are hard to discern and which is why their combined effect is considered (Höppe, 1999). Air temperature is one of the most influential climatological parameters in determining thermal comfort. On its own it is a suitable indicator of how people experience heat, but it has important interactions with the other parameters (Song, 2011). An important other parameter is MRT, which describes the weighted average temperature of all nearby surfaces, objects and sky that emit and/or reflect in the direction of the person. This gives a value to the combined impact of radiation exchange between the human body and its surroundings in °C. In combination with air temperature, MRT has a strong impact on the human body's thermoregulatory system (Pijpers van Esch, 2015).

Also, the presence and (varying) velocity of the wind play an important role in regulating body temperatures. Heat is transferred to and from the body as air movement can cause warm air or vapour to be 'taken' away from the body. Therefore, wind plays an important role together with air temperature in regulating the body temperatures of humans (Parson, 2014). The degree to which air can 'take away' warm air or vapour from the body is also related to the last climatological variable which is humidity as this influences the body's ability to cool down through sweating. When the human body experiences heat, it evaporates water from the skin to the surrounding environment and through this process, heat is transferred from the body to the environment and the body cools down. This process is driven by the absolute difference between the humidity of the air in the environment and the humidity level of the skin. Humidity levels are often expressed in relative humidity which is the ratio of the moisture level of the air compared to the amount of moisture the air could hold at that given temperature. Therefore, it indicates the air's saturation level (Parson, 2014). As a general rule, relative humidity levels above 65% are considered high, leading to reduced evaporation of sweat and increased heat sensation. Relative humidity levels below 30% indicate very dry air, which can cause discomfort by drying out the skin, mouth, and throat (Pijpers-van Esch, 2015).

PET levels are further classified qualitatively to make for easier interpretation. Table 1 provides an overview of the PET levels associated with their thermal perception and grade of physiological stress.

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

Table 1. Classification of different levels of PET in °C, thermal perception and grade of physiological stress. Based on Matzarakis et al. (1999).

2.3 The cooling effect of trees

Trees can play an important role in reducing heat stress and providing other benefits to cities. It is therefore important to understand these benefits and processes that make a tree effective in the urban environment. There are many different merits to be derived from increasing tree coverage in cities, which are classified as the urban ecosystem services of trees (Bolund et al., 1999). These ecosystem services can be divided into four categories. The first category includes provisioning services, which encompass direct outputs beneficial to humans, such as food, water, and medicinal plants. Additionally, urban nature provides supporting services, which include processes that indirectly benefit humans, such as providing habitats for species and preserving biodiversity. Other types of services encompass cultural aspects, such as tourism, recreation, and aesthetic value. The last category when considering urban ecosystems is the one of regulating services. These include urban temperature regulation, noise reduction, air purification, decreasing the impact of climate extremes, etc. (Bolund et al., 1999; Gómez-Baggethun et al., 2013; Salmond et al., 2016; TEEB, 2011).

The temperature-regulating potential of trees is particularly relevant in this research and is widely acknowledged for its effectiveness in urban areas (Bowler et al., 2010; Rahman et al., 2020). Trees influence urban microclimates and reduce the UHI through various processes that do not necessarily cool the air but rather reduce the warming of the air (Kurn et al., 1994). The primary mechanisms involved in this process are shading and evapotranspiration. Trees prevent incoming solar radiation from reaching the ground or surrounding surfaces that tend to absorb heat more easily than vegetation. This reduces the absorption of shortwave radiation by surrounding surfaces and minimises the emission of longwave radiation, resulting in decreased air temperatures (Winbourne et al., 2020). This effect however is strongly dependent on the characteristics of the tree such as the crown diameter and shape, height and structure (Rahman et al., 2020). Moreover, while trees cool the environment through shading during the day, they can trap longwave radiation under their canopy and increase temperatures at night (Zhang et al., 2022; Ziter et al., 2019). The other process through which trees can cool down the urban microclimate is evapotranspiration, which refers to the release of water from the leaves of a tree as vapour into the atmosphere (Bowler et al., 2010). Water is absorbed through the roots of the tree and stem and evaporates through the stomata of the leaf. The tree uses energy (called latent heat) for this evaporation process and to do this, it takes energy out of the air (which is called sensible heat). This decrease in sensible heat results in a reduction in air temperature (Dimoudi & Nikolopoulou, 2003; Winbourne et al., 2020). Figure 5 illustrates these two processes.

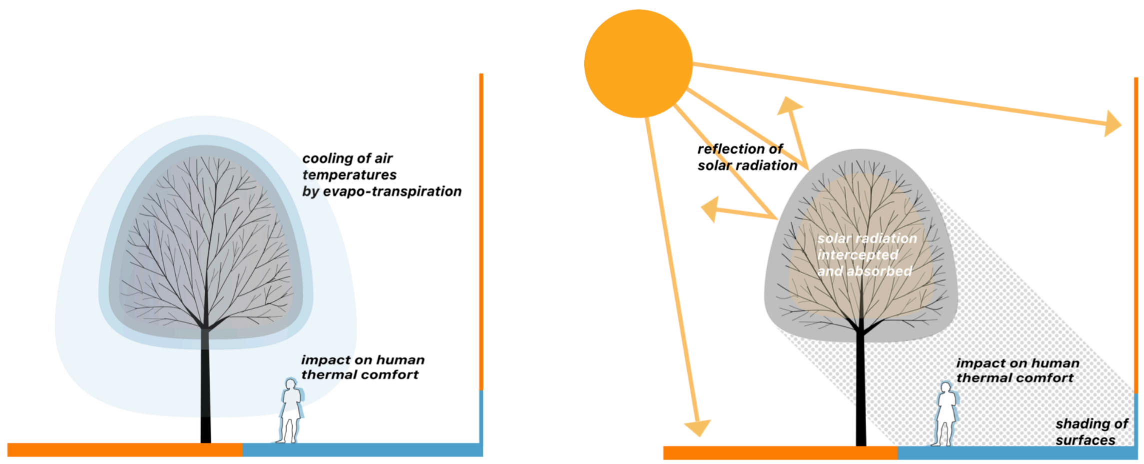


Figure 5. A visual representation of the two main processes through which trees cool down microclimates. Evapotranspiration on the left and shading on the right. Figure was taken from Powerpoint slides by Maiullari (2023)

2.4 Courtyard morphology and their microclimate

Not only vegetation plays an important role in the microclimatic processes within the courtyard, but also morphological components of the courtyard itself. The most influential morphological components are: height to width (H/W) ratio of the surrounding building, width to length (W/L) ratio of the courtyard space, orientation to the sun, natural ventilation and the sky view factor (SVF) and climatic conditions (Fu et al., 2022). These factors have different individual effects, but also have combined and location-specific effects which makes it challenging to derive universal guidelines (Al-Hafith et al., 2017). The different effects are first described as a basis for further extending the researched effects of tree configurations from the semi-controlled outdoor lab to real urban contexts.

2.4.1 Height to width ratio and width to length ratio

One of the most influential factors for microclimates of courtyards are the geometrical properties such as height, width and length of the courtyard. This ratio between height and width is often expressed as H/W or aspect ratio and is one of the most influential ratios (Al-Hafith et al., 2017; Oke, 1998; Rodríguez-Algeciras et al., 2018). As a general rule of thumb, higher aspect ratios can help to create microclimates in which less heat stress is experienced compared to the outside environment as it provides considerable shading. In the winter however, a higher aspect ratio can result in colder and less comfortable microclimates. This is due to reduced solar radiation entering the courtyard as a result of building height and the sun's lower position (Al-Hafith et al., 2017; Zamani et al., 2018). Although every research into courtyards is highly contextual, there are some general rules derived from previous research regarding optimal heights of courtyards in different climates during the year. For climates ranging from hot and arid to more temperate, courtyards with a height of two floors are most recommended. For cold climates, one story courtyards are ideal and in humid climates, higher courtyards of around three floors are recommended (Rodríguez-Algeciras et al., 2018).

Another important ratio considering courtyards is the width to length (W/L) ratio of the courtyard space. This ratio describes the shape of the courtyard space, with a value of 0.1 describing a rectangular shape and a value of 1 describing a squared courtyard. The W/L ratio is of influence as this ratio determines, together with the H/W ratio, how much solar radiation can reach the surface and therefore heat the surface. Research by Muhaisen & Gadi (2006) showed that increasing the W/L always increased the cooling load needed in the courtyard as temperatures increased and therefore the more W/L approaches 1, the more the courtyard heats up. A similar effect was observed in research by Mohsen (1979), but it is limited to a certain courtyard height.

These two ratios are crucial as they describe courtyard shapes and significantly influence the amount of heat entering a courtyard through solar radiation gain. In Chapter 5, these ratios are therefore used to analyse the Dutch courtyards. In the next section, the relationship with solar radiation and orientation to the sun is further explained.

2.4.2 Solar radiation and orientation

As mentioned before, an important factor that the height of the building influences is the amount of solar radiation entering the courtyard and this in turn is influenced by the orientation to the sun and geographical location of the courtyard. Different types of solar radiation transfers occur within courtyards and dense urban areas. These are the direct shortwave solar radiation, the reflected shortwave solar radiation, atmospheric long wave radiation and long wave radiation from urban surfaces as displayed in Figure 6 (Huang et al., 2014; Zamani et al., 2018). All these sun radiation transfers influence the microclimate of courtyards, but especially the amount of direct solar radiation that enters the courtyard as this in turn influences the amount of heat absorption by the facades and roofs and therefore the amount of long wave radiation they emit.

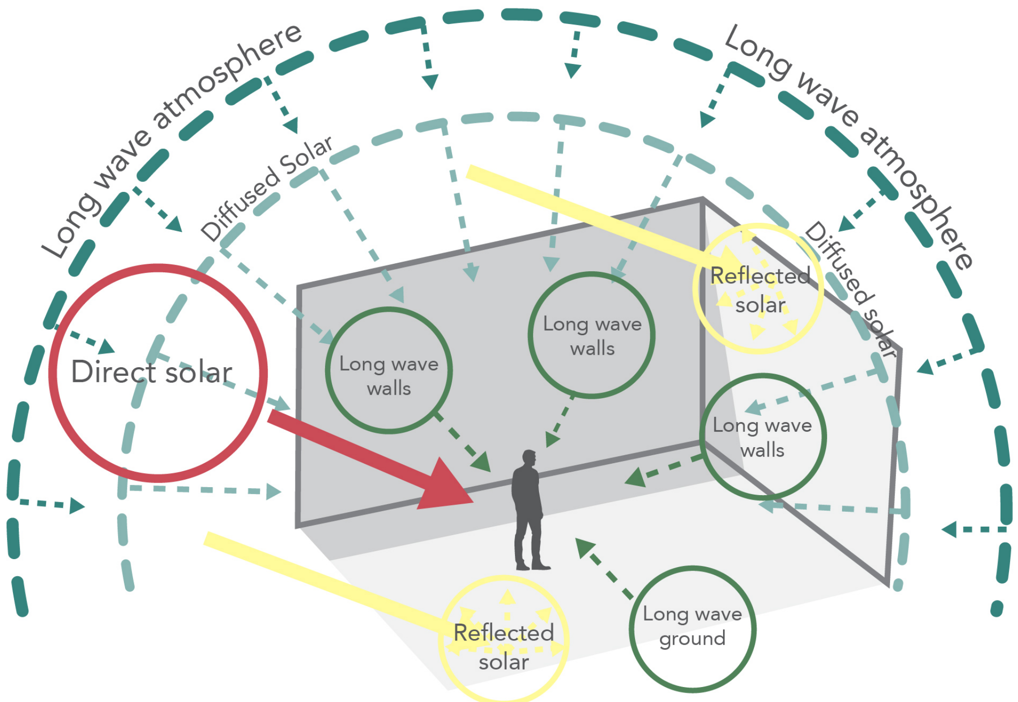
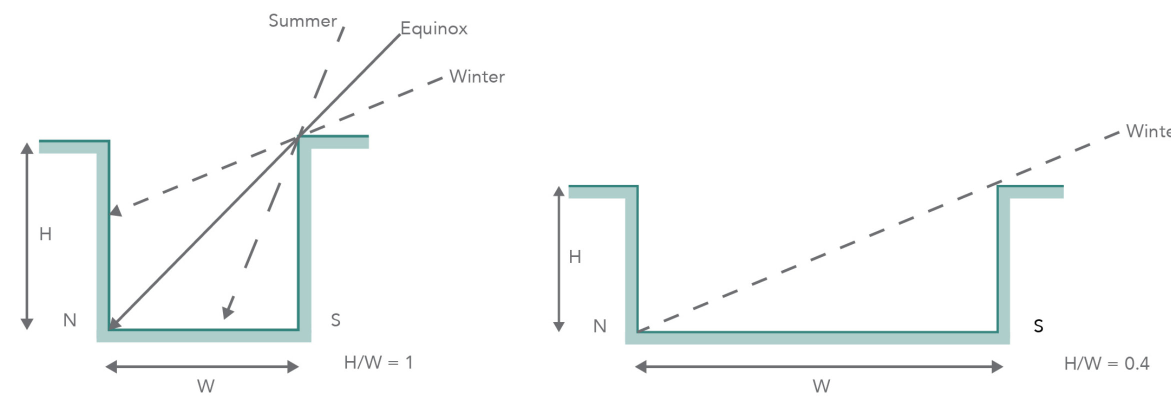


Figure 6. The different types of sun radiation transfer. Figure was adapted by author based on Huang et al. (2014)

The aspect ratio is a significant factor in determining the amount of solar radiation that enters a courtyard. Research by Yang et al. (2012) found that the height of the courtyard wall is one of the most influential factors in the amount of solar radiation that enters into a courtyard and therefore the thermal environment. The orientation to the sun, the position of the sun and the aspect ratio of the courtyard are all important determinants, as shown in Figure 7 and Table 2. Table 2 presents the percentage of an equator-facing wall, oriented east to west, covered by direct solar radiation at midday during the winter solstice. It considers various combinations of geographical locations (latitudes) and aspect ratios. Figure 7 gives an accompanying visual representation of these workings and how H/W ratio and position of the sun are related (Oke, 1998). As seen in the table and figure, both the aspect ratio as well as the position of the sun can greatly influence the amount of direct solar radiation entering the courtyard.



H/W ratio | latitude	0.3	0.4	0.5	0.6	0.8	1.0	2.0
40 °	100	100	100	83	62	50	25
45 °	100	98	79	66	49	39	20
50 °	99	74	59	49	37	30	15

Figure 7. Angles of indices of direct beam solar radiation at noon in an E-W canyon in at city at 45°N. Figure was adapted by author based on Oke (1988)

Table 2. The percentage that is exposed to direct sunlight of an equator facing wall that is oriented east to west on different latitude and with different H/W ratios of the urban canyon. Figure was adapted by author based on Oke (1988)

In research by Taleghani et al. (2014), four different orientations of courtyards with different width to length ratios have been modelled for the most severe climate scenarios for The Netherlands. It showed that for the different dimensions of the courtyard, the east to west (E-W) orientation resulted in the largest amount of direct solar radiation reaching the centre of the courtyard and leading to the highest level of heat stress. The north to south (N-S) orientation resulted in the shortest period of time in which direct solar radiation was present at the centre of the courtyard. An important factor influencing the amount of incoming solar radiation when talking about vegetation such as trees is the SVF. The sky view factor (SVF) is a parameter that quantifies the amount of obstruction between a point and the sky. It represents the fraction of sky visible from that point. Trees create obstructions that reduce direct, diffuse, and reflected shortwave solar radiation, thereby reducing heat buildup in the courtyard (Darvish et al., 2021). When considering the courtyard of the Urban Comfort Lab, it is oriented along a south west - north east (SW-NE).

The orientation is strongly related to the amount of solar radiation that comes in, which in turn is also related to the H/W and W/L ratios of courtyards. Therefore, the orientation of the analysed courtyards in Chapter 5 will also be considered.

2.4.3 Natural ventilation and Sky View Factor

Another factor influencing thermal behaviour within courtyards is the ventilation coming from pressure differences and through openings. Natural ventilation occurs as solar radiation hits the courtyard and heats parts of it. Other parts stay shaded which results in differences between warm and cool air and thus a natural, cooling circulation (Zamani et al., 2018). Natural ventilation is also influenced by the SVF. Due to the temperature difference between the sky opening and the surfaces of the lower parts of the courtyard, the sky acts as an energy sink, resulting in pressure differences and facilitating ventilation (Oke, 1998). The SVF, however, affects this relationship. Terrestrial objects that reduce the SVF emit higher levels of long wave radiation, limiting the exchange of energy between the sky and these objects. The SVF and thus natural ventilation are greatly influenced by the aspect ratio, and heat loss is considerably larger at the sky opening of the courtyards (Al-Hafith et al., 2017; Oke, 1988).

Next to ventilation as a result of pressure differences, ventilation can also happen as a result of general airflow patterns in the surrounding area. The effect of airflow patterns also depends on the aspect ratio of courtyards as different widths allow for more or less wind to circulate within the courtyard. This can create flows that can cool down the microclimate (Oke 1988; Moonen et al., 2011). Also, openings within the courtyard itself can have an increasing effect on ventilation (Zamani et al., 2018). When considering the angle to the predominant wind direction, maximum flux exchange was reached at 15-30 degrees between the long side and the predominant wind direction (Moonen et al., 2011).

These are general processes that happen within courtyards and form a part of the knowledge basis required for the interpretation of the simulation outputs of Chapter 6. In the hofjes analysis in Chapter 5 however, they will not be taken into account.

3. Methodology

This research was divided into two different phases with different methodologies. The research started with an analytical phase followed by a simulation phase. First, an overview of the two phases and the used methods is given (see Figure 8).

The analytical phase had the objective of identifying the most common tree configurations found in literature to decrease heat stress and to determine prevalent tree configurations in courtyards in Amsterdam. Two different types of analysis were performed in this phase related to sub question 1 and 2 and the combined findings of these chapters formed the basis for the tree planting patterns. First, tree configuration literature from different online sources such as Scopus and Google Scholar was researched on a macro scale. The objective of this literature analysis was to explore which tree planting patterns within courtyards were tested in existing research and which lessons could be derived from this. This part of the research related to sub question 1 and the findings of this literature analysis can be found in Chapter 4. Second, existing courtyards in Amsterdam were also analysed. More specifically, hofjes in Amsterdam were analysed which are courtyards built in the 17th century as a form of social housing. This analysis was both quantitative as well as qualitative and aimed to derive different design parameters of the planting patterns and to discover prevalent patterns in hofjes. This analysis of hofjes addressed sub question 2 and focused on the meso scale. The findings of this part can be found in Chapter 5. This analysis was performed using different softwares such as Rhino 7, the Grasshopper plugin in Rhino 7, Google Earth, and 3Dbag. As a result of the findings of the analytical phase, different planting patterns are established in the beginning of Chapter 6.

In the simulation phase of this research, different softwares and databases were used to simulate the urban microclimate of the Lab courtyard with the different tree planting patterns that were established as a result of the initial research phase. These softwares and databases included ENVI-met Spaces, ENVI-guide, ENVI-core, BIO-met and Leonardo (which are all part of the ENVI-met V5 software). Next to that, KNMI weather data (KNMI, n.d.) and the INX file of the courtyard model that was provided by the Urban Comfort Lab were used and modified for this research. From these microclimate simulations, the results on air temperature, mean radiant temperature, wind speed, wind direction, relative humidity and PET were analysed to determine the effectiveness of the different patterns in reducing heat stress. The focus of this subquestion was on the micro scale.

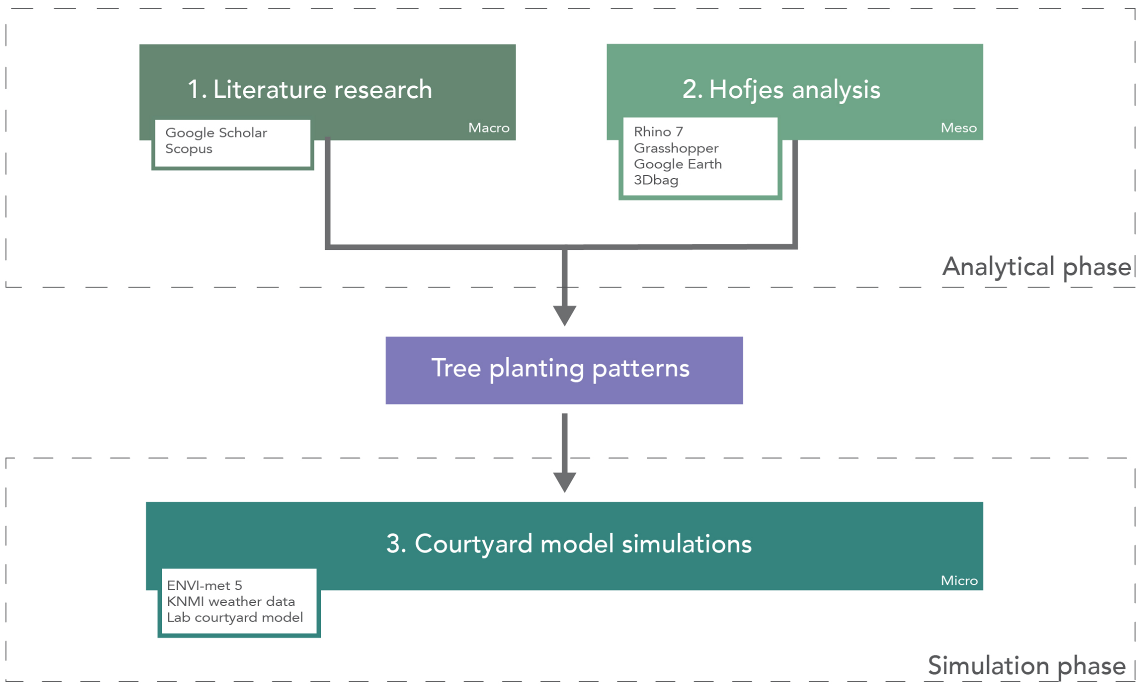


Figure 8. A simplified visualisation of the research setup and methodologies

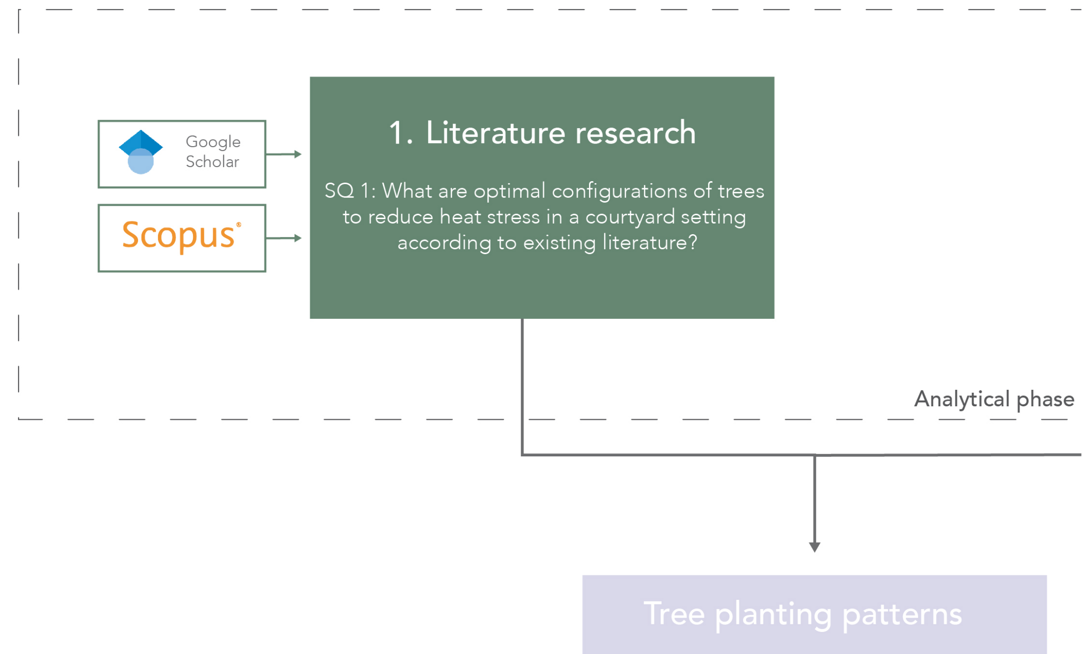


Figure 9. A visual representation of the methodology for the first sub question

3.1 Analytical phase

3.1.1 Tree configuration literature research

For the first sub question, online research of existing literature and journal articles was conducted to gather information on the effect of different tree configurations in courtyard across the world. The focus of this subquestion is therefore on a macro scale. First, an initial search including a combination of different keywords was done on Google Scholar to provide a basis of knowledge on the topic and to identify the most important keywords. After, a more specific search was conducted on Scopus based on these keywords. The keywords used were 'tree', 'pattern OR configuration', 'cit* OR urban' and 'microclimate OR "thermal comfort" OR "outdoor thermal environment"'. From this, general information of different factors that influence the microclimate (such as morphological features and vegetation) were derived for different urban contexts. These findings were then deepened through focusing on courtyards specifically by another search on Scopus in which the keywords 'courtyard OR enclosure' were added to the previous search. From both searches, research within the urban environment focusing specifically on tree configuration and their effect on the heat stress on the microscale were considered. From the findings on the effect of tree patterns on both the general urban context as well as courtyards, different lessons and design guidelines for tree planting patterns that mitigate heat stress were derived to serve as input for coming up with different planting patterns in courtyards. This section is visualised in more detail in Figure 9 and the findings of this chapter can be found in Chapter 4.

3.1.2 Hofjes analysis and tree configurations

The analysis of courtyards in Amstersdam focuses on hofjes and their tree configuration. These hofjes are courtyards mostly built around the 17th century by wealthy inhabitants of Amsterdam for the poorer and more disadvantaged members of society (Gemeente Amsterdam, 2019). The main objective of this section was to research whether prevalent tree planting patterns could be derived from a qualitative and quantitative analysis of hofjes in Amsterdam. This was done by quantitatively and qualitatively analysing hofjes' geometries and their tree planting patterns. After, a selection of these patterns were mapped. These analyses aimed to increase the realisticness of the patterns and to help create patterns fit to the Amsterdam Metropolitan context. This was done as The Lab is a very industrialised testing facility in which in theory, any tree planting pattern could be viable. Figure 10 gives a visual representation of the methodology for the second sub question and the sub objectives.

As a database for creating a list of hofjes in Amsterdam, the webpages hofjesinamsterdam.nl and jordaanweb.nl were used (Hofjes in Amsterdam, n.d.; Jordaanweb, n.d.). The analysis of the courtyards in Amsterdam that are hofjes had three sub objectives as shown in Figure 10. The coming sections explain the different methods and tools used. Parts of the methods used were based on existing literature, but as there was no comprehensive methodology known to the researcher for analysing tree configurations of courtyards, large parts of the method of this sub question have been developed for the purpose of this research. In this methodology section, the basis of this method and the tools used are explained.

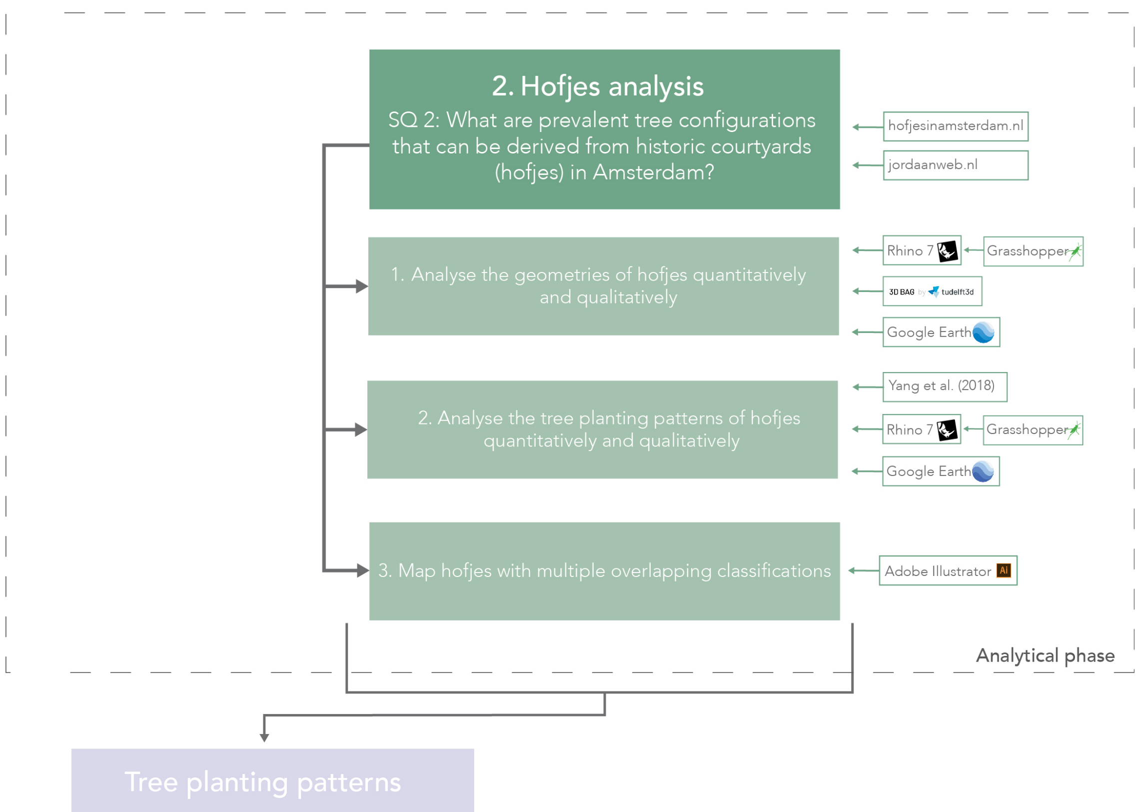
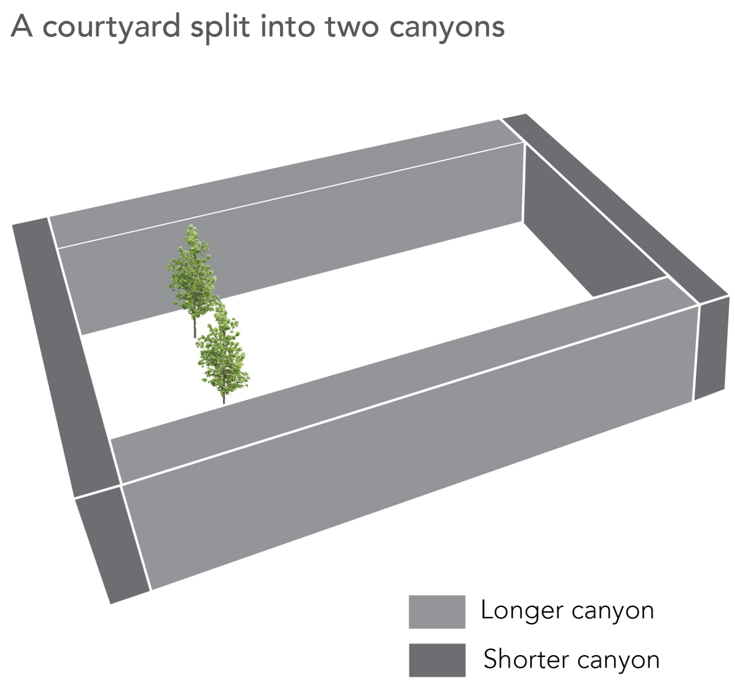


Figure 10. A visual representation of the methodology for the second sub question

In order to analyse the building and vegetation geometry of hofjes, 3D Bag, Rhino 7, the Grasshopper plugin and Google Earth were used. Building outlines of the hofjes were downloaded from 3Dbag.nl and opened in Rhino 7. Then, a Google Earth screenshot was added and with the use of Grasshopper, the tree coverage ratios, general greenery coverage ratios (including trees) and planting distance of trees to buildings were determined. In Appendix A, the Grasshopper and Rhino workflow is added. As a rule of thumb, a piece of vegetation was considered a tree when the estimated height from online imageries was more than approximately 2 metres. Regarding vegetation, also the mean number of trees per hofje was calculated using these methods. Next to this, the H/W ratio and W/L ratio, the courtyard shape and orientation were determined for the hofjes. The length and widths of the courtyards were established using Google Earth. Not all real world courtyards are perfect shapes however. Many are characterised by an alley leading into the courtyards or other irregularities in shapes as a result of the surrounding buildings. Therefore, the length and width that describe the largest courtyard space were considered. The height of the building was derived from 3Dbag. The orientation was determined using Google Earth imagery. These findings were then qualitatively labelled based and classified based on academic literature.

In order to quantitatively assess the tree planting patterns of the hofjes, a method based on the one by Yang et al. (2018) was developed. In their research, they assessed the placement of trees within an urban canyon by looking at the ratio of the distance of the trunk to the nearest building to half the width of the canyon. This ratio provided a number between 0-1, with values closer to one indicating a placement closer to the centre. When building up on this approach, courtyards in this study were considered as two canyons: the longer and the shorter canyon. The long canyon represents the courtyard's length, the shorter canyon represents the courtyard's width (see Figure 11). To analyse the tree placement within these two canyons, two ratios per tree were determined which are ds:DS and dl:DL. ds refers to the mean distance between the trunk and the short canyon of the courtyard and dl refers to the mean distance between the trunk and the long canyon of the courtyard. DS is obtained by dividing the length of the courtyard by two and DL is obtained by dividing the width of the courtyard by two. The ratios were divided into three different ranges: perimeter, midway or centre. Figure 12 gives a visual representation of this approach. Further explanation is given in Chapter 5.

Combining the results of the analytical phase, different tree planting patterns were established to test in the simulation phase.



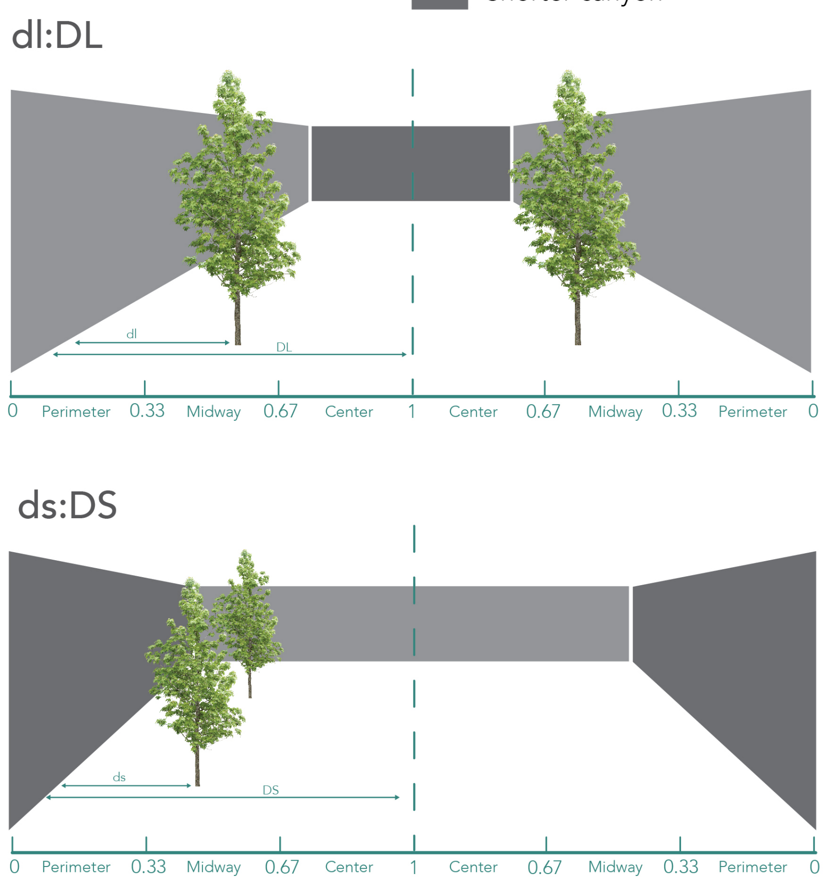


Figure 11. A visual representation of dividing a courtyard into a long and short canyon
Figure 12. An example of the methodology of analysing the planting patterns for a courtyard in which the trees have values between 0.33-0.67 for both dl:DL and ds:DS.

3.2 Simulation phase

In this phase, the different tree planting patterns were simulated in ENVI-met 5 to derive their influence on heat stress. First, an overview of the study area is given after which the different model parameters and input is given. A more detailed visualisation of the steps performed in the third subquestion is given in Figure 13.

3.2.1 Modelled area

This thesis is part of a larger study at a testing facility in Hoofddorp (Longitude: 4° 41' 57.75" E, Latitude: 52° 16' 53.15" N), The Netherlands in which the effect of different design configurations and different types of vegetation of courtyards on noise pollution and heat stress is explored. This research focuses specifically on the effect of heat stress and finding the optimal tree planting pattern to achieve this. The climate in the Amsterdam area can be classified as Cfb according to the Köppen and Geiger climate classification. This means the climate is tempered without a dry season and generally warm summers and significant rainfall throughout the year. The average temperature is 10.8 °C and average annual rainfall is 930 mm. During summer, average maximum temperatures rise to 20.7 °C (Climate-Data, 2021). The location of the lab is -4.75 metres under sea level (AHN Viewer, n.d.).

As part of the Lab, courtyards are built using shipping containers to simulate a real world setting. Three courtyards have been built adjacent to each other with this thesis focusing on the centre courtyard. The dimensions of the courtyard are 36.6 metres long, 18.3 metres wide and 7.8 metres high. Figure 14 gives an overview of the geographical location and setting of the Lab.

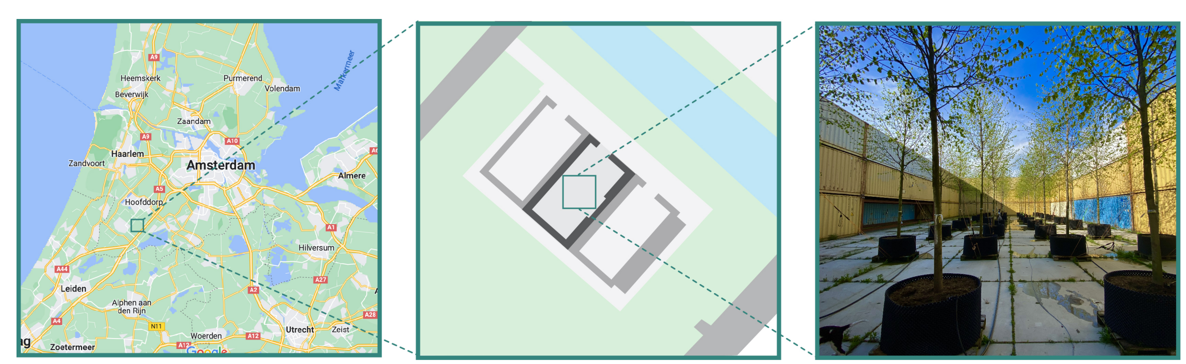


Figure 14. The location and setup of the Lab

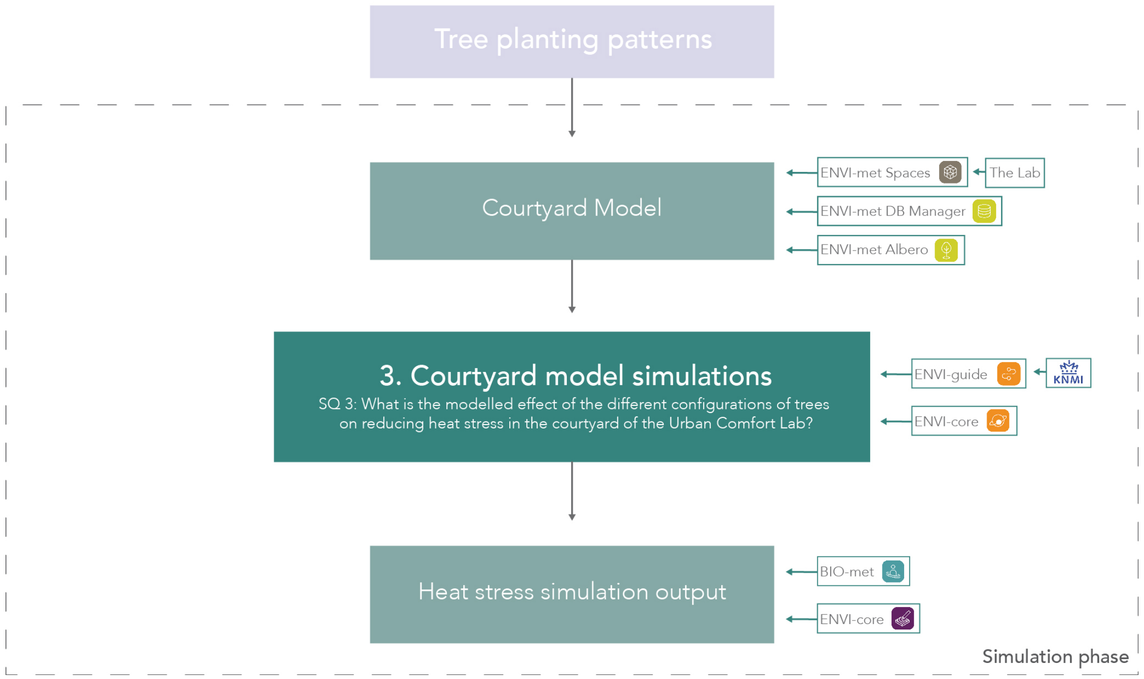


Figure 13. A visual representation of the methodology for the third sub question

3.2.2 Boundary condition settings

For the third subquestions, different simulations were performed to assess the effectiveness of the tree planting patterns on heat stress within the courtyard. The used software for the simulations is ENVI-met 5, which is a 3D model simulation software that is one of the most commonly used tools for modelling urban outdoor microclimates when considering greenery configurations (Fu et al., 2022). The INX file for the spatial model used was provided by the Urban Comfort Lab. The bare courtyard model has been validated (Wuite et al., 2023). The model with trees is planned to be validated in July 2023, which was out of scope for the timeline of this thesis.

The provided model was adapted in ENVI-met Spaces to incorporate the different tree patterns. With regards to the model used, the computational domain stretches an area of 165 m x 165 m with a vertical height of 24 metres. The grid cell sizes are set at 1m x 1m x 1m (L x W x H). The highest building in the domain is 8 metres and telescoping starts after 9 metres height. As the buildings are composed of shipping containers, the database has been updated in the ENVI-met DB manager to add CortenSteel to the materials. CortenSteel2 has been used in the model for the containers. The solar absorption for CortenSteel2 is 0.9 and the emissivity is 0.9 as well. The soil in the interior and parts surrounding the courtyards has been set to Concrete Pavement Light [0100PL]. The

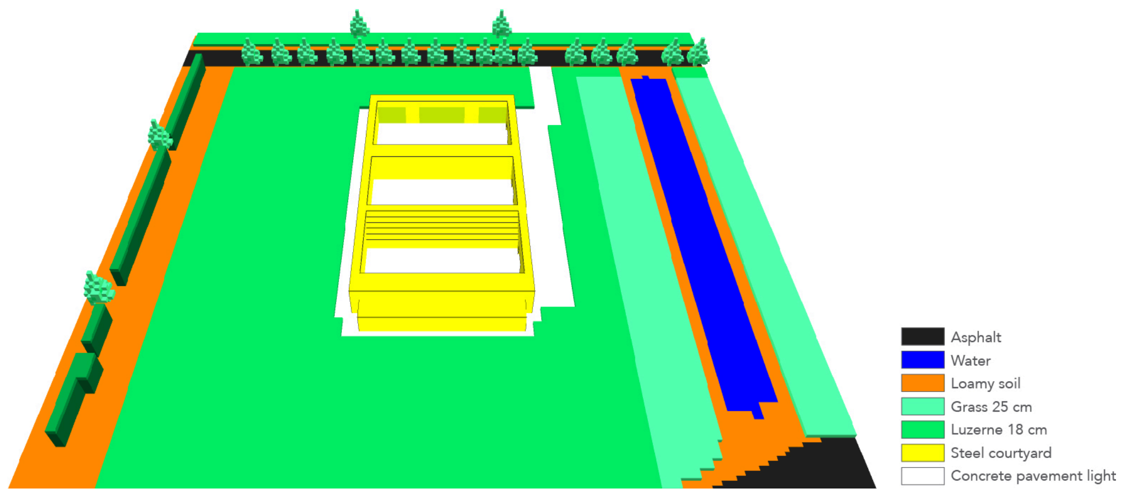


Figure 15. A 3D visualisation of The Lab courtyard model in ENVI-spaces

albedo of this concrete material is 0.8 and the emissivity is 0.9. Figure 15 and provides 3D visual of the model in ENVI-met Spaces without any trees in the courtyard yet.

The weather data used in the simulations was obtained from the KNMI Schiphol weather station (KNMI, n.d.). The simulated period started from July 18 2022 5:00 and ran for 48 hours. Within ENVI-guide, wind, air temperature, relative humidity were forced, radiation and precipitation were not forced. The simulated day is July 19, 2022, the hottest day of 2022 in which temperatures reached 35.4 ˚C. Figure 16 shows a graph of the maximum temperatures in ˚C for the days preceding and following July 19th and shows that on this day, temperatures were particularly high. Considering wind, wind speeds vary between 1 and 3 m/s coming from an eastern/south-eastern direction.

Different vegetational species were used in the model. Outside of the courtyard area, there are 21 Dutch Elms at different locations. These trees have a height of 12.22m and a width of 5.02 m x 5.07 m. The trees used in the testing facility were 36 Tilia europaea. These trees were not present in the ENVI-met tree database, so the Little Leaf Lime "Rancho" was chosen because of their similar shape and dimensions. After measuring the trees at the Lab, the Little Leaf Lime "Rancho" trees were scaled with a factor 0.75 in ENVI-met Albero to emulate the real life trees. The dimensions of the model tree were 6.68 m in height and 2.92 m x 4.09 m. Figure 17 gives a comparison of the dimension of the tree in the Lab and the tree in the model. Figure 18 gives a specification of the tree geometry and leaf arrangement of this tree. During the simulation that were run in ENVI-core, 16 trees were simulated as opposed to the 36 real life trees present at the lab to create a realistic coverage ratio based on the hofjes analysis.

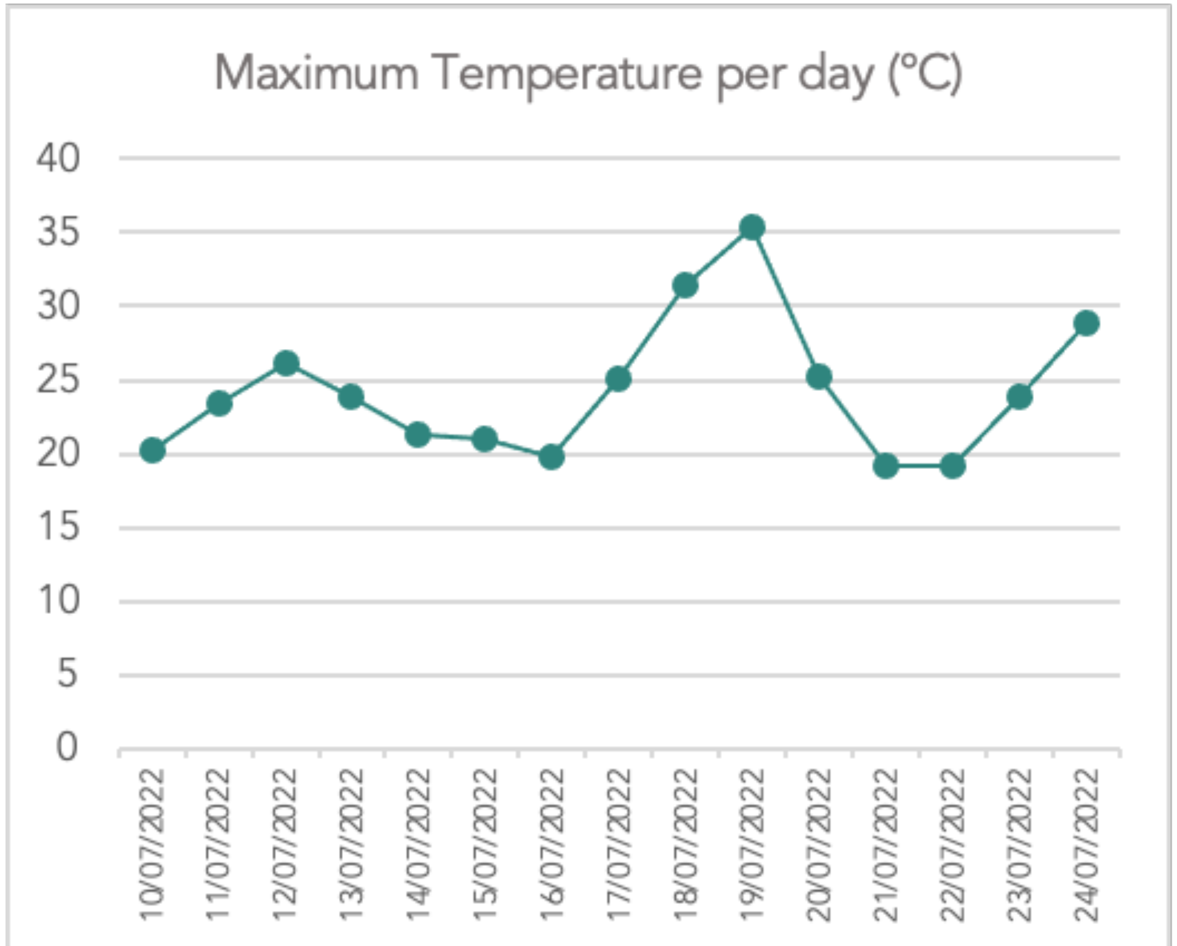


Figure 16. A graph of the maximum day temperatures in ˚C preceding and following the simulated day

After simulation, the output was first processed in BIO-met at 1.5 metres height. PET levels have been calculated for an average male of the age of 35 years old, 75 kg, 1.75 m height and a clo value of 0.90. The metabolic rate of this person (M) has been set to 164.49. The model output was later visualised using Leonardo, which is also part of the ENVI-met software.

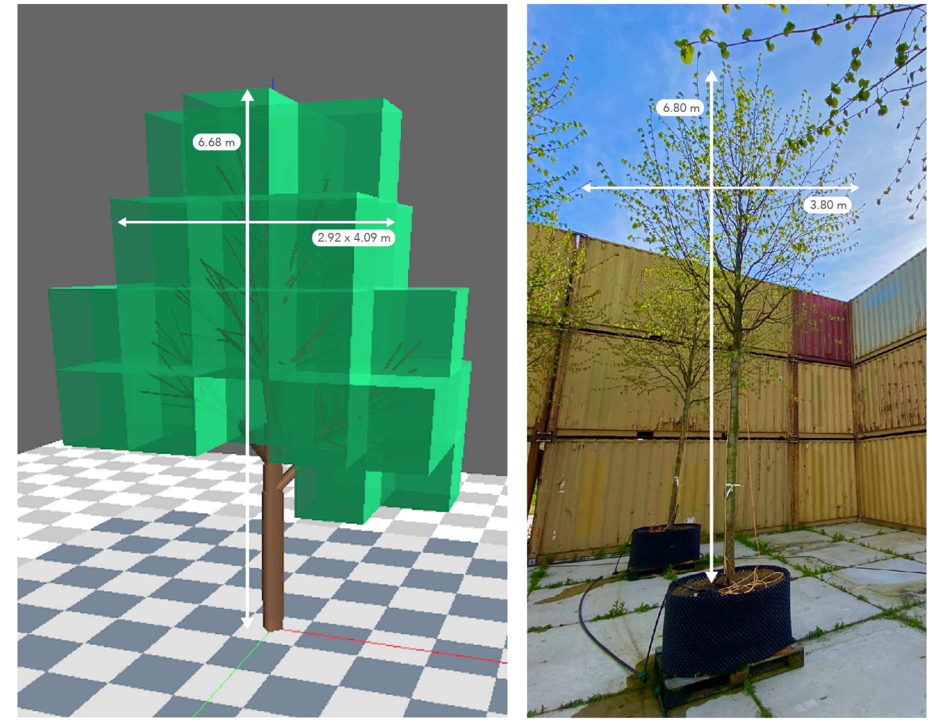


Figure 17. The chosen Little Leaf Lime Rancho and its dimensions scaled at 0.75 compared to the dimensions of the tree in the Lab (tree was not yet in full bloom)

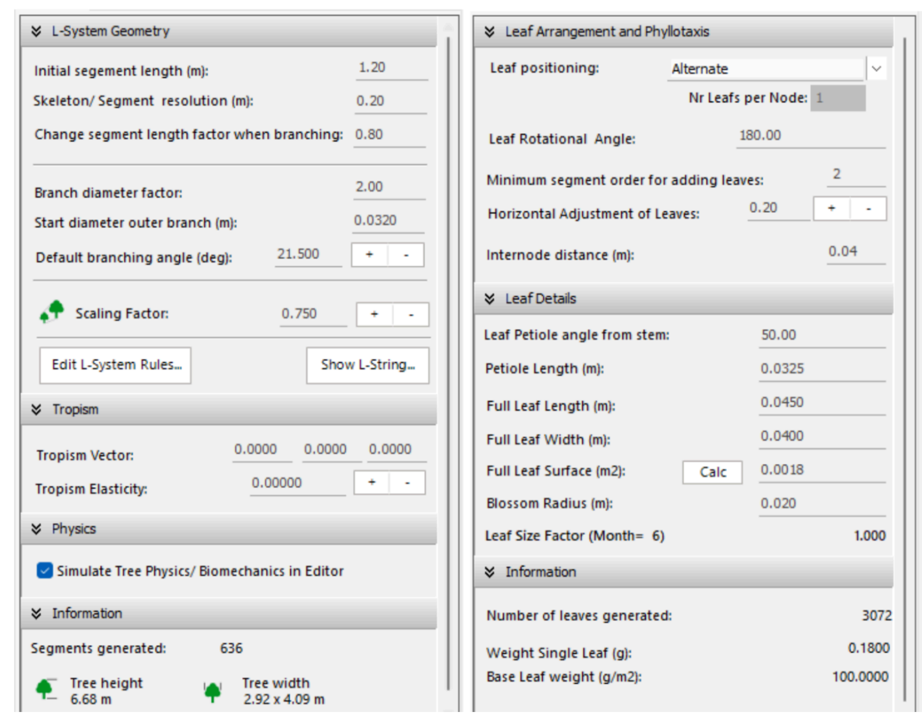


Figure 18. The tree geometry parameters and leaf arrangement for the Little Leaf Lime “Rancho” scaled at 0.750 that was used for this research

4. Tree Configuration Literature Research

This chapter addresses the findings of the first sub question, which is: *"What are optimal configurations of trees to reduce heat stress in a courtyard setting according to existing literature?"*. These findings are gathered through a literature review of different researches related to this topic as explained in Section 3.1.1. Adding trees to the urban environment can play an important role in creating comfortable microclimates, and their main effects depend on their planting density and configuration (Fu et al., 2022). Therefore, the density of adding urban greenery will first be discussed in different urban settings. After, studies on different patterns in different urban settings as well as courtyards are presented. Based on these two findings, different tree planting patterns in courtyards that lead to reduced heat stress are provided.

4.1 Tree planting density

4.1.1 General urban context

From a review of the last ten years of research by Fu et al. (2022), it becomes apparent that tree planting density is an important contributor to the cooling effect of trees. However, the effect of density is also influenced by the morphology of the surrounding urban environment and wind flow. Research in Wuhan, China has modelled three different cases of tree densities in a residential neighbourhood. For classifying these densities, the research used the height to distance ratio of trees (or ART, the aspect ratio of trees). Three different tree densities were looked at: the "sparse" case with an ART smaller than 1, the "covering" case with an ART of 1 and the "density" case with an ART of 2. The total tree coverage in all cases was the same, but for the "density case" overlapping tree coverage ratios diminished the overall effect on reducing air temperature. In the "covering" case, trees were also creating less shade overall as a result of their planting structure closer to each other and the "sparse" case proved to be most effective on the neighbourhood level to reduce air temperatures. Taking into account the effect on wind speed however, the covering case allowed for more wind to flow around the trees and buildings. Looking at the combined results of their effect on air temperature and wind speed through the influence on PET, the "sparse" and "covering" case with an ART < 2 were most effective in reducing heat stress during summer (Zhang et al., 2018). Other research also looked at the spacing of different heights (and thus sizes) of trees and their effect on the mean radiant temperature in Korea. In an east to west oriented canyon, optimal reductions in mean radiant temperatures were achieved with smaller trees (in this case with a height of 5.9 metres and a width of 3 metres) with spacing smaller than 10 metres away from each other (Park et al., 2019). Next to the height of trees, the crown diameter and the relation between the aspect ratio of the buildings is of importance as well. In research conducted in Shantu, China the combination of street configuration (orientation and aspect ratio), density of the canopy and planting density was studied. By modelling different tree species in canyons with different aspect ratios, the research found that the planting density did not influence wind speed, but significantly lowered air temperatures. It was concluded that for fully grown trees, a distance equal to the size of the canopy is optimal to reach these cooling effects (Zheng et al., 2018). Another research conducted in Germany also focuses on crown diameter rather than trunk height in relation to aspect ratios of different canyons with an E-W orientation. The research also concludes that planting trees at crown distance from each other is optimal when it comes to thermal comfort on hot summer's days, but do note that it could be negatively influencing wind flows and therefore other elements such as air quality and nocturnal cooling. Also, the heat stress mitigation is larger in the shallow canyon with an aspect ratio of 0.5 as compared to the deep canyon with an aspect ratio of 2 (Lee et al., 2020). These findings were also supported in research by Morakinyo et al. (2017) in which it was found that the impact of trees during the day time decreased with increasing urban densities but that the opposite effect was visible during night time. Similar research in Montreal, Canada yielded similar results in a neighbourhood where a maximum decrease in general MRT of 10.2 °C was observed when trees were planted at crown distance (Wang & Akbari, 2016).

Another morphological factor influencing microclimates is the orientation of trees to the sun. Research showed the importance of enlarging the shaded area through an even distribution of trees rather than intensifying the shade. With that, proper orientation towards the sun was stressed, as lines of trees that were oriented N-S resulted in similar SVF as lines of trees oriented E-W, but different effects on thermal performance later during the day. The N-S orientation resulted in a larger area being shaded (Liu et al. 2020). The effect of shading also influences the need for trees, as research by Lee et al. (2020) showed that for the E-W canyon, adding trees on the north facing sidewalk had little to no effect on thermal comfort as a result of the shade of the building.

Based on these findings regarding the density of tree planting in the urban area, the main findings can be summarised in the following way:

- It is a careful balancing act between reaching an optimal density without obstructing wind flow too much. As a rule of thumb, an ART < 2 should be adopted (Zhang et al., 2018; Park et al., 2019). Next to that, planting trees at crown distance also showed to be generally most effective in different urban settings (Lee et al., 2020; Wang & Akbari, 2016; Zheng et al., 2018).
- Heat stress reducing effect depends on the aspect ratio of the urban structure (Morakinyo et al., 2017), with higher effects for structures with lower aspect ratios (0.5) compared to higher ratios (2) (Lee et al., 2020).
- The planting orientation is of effect when it comes to the amount of shade created, with N-S orientation being advised as this maximises shading throughout the day (Liu et al. 2020).
- Planting in the shadow side of a building is not advised, as the building's shade counteracts the benefits provided by trees (not considering other ecosystem services of trees) (Lee et al., 2020).

4.2 Tree planting patterns

4.2.1 General urban context

Next to the density of trees, the tree planting pattern is an influential factor in the abilities of trees to regulate microclimates. When considering tree patterns in urban areas, the most researched configurations for reducing cool microclimates are clustered, rectangular and double-row planting (Fu et al., 2022).

When different species of trees are planted in a clustered way in Brazil, they act as a microclimate thermoregulator that reduces heat stress through an umbrella effect (De Abreu-Harbich et al., 2015). Similar results were found in a study by Rahman et al. (2020) in Germany in which clustered trees reduced the velocity of tree growth, but showed lower air temperatures. Also in research in Xi'an, China the clustered tree planting pattern in the greenspace of a university campus showed larger improvements in urban microclimate as compared to a row of trees or a singular tree (Zhao et al., 2020). However, the positive effect of clustered tree planting is not always evident and depends largely on the morphological and spatial characteristics of the surrounding area, as shown by Bartesaghi-Koc et al. (2020) and Milward et al. (2014). The researches specified that for example high levels of impervious surfaces around trees offset the added beneficial effect of having multiple trees clustered.

Another pattern that has been researched more frequently in the urban context is a rectangular planting pattern that can potentially divert wind and distribute shading more evenly. Abdi et al. (2020) compared a rectangular planting pattern to a triangular pattern for evergreen and deciduous trees with different orientations relative to the predominant wind direction in an Iranian university complex. The study found that a rectangular pattern of a combination of evergreen and deciduous trees perpendicular to the prevailing wind resulted in the highest reduction in predicted mean vote (PMV) index, an index used to measure thermal sensation. Slightly different results were observed in research by Sodoudi et al. (2018). The study simulated a potential park in Berlin, Germany and compared different vegetational types (short and long grass, shrubs and small and canopy large trees) in different patterns with a coverage ratio of 25% in all scenarios. These scenarios can be described as clustered, scattered and two rectangular patterns one with W-E and one with N-S orientation. It was found that big canopy trees had the largest cooling effect in all configurations and that rectangular configuration yielded the best results. When looking at the orientation of that rectangular pattern, the N-S orientation provided slightly better results as compared to the E-W orientation as it was more aligned to the south western wind that was blowing. This increase in air ventilation further increased the cooling effect. When looking at more general research about urban form and wind velocities, aligning the long facade of buildings surrounded with a line of trees with the prevailing wind has shown to be most effective in creating comfortable microclimates at pedestrian levels, which supports the argument to align trees towards the prevailing wind (Hong & Lin, 2015). Research by Liu et al. (2020) also showed the increased, positive effects on the local microclimate as a result of evenly spaced tree planting structures in a rectangular form. Wind direction was not incorporated but planting orientation towards the sun. It was found that trees should be oriented in such a way that optimal shading is reached.

The third pattern that is researched more often in the urban context is the one of double row trees. Research by Morakinyo & Lam (2016) compared double row planting arrangements with clustered and leeward and windward planting arrangements for a canyon with an aspect ratio of 2. The study found that higher reductions in PET were achieved for a double row pattern on a hot summer's day in Hong Kong as compared to a centred tree planting pattern with the same coverage. Same results were found in an urban neighbourhood in Phoenix, Arizona. Compared to a clustered tree planting pattern, double trees at equal intervals in front yards or a single tree in the front yard were found to be more effective for reducing PET levels in summer (Zhao et al., 2018). In both studies, the double row spacing had this effect, despite clustered tree planting patterns having the highest wind speed. This indicates that the increased level of shading had a larger effect on reducing PET compared to increasing wind speeds. Similar results were found in Egypt, where Atwa et al. (2020) showed that on a level of a business park, double row planting was more effective in reducing PMV as compared to single row trees although double row trees lead to larger reductions in wind velocity. The effect is dependent on orientation, the planting distance from the building and tree height. In research by Yang et al. (2018), adding trees of different height in a N-S canyon was compared to an E-W canyon. It was found that for the N-S canyon, trees planted in the centre of one side of the road were most effective whereas in an E-W canyon, trees planted closer to the buildings provided better thermal conditions.

Based on these findings regarding the patterns of tree planting in the urban area, the main findings can be summarised in the following way:

- The effect of clustered tree planting is ambiguous in the general urban setting as the extra cooling effect of clustering seems to be dependent on the surrounding surfaces as well (De Abreu-Harbich et al., 2015; Bartesaghi-Koc et al., 2020; Milward et al. 2014; Rahman et al., 2020).
- For rectangular planting, the effect of planting trees in line or perpendicular to the prevailing wind is ambiguous as well. This indicates it could be dependent on different morphological factors of the surrounding environment (Abdi et al., 2020; Sodoudi et al., 2018). This is further indicated in research by Hong & Lin (2015) in which different urban forms surrounded by a line of trees with different alignments to the wind showed different effects on comfortability on pedestrian levels. Aligning the long facade with the wind showed to be most effective.
- For double row tree planting, the increase in shade seems to offset the reduced wind velocity which was indicated as an important balancing act for the research in densities. Double row tree planting offers a potential balance between tree density and minimal obstruction of wind flow (Atwa et al., 2020; Morakinyo & Lam, 2016; Zhao et al., 2018).
- The overall effect of the tree planting pattern also depends on orientation to the sun of the urban context in which the trees are placed (Yang et al., 2018).

4.2.2 Courtyards

When examining research related to courtyards and tree planting configurations, it becomes evident that there is a relatively scarce amount of available research in this specific area. Some of the research that focused specifically on tree configurations in courtyards did not yield relevant output for this study. The effect of adding trees on reducing air temperature in courtyards has been shown in the study by Shashua-Bar et al. (2005). The study compared 100 observations in 11 different urban forms including canyons, generic streets, colonnaded buildings and enclosed courtyards, in Tel-Aviv, Israel. The cooling effect of trees in courtyards at a 70% coverage ratio was smaller compared to the situation in canyons, but the overall decrease in air temperature was larger which can be explained by the different built forms of courtyards and increased shading levels. However, the specific observed pattern was not specified and therefore the findings cannot be used as input for tree configurations in this research. Research by Darvish et al. (2021) compared two identical courtyards in Iran, one with vegetation and the other without. It continues to model the placement of trees in different corners of the courtyard but only focuses on indoor thermal conditions and related energy consumption. Research by El-Bardisy et al. (2016) was conducted in similarly hot and arid conditions and looked at different tree arrangements to reduce the PMV of a school courtyard. The study considered different types of tree arrangement: linear, group and random and refined those arrangements based on the courtyard's use as a children's playground. Therefore, the placement of greenery within the courtyard is very specific to the context and use of that specific courtyard and the findings are hardly generalisable. Next to that, the school's playground was rather a large square with a wall around it rather than a courtyard as considered in this study and the Lab.

Other studies focusing specifically on tree planting patterns in courtyard settings did provide valuable results for this study. A more in-depth overview of these different researches will be given in the next part. Although these researches were still highly contextual, these research findings provide some generalisable outputs.

The study by Li et al. (2019) showed considerable similarities in research set up and methodologies to this thesis. The research focused on a courtyard building that functions as a student's commons at the University of Maryland and has a square shape. The courtyard dimensions were 38 metres x 38 metres with a height of 13,5 metres (H/W ratio = 0,36) and an orientation aligned north. After validating the ENVI-met model with real life data, the research looked at the modelled effect of different tree planting patterns on air temperature, wind velocity, wind direction and relative humidity. The five patterns considered were: F) the focused tree planting pattern (which was centred), C) the cornered tree-planting pattern (in the northern eastern and north western corners), R) the multi-row tree-planting pattern (an evenly dispersed tree planting pattern on an east to west orientation), S) the surrounding tree-planting pattern (following a circle shape) and N) the no-tree planting pattern. Figure 19 illustrates these patterns.

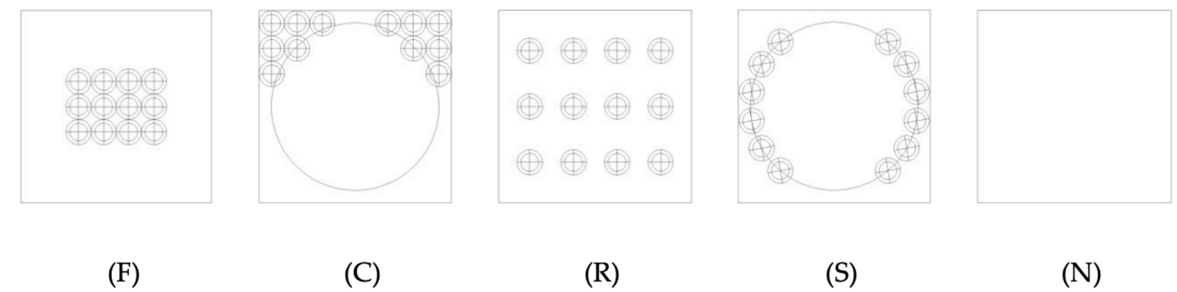


Figure 19. The five tree planting patterns as adopted in the research in Maryland (Li et al., 2019)

In terms of air temperature, the F pattern obstructed wind flows which prevented cool air from circulating in the courtyard and therefore had less effect on air temperature as compared to the other patterns. The R pattern showed cooler areas dispersed around the courtyard as the rows formed corridors through which wind could ventilate. Also, it created one of the coolest spots created by a pattern in the south western corner. The C pattern showed the most even dispersion of cooler areas of around 1 ˚C difference compared to the N pattern, but lacked cooler spots compared to F, R and S where temperature differences of up to 2 °C were measured as compared to N. The S pattern created the highest local temperatures along the courtyard walls.

When considering wind velocity and direction, the F and R patterns with elements in the centre of the courtyard reduced wind velocities in the western part of the courtyard most by changing the direction and speed of the incoming wind from the south to south west. The patterns C, S and N that did not occupy the centre space of the courtyards resulted in higher overall wind velocities and especially in the eastern and western side.

Regarding relative humidity, all tree patterns increase humidity as compared to the case without trees. For the R and S pattern, humidity increased in the south west corner. The F pattern caused higher humidity near the south entrance through which the wind was blowing which again indicated the wind blocking feature of placing trees in the centre. For C, relative humidity was quite evenly dispersed.

Another relevant study, is the one conducted by Manneh & Taleb (2017) in a campus courtyard in Doha, Qatar. The courtyard considered in the research had dimensions of 36 metres x 56 metres and the average height ranged from 10 metres to 13 metres. As a result, most of the area was unshaded in the courtyard. The baseline scenario was first validated using real life data in ENVI-met and afterwards eight different scenarios and their effects on air temperature, wind speed and MRT and PMV at 12 am and 10 am were modelled. The current baseline consisted of 43 deciduous trees with a height of 10 metres and 1 deciduous tree with a height of 15 metres and 212 square metres of grass. The scenarios were 1) the baseline, 2) all vegetation replaced by grass, 3) all vegetation removed and replaced by hardscape, 4) replacing all trees in the baseline scenario with the taller 15 metres high trees, 5) replacing trees by a 3 metres high shading structure, 6) increased shading surfaces as compared to scenario 5, 7) alternative vegetation pattern using the same types and number of plants as the baseline and 8) same vegetation configuration as scenario 7 but all trees were the larger tree type. Whereas the vegetation in the baseline scenario were planted mostly in groups on the periphery of the courtyard and randomly dispersed in the centre, the new patterns in scenario 7 and 8 were based on a more evenly dispersed and alternating softscape pattern in the middle of the courtyard. For this study, scenarios 4, 7 and 8 are therefore most relevant. The baseline configurations of trees and the new configuration for scenarios 7 and 8 are found in Figure 20.

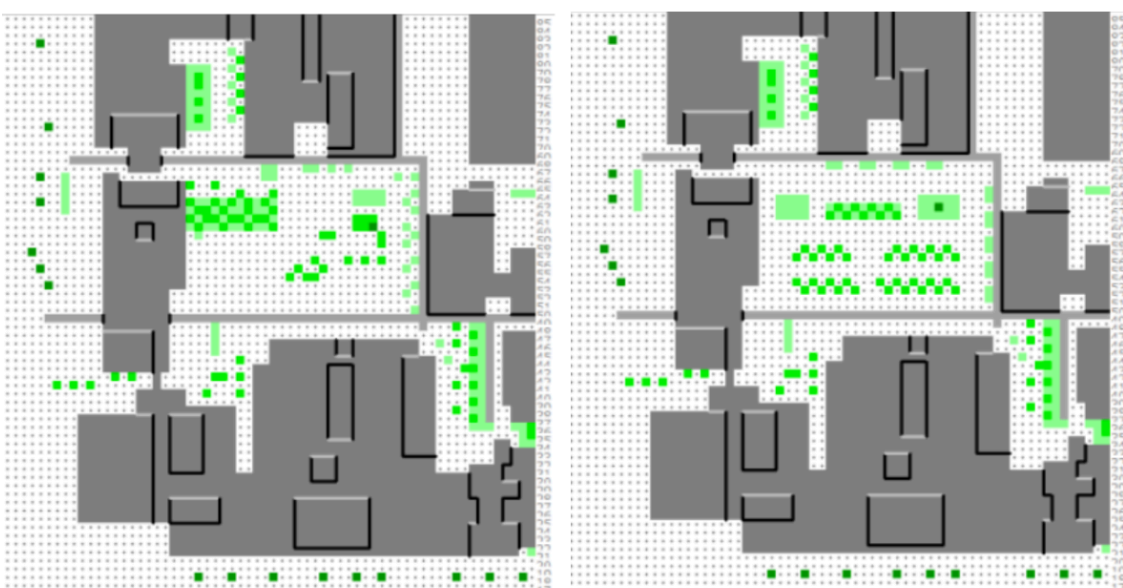


Figure 20. The baseline scenario left and the new pattern for scenario 7 and 8 right for the research in Doha (Manneh & Taleb, 2017)

With regards to air temperature, scenario 7 yielded the lowest average air temperature levels at 10 am, and scenario 4, the baseline scenario but with higher trees, yielded the lowest average air temperatures at midnight. During the day, the more evenly spread pattern of vegetation and trees seems to have a cooling effect and during night time, the heat seems to be getting away easier as a result of the higher trees.

The new patterns of scenarios 7 and 8 provide in theory more obstruction to the wind in the courtyard. The lowest levels of wind velocity were measured in scenario 7, but closely followed by scenario 1. When comparing scenario 1 to scenario 4 and scenario 7 to scenario 8, the results show that the higher trees in scenarios 4 and 8 as compared to scenarios 1 and 7 respectively decrease the obstruction caused by vegetation which increases wind speeds.

Scenario 7 resulted in the highest average mean radiant temperature reductions for both midnight as well as 10 am. As expected, similar but slightly lower effects were found for scenarios 1, 4 and 8. The better performance in scenarios 7 and 8 is related to the shading impact of the more evenly distributed vegetation. It is interesting to note however that scenarios 7 and 8 also show the highest maximum MRT. The reason for this is the reduced wind velocity as explained in the previous paragraph. The reduced wind speed resulted in temperature being absorbed by the buildings in specific corners of the courtyard and thus more long-wave radiation and therefore increased MRT.

PMV - When considering PMV, configuration 8 is most effective at 10 in the morning and configuration 7 at midnight as compared to the other scenarios. The higher average MRT, but lower PMV at 10 in the morning is a direct result of the higher wind velocity and reduced energy absorption by surrounding surfaces as a result of the higher trees. A similar effect of the height of trees is also visible in scenario 4.

The study by Ngo et al. (2022) differs from the other two aforementioned studies as it considers a green playground space in the centre of a neighbourhood on a scale of 300 metres x 300 metres in Ha Tinh, Vietnam. The neighbourhood is conFigured in such a way that it represents a courtyard to a certain extent and is therefore considered in this research. It is however not an 'enclosed' courtyard but there are rows of houses built along the central green space. An ENVI-met model was first validated after which median air temperature, wind speed, MRT and PET were considered for four scenarios on a hot summer's day. These cases are: 1) bare grass and high plants along the perimeter, 2) grass ground fully occupied with trees, 3) a water body in the centre and high plants along the perimeter and 4) mixed ground surfaces of water, hard pavement and grass and partially occupied high trees. Cases 1 and 2 are most relevant for this research. Figure 21 gives an overview of the studied area and the different cases.

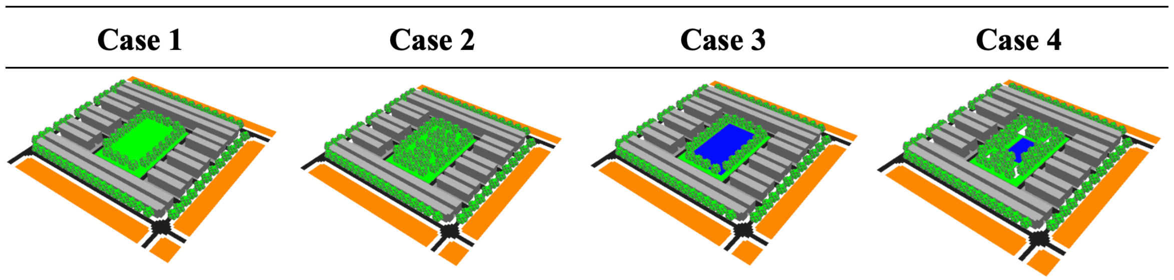


Figure 21. The four different cases of the study in Vietnam (Ngo et al., 2022)

In this study there were hardly any variations observed in the median values of air temperature during the observed day. Only case 2 has slightly higher temperature reductions as compared to scenario 1.

Also for wind speed, little variation was observed in between the simulations of the different scenarios. Only for the case with full placement of trees in case 2, wind speed reduced around 0.2 m/s because of the placement of those trees.

The lowest MRT is observed in scenario 2 with full tree coverage. The higher number of trees creates more shade which blocks the incoming solar radiation. The other scenarios showed similar results in MRT.

The only significant reduction in PET is again measured in scenario 2, where it resulted in a 15 °C reduction in the afternoon.

The last research relevant for this thesis is a study conducted in Tiruchirappalli, India by Mundra & Kannamma (2019). The research does not consider trees, but shrubs with a height of 2 metres. The courtyard is oriented east to west and has dimensions of 14 metres x 34 metres and a height of 12 metres (H/W is 0.85). Through ENVI-met validation and simulation, the effect of different planting densities along the perimeter of the courtyard on PET and MRT on a hot day is measured. There are 5 different scenarios: 1) 0% plantation, 2) 100% grass, 3) 25% dense vegetation along the borders of the courtyard, 4) 50% dense vegetation along the borders of the courtyard and 5) 75% dense vegetation along the borders of the courtyard. In this study, dense vegetation is considered 2 metres

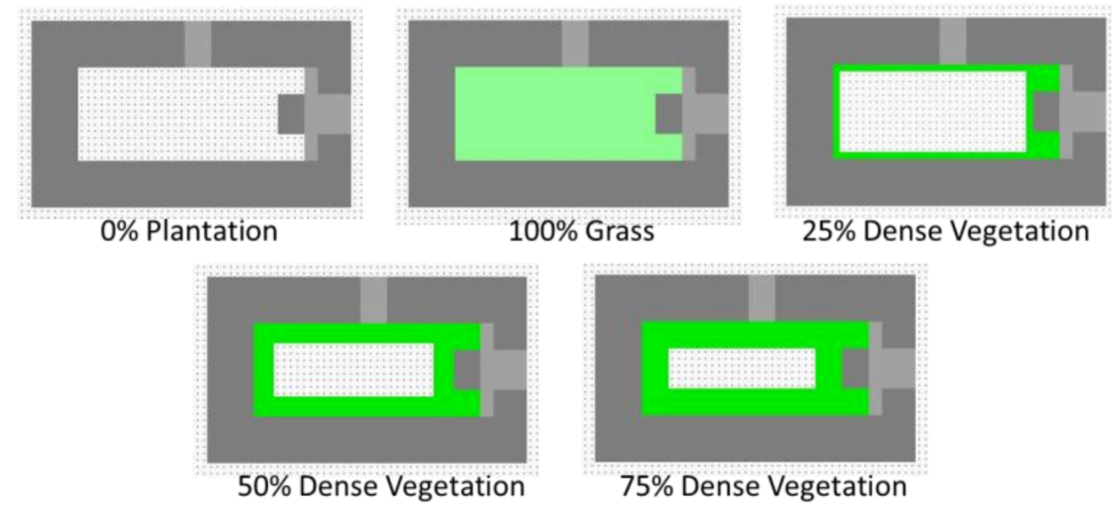


Figure 22. The five different scenarios for the research in India (Mundra & Kannama, 2019)

high dense hedges, and grass is considered 25 cm high. Figure 22 gives an overview of the 5 different scenarios.

Regarding the effect on MRT and PET, higher densities resulted in lower MRT and PET. For this case, all increments in percentages of dense vegetation yielded better results with the best result reached at 75% of vegetation cover along the perimeters of the courtyard. Based on the findings of the different studies, the main findings can be summarised in the following way:

- A pattern of dispersed trees in a courtyard often leads to air temperature reductions which is generally found to be the best or among the best performing patterns. Next to a reduction in air temperature, this type of pattern generally also reduces wind speed, and has shown that they could potentially alter wind directions. The height of trees and planting distance play important roles in this relation with the wind. This is because the height of the tree allows for wind to flow through more easily. Additionally, planting distance can increase wind speeds (Li et al., 2019; Manneh & Taleb, 2017; Ngo et al., 2022).
- Clustered trees in the centre of the courtyard block the flow of incoming wind and the ability of wind to circulate. Moreover, the trees can change the direction of the wind which interferes with relative humidity and air temperature. Opposite effects are visible for patterns with open spaces in the centre, as open space in the centre can cause cool and humid air to spread around more easily. This positively affects PET (Li et al., 2019).

- Trees or vegetation along the perimeter of the courtyard can have a positive effect on the microclimate on warm days as well. Either in the sun-exposed corners or along the whole perimeter, up to a 75% coverage (Li et al., 2019; Mundra & Kannamma, 2019).

4.3 Summary of findings and related tree patterns

Combining all the findings of the research on tree planting densities and patterns in urban contexts, as well as those in courtyards, the literature identifies four primary tree planting patterns. These patterns will serve as the basis for simulating tree planting patterns in this research. Now, the justification of the choice for the different patterns will be given, as well as general guidelines for all the different preliminary patterns. In the next chapter, these patterns will be further refined based on the analysis of the courtyards in the real urban context of Amsterdam.

There are two important general guidelines when it comes to tree planting patterns: density and orientation. Regarding planting density, the distance should be somewhere between crown distance and two times the height of the tree (ART < 2). However, trees at crown distance were generally most effective in reducing heat stress. Regarding orientation, a N-S planting direction is advised as it maximises the provided shade.

1. The Cornered tree planting pattern

One of the most effective ways of reducing heat stress for the specific courtyard setting was to place trees in the corners of the courtyard that were exposed to direct solar radiation. The effectiveness of placing trees in areas exposed to direct solar radiation rather than in shaded corners was underpinned in canyons. The open space that is created in the middle because of this pattern allows wind to flow and disperse heat and relative humidity.

2. The Perimeter tree planting pattern

Placing vegetation along the perimeter of different types of courtyard has shown to be effective, with decreasing heat stress experienced up to a coverage ratio of 75%. Depending on the amount of trees used in this study, the trees will be placed along the perimeter of the sun exposed facades of the courtyard. As is the case with the Cornered tree planting pattern, the open space in the centre can allow for wind to flow around more easily.

3. The Dispersed tree planting pattern

Trees placed in the centre in the courtyard generally reduce air temperatures but also obstruct wind velocity. They do however provide a large amount of shading, which reduces long wave radiation and therefore often result in overall better microclimatic conditions in different courtyard settings observed in previous research. The trees are placed in alignment with the long facade of the courtyard as the lines of trees will be along a NE-SW line.

4. The Double Row tree planting pattern

As it is a careful balancing act between placing trees but not obstructing windflow too much, double row tree planting has been identified as a potential way to provide ample shading but not block wind velocities too much. The trees in this pattern are also aligned along the long facade, as is the case for the Dispersed pattern.

Figure 23 gives a schematic overview of the different planting patterns that are found to be most effective in different studies. For now, these patterns serve as a general overview of the areas in which the trees should be planted. In the next part of this thesis, input will be gathered on the planting distances from buildings, tree coverage ratios and patterns found in historic hofjes in the Amsterdam urban context.

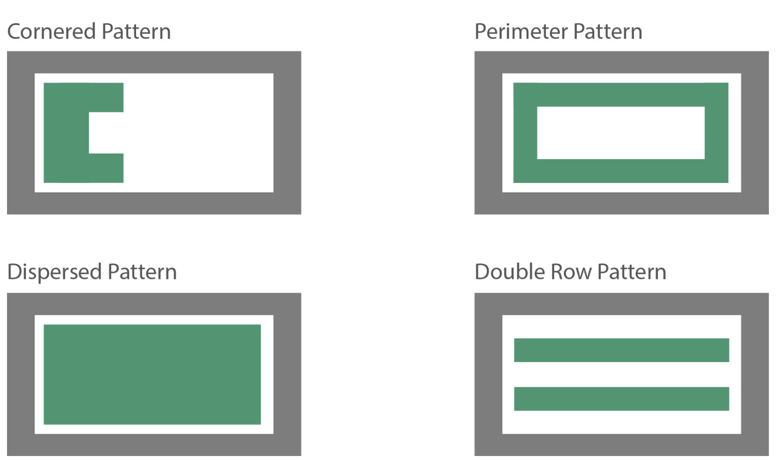


Figure 23. The four different tree planting patterns derived from literature

5. Hofjes Analysis

In the previous chapter different studies investigating tree planting patterns and their microclimate performance in different urban contexts have been reviewed as part of the first sub question. This chapter addresses the findings of the second sub question, which is: *"What are prevalent tree configurations that can be derived from historic courtyards (*hofjes*) in Amsterdam?"*. The objective of this sub question is to better understand the tree planting patterns in historic hofjes and to use these findings to create realistic tree planting patterns that can be simulated in the next chapter. The hofjes are therefore quantitatively and qualitatively analysed in three different steps in this chapter. First, a quantitative and qualitative analysis of the geometries of hofjes will derive information on their shape, configuration, tree coverage and greenery coverage ratios and planting distances from buildings to identify types of hofjes according to their morphological characteristics. Second, the tree planting patterns in hofjes will be quantitatively and qualitatively analysed by using the method described in Section 3.1.2. Third, the tree planting patterns of hofjes that with similar classifications as the courtyard in the Lab will be mapped.

5.1 The history of hofjes

Hofjes were originally built by rich inhabitants of Amsterdam, often merchants, for the poorer people of society, often old women or widows. In most cases, it was not solely an act of generosity to build a hofje but rather a way of ensuring a peaceful afterlife as they were often built as part of an inheritance. Hofjes offered a form of communal living and started being built in the 17th century. In modern day terms, it was a combination of social housing and retirement home in one as inhabitants were offered free medical care and basic food amenities. It was however not so easy to acquire a position to live in such a hofje, as it required you to have had a solid reputation and it was not allowed to drink alcohol and lights had to be out at a certain time at night. In general, hofjes are not visible as they were often built in back alleys. Most of the hofjes are to be found in the Jordaan neighoborhood as this area had the cheapest plots of land at that time. Later, the hofjes expanded to different parts of Amsterdam as well (Gemeente Amsterdam, 2019).

The majority of the courtyards (25) are currently still used for residential purposes. Interesting to note is that 8 out of those 25 residential courtyards are still reserved solely for housing women. Also, the original purpose of providing people with a lower income is still visible in current day use, as 7 out of the 25 courtyards offer housing to students, young professionals or women with a low income. Next to that, almost half of all the hofjes (14) are located in the Jordaan neighbourhood. Figures 25 - 27 show photographs taken from a variety of hofjes in Amsterdam.

5.2 Criteria for selecting hofjes of interest

Before starting the analysis, a list of the different hofjes has been created using the websites hofjesinamsterdam.nl and jordaanweb.nl (Hofjes in Amsterdam, n.d.; Jordaanweb, n.d.). From this, it became apparent that not all hofjes are courtyards. Some buildings that were considered a hofje are just regular rowhouse buildings which had the function of a hofje but not the courtyard typology. Therefore, the further analysis focused on the hofjes that are a courtyard and 34 of the original 50 hofjes will be selected for further analysis. These are hofjes that comprise out of at least two of the four sides that are part of a courtyard. So all buildings that consist of an L, U or full courtyard shape and have some garden in this shape. These building types will be referred to as hofjes in the rest of this thesis. Figure 24 gives an overview of the location of the different hofjes on a map and whether they are considered for this thesis based on the aforementioned criteria.

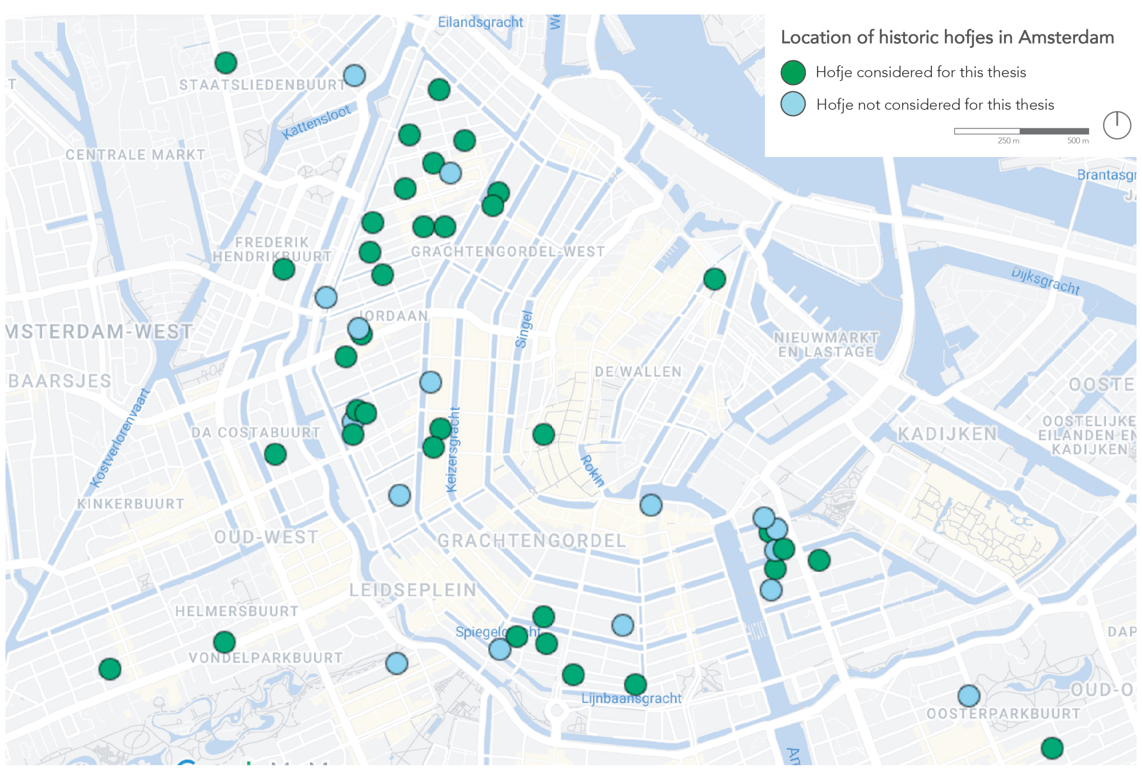


Figure 24. An overview of the location of hofjes in Amsterdam that are and are not considered for this study

Figures 25 - 27. Photographs taken by the author of the van Brienenhofje, Suykerhofje and Karthuizerhofje

5.3 Hofjes geometry analysis

Different geometrical characteristics of vegetation and buildings of the hofjes are analysed in this section.

First, the tree coverage ratio, planting distance of trees to buildings and number of trees per courtyard are analysed. The mean tree coverage percentage is relatively high (*M* = 24%, *SD* = 18%), especially considering the mean value of 14.3% in Amsterdam (European Environment Agency, 2018). When considering the total vegetational cover (including trees, shrubs and grass), the mean greenery coverage percentage was even considerably higher (*M* = 48.9%, *SD* = 19.9%) then that of Amsterdam which lies at 31%. When zooming into the number of trees, the mean number of trees planted in a hofje is 4.6 (*SD* = 3.5). From these means and standard deviations, it is visible that it can vary greatly among hofjes and that trees with relatively large crowns are often planted in hofjes. When it comes to the planting distance of trees from the building, the mean value of the mean planting distance per hofje is 3.5 metres (*SD* = 1.8). A complete overview of the different tree and greenery coverage ratios, number of trees per courtyard and mean planting distance from the buildings for all hofjes is given in Appendix B.

Next to the analysis of the trees, other geometrical aspects related to the hofjes are considered such as H/W ratios, W/L ratios, orientation and courtyard shape. For all these different aspects, the calculated values are given in Table 3. The values are further classified based on academic literature as explained in the following section.

The first classification has happened according to the H/W ratios of the hofjes. The H/W ratios of the different hofjes can be found in Table 3 and from this, it can be derived that the mean H/W ratio of the hofjes is 1.1 (*SD* = 0.6). In academic literature regarding courtyards, there is no general qualitative classification for the H/W ratios. The value of the H/W ratio is often described in terms such as shallow or deep with values around 0.5 often being referred to as shallow and values from 2 and upwards being referred to as deep (Ali-Toudert & Mayer, 2006; Deng & Wong, 2020; Lee et al., 2020). In the context of this research where the maximum H/W ratio is 2.9, the hofjes' H/W ratios are therefore classified as follows: hofjes with a H/W ratio <= 0.75 are classified as 'shallow', courtyards with H/W ratios of 0.75 - 1.5 are referred to as (near) unity and courtyards with H/W ratios of >= 1.5 are considered deep.

The mean W/L ratio of the hofjes is 0.6 (*SD* = 0.4) indicating a rectangular shape in which the length is 1.67 times the width. With regards to the classification according to their width to length ratio, there is also no consistent classification within courtyard literature (Al-Hafith et al., 2017; Mohsen, 1979; Muhaisen & Gadi, 2005). For this research, the ratios are classified as follows: hofjes with a W/L ratio <= 0.33 are considered narrow, courtyards with a W/L of 0.33 - 0.67 are considered moderately wide and courtyards with a W/L ratio of >= 0.67 are considered (near) square.

Another important aspect is the courtyard's orientation towards the sun. The hofjes' orientations in this thesis are classified based on the degrees the long axis is tilted from the north line. The classification was according to the following values: <= 22.5 or >= 337.5 or 157.5-202.5 are considered a north to south (N-S) orientation. Values of 22.5-67.5 or 202.5-247.5 are classified as north-east to south-west (NE-SW), values of 67.5-112.5 or 247.5-292.5 are classified as east to west (E-W). Lastly, values 292.5-337.5 or 112.5-157.5 are classified as north west to south east (NW-SE). The E-W and N-S were both the mode of the hofjes studied and occurred 14 times.

Another classification used in the analysis of the hofjes is the degree to which they form a fully enclosed courtyard. A full courtyard building consists of four sides that enclose the courtyard itself. Therefore, the hofjes are classified into quarter, half, three quarter or full courtyards based on their shape. The values per hofje and their classification are given in Table 3.

Name	~Length (m)	~Width (m)	Height (m)	H/W	H/W class.	W/L	W/L class.	Orientation (°)	Orientation class.	Courtyard shape	Court. shape class.	Prevalent pattern
Begijnhof	85	40	9	0.23	Shallow	0.47	Moderately Wide	12	N-S	1	Full	No
Bossche Hofje - Het Raepenhofje	17	8	10	1.25	(Near) Unity	0.47	Moderately Wide	350	N-S	0.75	Three Quarter	Yes
Catharinahofje	20	7	9.7	1.39	(Near) Unity	0.35	Moderately Wide	340	N-S	0.5	Half	Yes
Claes Claeszhofje (Anslo + Zwaardvegershofje)	17	5	9.5	1.90	Deep	0.29	Narrow	339	N-S	1	Full	Yes
Claes Reinierszhofje	20	16	6.9	0.43	Shallow	0.80	(Near) Square	272	E-W	0.75	Three Quarter	Yes
Concordiahofje Noord	39	12	13.6	1.13	(Near) Unity	0.31	Narrow	74	E-W	0.5	Half	Yes
Concordiahofje Zuid	35	15	12.4	0.83	(Near) Unity	0.43	Moderately Wide	67	NE-SW	1	Full	Yes
Constantia Hofje	22	15	10.9	0.73	Shallow	0.68	(Near) Square	79	E-W	1	Full	Yes
Deutzenhofje	30	21	8.2	0.39	Shallow	0.70	(Near) Square	12	N-S	1	Full	Yes
Elisabeth Otter-Knoll Stichting	20	20	15.5	0.78	(Near) Unity	1.00	(Near) Square	68	E-W	1	Full	Yes
Everdina de Lanoyhof	22	12	10.5	0.88	(Near) Unity	0.55	Moderately Wide	346	N-S	0.75	Three Quarter	Yes
Fontainehofje	30	13	11.4	0.88	(Near) Unity	0.43	Moderately Wide	68	E-W	0.75	Three Quarter	No
Hilmanhofje	15	6	12.5	2.08	Deep	0.40	Moderately Wide	279	E-W	0.5	Half	Yes
Hodshon-Dedelhof	27	12	9.7	0.81	(Near) Unity	0.44	Moderately Wide	102	E-W	0.75	Three Quarter	Yes
Hofje de Kalverengang	20	5	9.5	1.90	Deep	0.25	Narrow	95	E-W	0.5	Half	Yes
Hugo de Groothofje	30	13	14.2	1.09	(Near) Unity	0.43	Moderately Wide	21	N-S	0.5	Half	Yes
Karthuizerhofje	43	17	11	0.65	Shallow	0.40	Moderately Wide	82	E-W	1	Full	Yes
Lindenhofje	18	11	11.6	1.05	(Near) Unity	0.61	Moderately Wide	346	N-S	0.75	Three Quarter	No
Magdalena Hodshonhof	12	7	12	1.71	Deep	0.58	Moderately Wide	75	E-W	0.75	Three Quarter	Yes
Occohofje	48	28	14.2	0.51	Shallow	0.58	Moderately Wide	344	N-S	0.75	Three Quarter	Yes
P.W. Janssenhofje	24	13	16	1.23	(Near) Unity	0.54	Moderately Wide	336	NW-SE	0.75	Three Quarter	Yes
Platanenhof	45	20	12	0.60	Shallow	0.44	Moderately Wide	338	N-S	1	Full	Yes
Regenboogs-Liefdehofje	18	5.5	9.2	1.67	Deep	0.31	Narrow	342	N-S	0.5	Half	Yes
Rijpenhofje	20	10	10	1.00	(Near) Unity	0.50	Moderately Wide	340	N-S	0.75	Three Quarter	Yes
Rozenhofje	24	20	10.4	0.52	Shallow	0.83	(Near) Square	70	E-W	1	Full	Yes
Sint Andrieshofje	11	11	11.8	1.07	(Near) Unity	1.00	(Near) Square	74	E-W	1	Full	No
Staringhofje/Lutherhofje	20	18	15	0.83	(Near) Unity	0.90	(Near) Square	70	E-W	0.75	Three Quarter	Yes
Suykerhofje	24	13	8.6	0.66	Shallow	0.54	Moderately Wide	358	N-S	0.75	Three Quarter	No
Van Brants Rus hofje	18	7	12.9	1.84	Deep	0.39	Moderately Wide	344	N-S	1	Full	No
van Brienenhofje	27	16	11.9	0.74	Shallow	0.59	Moderately Wide	298	NW-SE	1	Full	Yes
Venetiaehofje	25	23	10	0.43	Shallow	0.92	(Near) Square	66	NE-SW	1	Full	Yes
Vredenburgh hofje	14	5	14.3	2.86	Deep	0.36	Moderately Wide	299	NW-SE	1	Full	No
Zevenkeurvorstenhofje	26	5	9.7	1.94	Deep	0.19	Narrow	72	E-W	0.75	Three Quarter	Yes
Zon's hofje	16	10	14.5	1.45	(Near) Unity	0.63	Moderately Wide	30	NE-SW	0.5	Half	Yes
Urban Comfort Lab	**36.6**	**18.3**	**7.8**	**0.43**	**Shallow**	**0.50**	**Moderately Wide**	**48**	**NE-SW**	**1**	**Full**	-

Table 3. An overview of the approximate length (m), approximate width (m), height (m), H/W, H/W classification, W/L, W/L classification, orientation (degrees), orientation classification, courtyard shape, courtyard shape classification of the analysed hofjes and whether or not they have a prevalent pattern

5.4 Tree planting patterns of analysis

As a next step in the analysis, the tree planting patterns of hofjes are analysed. The method for this analysis is developed based on the method used in the study by Yang et al. (2018). This method that was developed for this research will be shortly repeated first. The hofjes in this study are divided into two canyons: a longer canyon representing the courtyard's length and a shorter canyon representing its width. To analyse the tree placement within these two canyons, two ratios per tree are determined which are ds:DS and dl:DL. ds refers to the mean distance between the trunk and the short canyon of the courtyard and dl refers to the mean distance between the trunk and the long canyon of the courtyard. DS is obtained by dividing the length of the courtyard by two and DL is obtained by dividing the width of the courtyard by two. This approach is illustrated in Figures 11 and 12. These ratios yield a value between 0-1 and together give an indication into which area the trees are planted on average. The ratios are classified into three parts: perimeter planting from 0-0.33, midway planting ranging from 0.33-0.67 and centre planting ranging from 0.67-1.

The following scatterplot in Figure 28 shows the values of the different hofjes. Two different prevalent patterns can be derived from this analysis. 62.9% (or 22) of the hofjes have tree planting patterns in which the average tree is planted within the midway area of the shorter part of the courtyard and in the midway or centre area of the longer part of the courtyard. This pattern is indicated by the dark green dotted rectangle in the graph and called the Two Sided Double Row pattern. The second most prevalent planting pattern, including 44.1% (or 15) of the hofjes, indicates trees that are planted in the centre are along the longer part of the courtyard and the midway and centre area of the shorter part of the courtyard. This pattern is indicated by the orange dotted line and is called the Clustered Double Row pattern. The complete overview of ratios per courtyard together with their classification is given in Appendix B.

Translating these ratios from a graph to a courtyard, Figure 29 indicates where the trees are planted in these prevalent patterns in a courtyard with the same dimensions as the courtyard in the Lab based on this scatterplot.

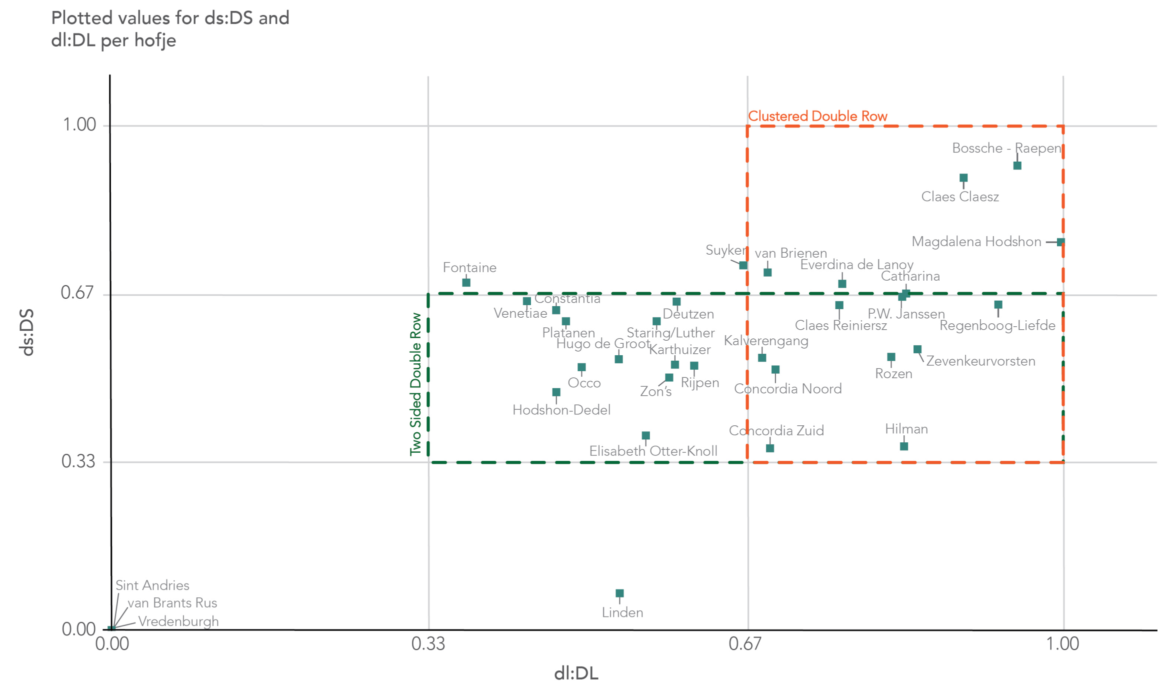


Figure 28. A scatterplot of the values for ds:DS and dl:DL per hofje

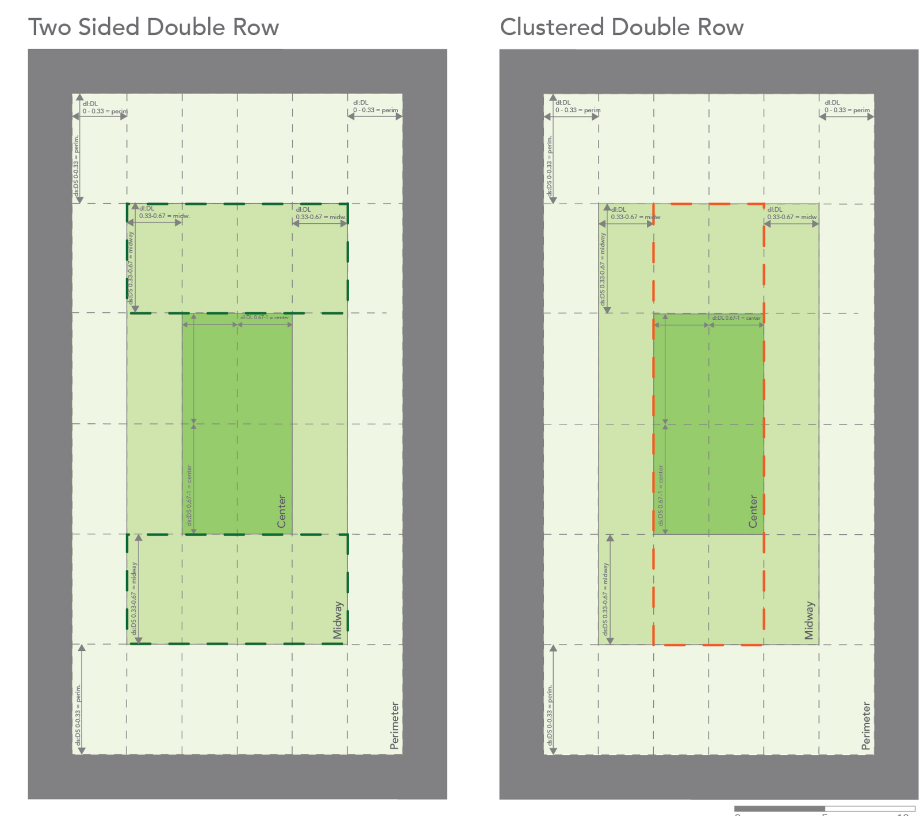


Figure 29. The two prevalent planting patterns illustrated in a courtyard similar to the courtyard in the Lab

5.5 Mapping of hofjes with similar classifications to the Lab

As a final step in this chapter, the tree planting patterns of hofjes that have similar classifications as the courtyard in the Lab are mapped. In Table 3, the hofjes and their classification have been provided, including the classification of the Lab courtyard. In this part of the research, another classification is added to this table in which it is indicated whether or not the hofjes have a tree planting pattern that falls within the prevalent tree planting patterns of the previous step of the analysis. The hofjes that have two or three similar classifications as the courtyard in the Lab, and that have a tree planting pattern that falls within the prevalent patterns, are given in Table x. The tree planting patterns of these hofjes are further mapped in Figure 30 to get a deeper understanding of the tree configurations in courtyards with similar H/W ratios, W/L ratios, orientation and shape as these are important criteria that can influence tree planting patterns.

The hofjes that have two or three similar classifications as the courtyard in the Lab, and that have a tree planting pattern that falls within the prevalent patterns, are as followed:

- Two of the same classifications: Concordiahofje Zuid, Constantiahofje, Deutzenhofje, Karthuizerhofje, Occohofje, Rozenhofje and Zon's hofje.
- Three of the same classifications: Platanenhof and Venetiaehof.

The tree planting patterns of these hofjes are further mapped to get a deeper understanding of the tree configurations in courtyards with similar H/W ratios, W/L ratios, orientation and shape as these are important criteria that can influence tree planting patterns. Interesting to note is that when considering the hofjes with similar classifications, there is also a change in parameters such as the tree coverage ratio. For full courtyards, the mean tree coverage ratio increases to 25.9% (*SD* = 21.5). For moderately wide courtyards, the mean tree coverage ratio is 24.2% (*SD* = 17.5). When considering shallow courtyards and courtyards with the same orientation separately, they both have a mean coverage ratio of 31.3% (*SD* = 19.7 and *SD* = 15.4 respectively).

Figure 30 gives an overview of the different hofjes analysed. Prevalent pattern 1 is clearly visible in for example the Constantiahofje and Karthuizerhofje and considering the ratios take into account the average planting distance also Zon's Hofje, Venetiaehofje, Platanenhof, Concordia Zuid and Occohofje. Prevalent pattern 2 is clearly visible in Rozenhofje.

5.6 Summary of findings

In this chapter, different types of analysis have been performed on hofjes in Amstredam. The quantitative and qualitative analysis of the geometries of these hofjes yielded the following results: the mean tree coverage ratio is 24% (*SD* = 18%) and the mean greenery coverage ratio (including trees) is 48.9% (*SD* = 19.9%) which makes hofjes considerably more green compared to Amsterdam as a whole. The mean number of trees is 4.6 (*SD* = 3.5) and trees are planted at a mean distance of 3.5 metres from the building (*SD* = 1.8). When considering the different ratios associated with courtyards, the mean H/W ratio is 1.1 (*SD* = 0.6) and the mean W/L ratio is 0.6 (*SD* = 0.4). The E-W and N-S orientations were most occurring (both 14 times) and hofjes were further classified according to whether or not they formed a full courtyard.

For analysing the different tree planting patterns, the methodology as explained in Section 3.1.2 was used. From this, it became apparent that 62.9% (or 22) of the hofjes have tree planting patterns in which the average tree is planted within the midway area of the shorter courtyard and in the midway or centre area of the longer courtyard this is the first identified prevalent pattern which was named Two Sided Double Row. The second most prevalent planting pattern which was identified for 44.1% (or 15) of the hofjes has trees that are planted in the centre are along the longer canyon of the courtyard and the midway and centre area of the shorter canyon. This planting pattern was called Clustered Double Row.

Next, hofjes that had two or three similar classifications (that is, H/W ratio, W/L ratio, orientation or courtyard shape) and had one of the prevalent patterns were mapped to get a deeper understanding of their tree planting pattern. Also, considering these hofjes with overlapping characteristics, mean tree coverage ratios increased up to 31.3%.

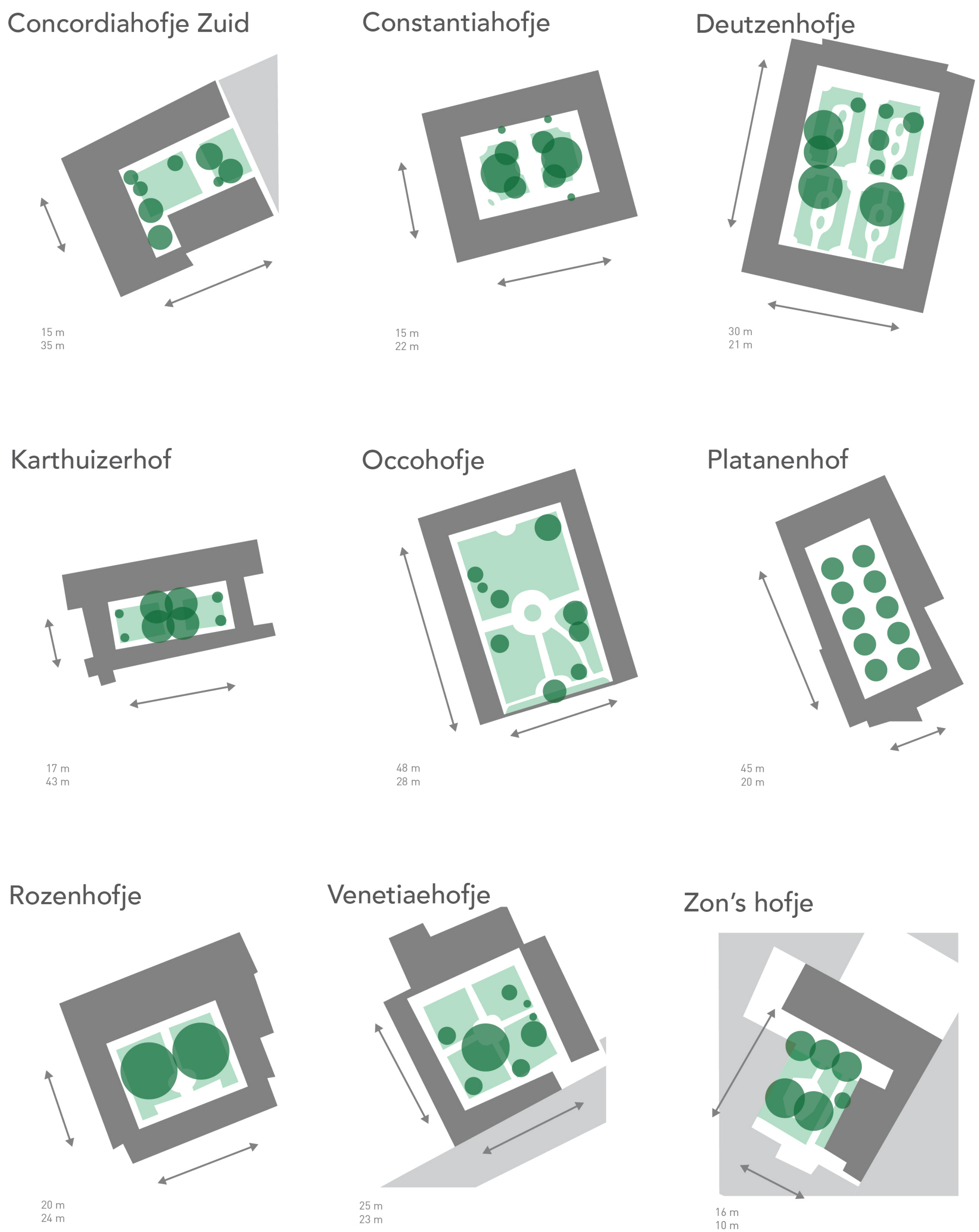


Figure 30. Mapping of the tree planting patterns of hofjes with two or three similar classifications and one of the prevalent tree planting patterns

6. Microclimate Simulations of the Courtyard and Tree Patterns

This chapter displays the results of the simulations of the different tree planting patterns in the Lab courtyard. This chapter addresses the findings of the third sub question, which is : *"What is the modelled effect of the different configurations of trees on reducing heat stress in the courtyard of the Urban Comfort Lab?* The objective of this simulation is to determine which patterns are most effective in reducing heat stress measured in PET. First, the final tree patterns are created based on the findings of the previous two chapters. The simulation results of these tree planting patterns are then discussed. To get a deeper understanding of the effect of the different patterns on PET, the other meteorological parameters looked at are air temperature, mean radiant temperature, wind speed and direction and relative humidity. Three different times of the day are considered, which are the morning, afternoon and late afternoon at 10:00, 14:00 and 18:00 respectively. These times were chosen to see if there are differences in effectiveness of the patterns to reduce heat stress throughout the day, and because maximum temperatures of 35.4 °C were measured at 14:00. The simulation output for the different climatological parameters are presented for the three different times first after which the results are interpreted.

6.1 Selected tree configurations

Based on the previous analyses in Chapters 4 and 5, different tree planting patterns are derived to perform the simulations with. For these simulations, the Tilia europaea that are present in the Lab are simulated. These trees have a crown diameter of around 4 metres, giving it a surface area of 12.6 square metres. The surface of the Lab itself is 669.8 square metres. When adopting a coverage ratio of 30%, which is in line with courtyards in Amsterdam with similar morphological features, 16 Tilia europaea should be simulated. Considering the planting distance from the buildings, the mean is 3.5 metres, with a minimum mean value of 0.7 (not considering the courtyards that do not have trees, and therefore the value 0). As the trees' crown diameters are 4 however, minimal planting distance should be 2 metres. For densities, the rule of thumb by Zhang et al. (2018) of an ART < 2 should be satisfied (see Section 4.1.1). Moreover, the trees should ideally be planted in a north to south orientation which was indicated by Lee et al. (2020) to be the most effective. The following Figure 31 gives the different patterns that are chosen, placed corresponding to how they are placed in ENVI-met Spaces. The thin dotted line indicates the 2 metre boundary that is the minimum planting distance. The thick dotted line indicates the 3.5 metres average planting distance.

1. The Cornered tree planting pattern

This tree planting pattern is characterised by trees planted in the sun exposed corner of the courtyard. The trees are planted at crown distance from each other.

2. The Perimeter tree planting pattern

This planting pattern is characterised by a single line of trees along the perimeter of the courtyard. The trees along the short side of the courtyard are placed at 3.5 m from the building, which is the average planting distance that came from the hofjes analysis. The trees are planted at a density in which ART<2 holds.

3. The Dispersed tree planting pattern

This planting pattern is characterised by rows of trees that are evenly spread out along the courtyard. The outer two rows of trees are planted at the 3.5 m distance from the building, which is the average planting distance. For this pattern, also ART < 2 holds.

4. The Double Row tree planting pattern

This planting pattern is characterised by two rows of trees along the center of the courtyard. Both rows of courtyards start and end with the trunk of the tree on the 3.5 m line from the building. The trees are planted in a NE-SW orientation to maximise shading in the courtyard with this orientation.

5. The Two Sided Double Row tree planting pattern

This planting pattern is characterised by two double rows of trees that are planted on either side of the courtyard. This is one of the prevalent patterns that were derived from the hofjes analysis and is the most prevalent pattern.

6. The Clustered Double Row pattern

This planting pattern is characterised by two rows of trees planted at a distance equal to their crown from each other. The trees are again planted in a NE-SW orientation to maximise shading in the courtyard with this orientation. This is the second most prevalent pattern coming from the hofjes analysis.

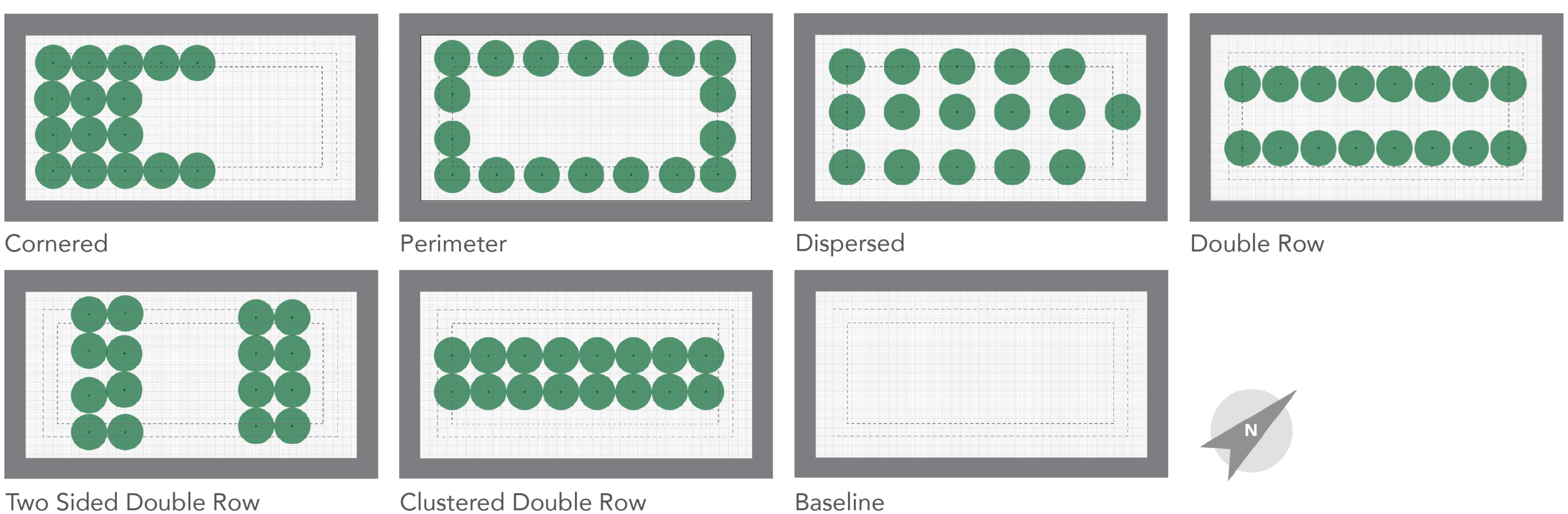


Figure 31. Overview of the tree planting patterns used in the modelling

6.2 Simulation Results

6.2.1 Morning simulations

Air temperature

As can be seen in Figure 32, air temperatures in the morning range between 31.51 °C and 32.04 °C for all different patterns. The climatic boundary condition air temperature was 31.5 °C at 10:00 in the morning and therefore, air temperatures in the courtyard are slightly higher as compared to this climatic boundary condition. When considering air temperature, the Two Sided Double Row, Perimeter and Clustered Double Row patterns have the highest temperatures in the western side of the courtyard with the Two Sided Double Row pattern having temperatures reaching up to above 32.04 °C. The Two Sided Double Row has the highest occurring air temperature in the western corner. The eastern side of the courtyard shows the lowest results but is also still partially shaded at this time of day. The best performing pattern is the Double Row pattern followed by the Dispersed pattern with the lowest temperatures along the western side of the courtyard.

Mean radiant temperature

When looking at the simulation results of MRT in Figure 33, the effect of the heating of the material is clearly visible. The south eastern side is still relatively cool as it is shaded, but the parts of the courtyard that are not covered by trees or shade of trees show considerable increases in temperature. MRT values of above 71.8 °C are observed most in the Cornered pattern (12.1% of the courtyard) followed by the Perimeter pattern (8.4% of the courtyard) and the Two Sided Double Row patterns (5.4% of the courtyard). For the patterns with trees spaced out more evenly or in such a way that they create ample shade (Dispersed, Double Row and Clustered Double Row patterns), MRT levels are overall lower with reductions of up to 26.4 °C surrounding the trees. When considering the Clustered Double Row and Double Row pattern, the maximum values of MRT are lower, between 69.60 °C and 71.80 °C. The Clustered Double Row pattern has the least occurrence of these values with 0.3% of the courtyard experiencing an MRT between 69.60 °C and 71.80 °C, compared to 1.9% for the Double Row pattern. Therefore, the Clustered Double Row is the most effective pattern in reducing maximum MRT values, followed by the Double Row pattern.

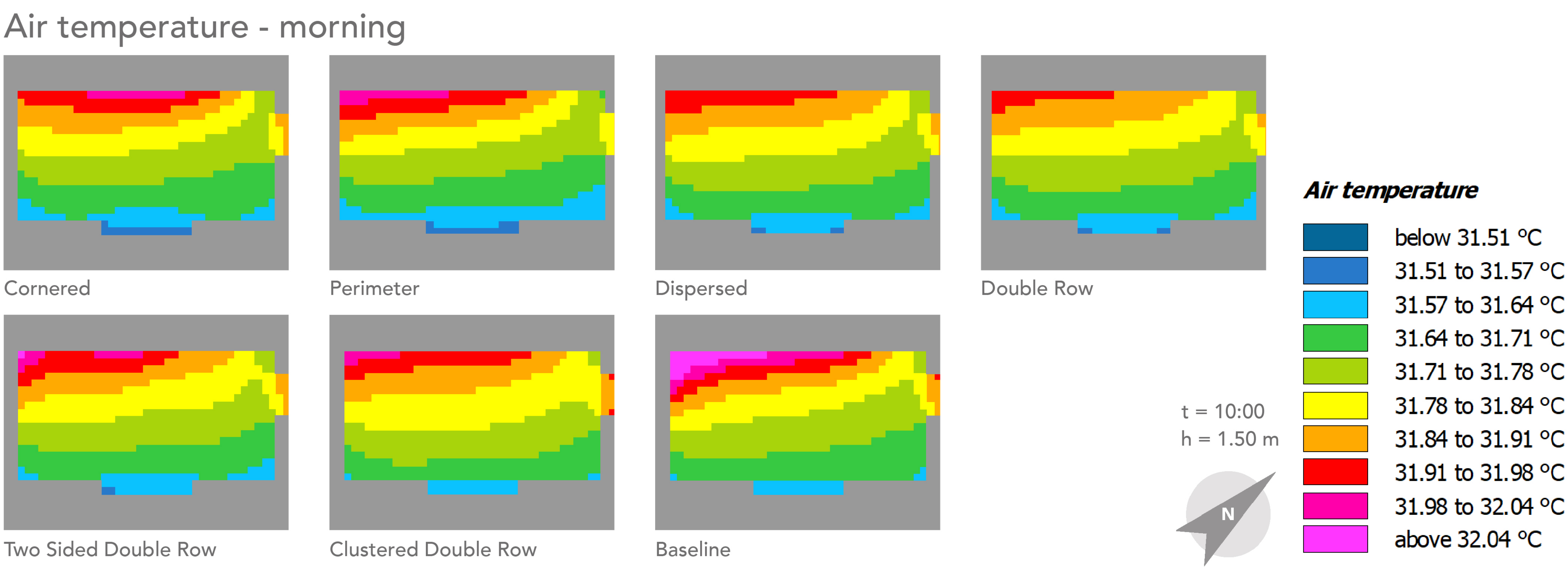


Figure 32. Simulation output of air temperature in the morning (t = 10:00)

Mean Radiant Temperature - morning

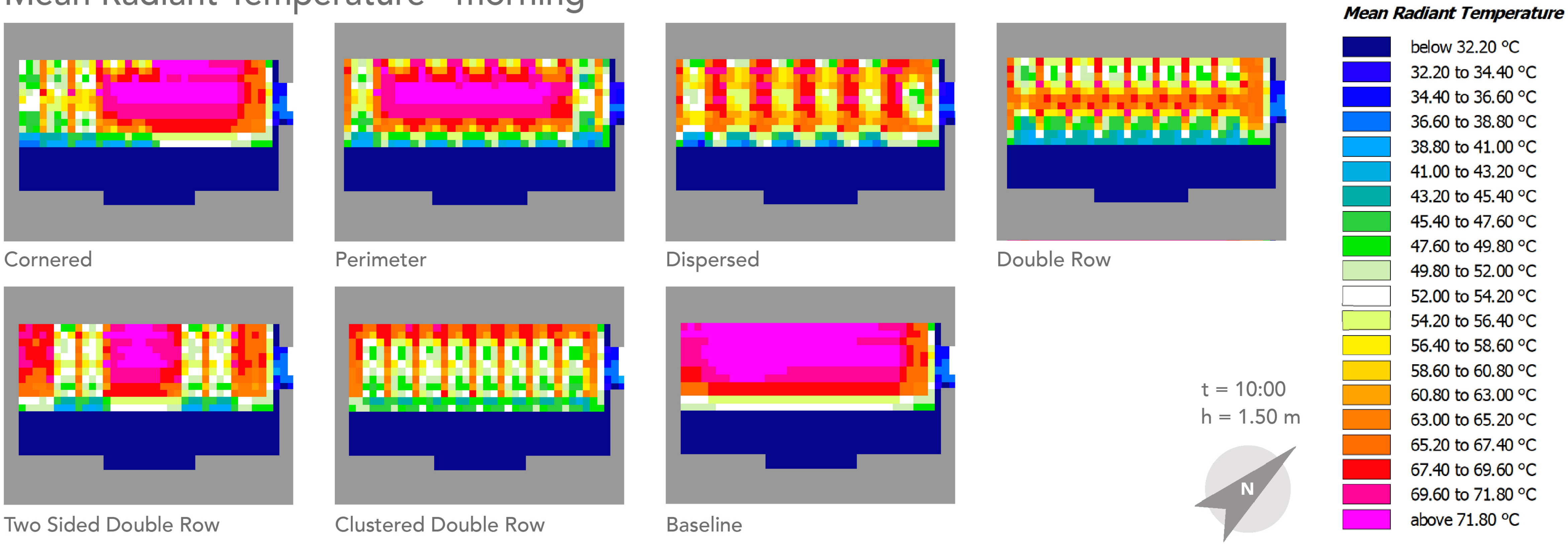


Figure 33. Simulation output of MRT in the morning (t = 10:00)

Wind speed and direction

As shown in Figure 34, the effect of the trees on wind direction and speed is limited. In general, wind speeds within the courtyards are very low and range between 0 m/s and 0.18 m/s for most of the courtyard compared to the 2.1 m/s wind speed that was used as input in the model at this time. Outside of the courtyard, the wind comes from the south east (or 120 degrees). The wind enters the courtyard in the western corner and spreads out in a north and south direction. The wind speed along the south western facade stays relatively equal for the different patterns, but for the Dispersed, Double Row and Clustered Double Row patterns there is a larger area with winds of 0.12-0.18 m/s. In the centre of the courtyard, there are larger areas with higher wind speeds for all the patterns that have trees when comparing them to the baseline case. The patterns with more open spaces in the centre, which are the Cornered and Perimeter patterns, show slightly larger parts with higher wind speeds as compared to the other patterns. Where the wind leaves the courtyard through the opening, wind speed increases again up to above 0.54 m/s.

Relative humidity

The simulation results for relative humidity are shown in Figure 35. Relative humidity levels are the lowest in the south western corner and along the south western facade, which is similar to the results shown for air temperature. The Double Row pattern has the highest overall relative humidity followed by the Dispersed and Cornered patterns. As higher levels of relative humidity indicate that it is more difficult for a human body to cool down through sweating, they are the least effective patterns. For the Two Sided Double Row and Clustered Double Row patterns, low relative humidity levels are most prevalent in the south western corner. The overall relative humidity levels are around 37-38% which is considered low but not uncomfortable (Pijpers-van Esch, 2015).

PET

Figure 36 shows the simulated results for PET in the morning. For the patterns with larger open spaces, which are the Cornered, Perimeter and Two Sided Double Row patterns, large parts of the courtyard have high PET levels of above 57 °C. A raster

Wind speed and direction - morning

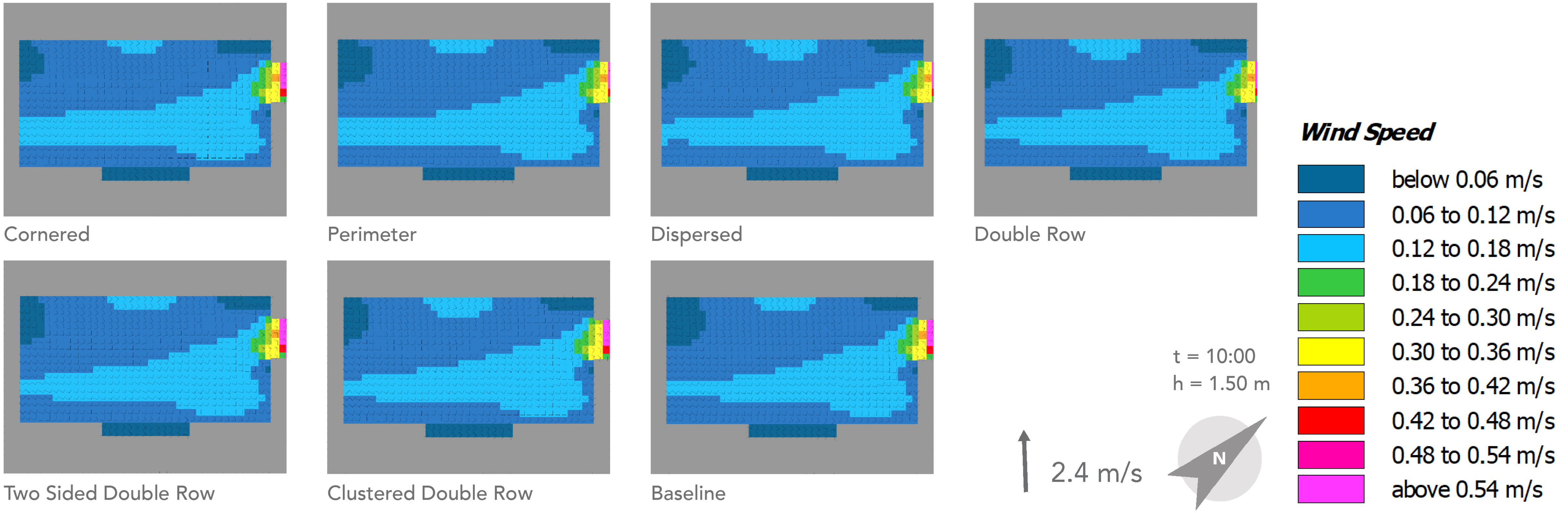


Figure 34. Simulation output of wind speed and direction in the morning (t = 10:00)

analysis of these patterns shows that for the Perimeter pattern, 32.1% of the courtyard has PET values of above 57 °C followed by the Cornered pattern (29.5%) and the Two Sided Double Row pattern (27.0%). The Perimeter pattern therefore has the largest share of highest PET values and is therefore least effective. The Double Row and Clustered Double Row have the lowest occurrence of PET values above 57 °C. For the Double Row pattern, 10.6% of the courtyard has these values followed by the Clustered Double Row pattern for which 12.7% has these values. Therefore, the Double Row pattern is most effective in reducing maximum PET levels. Already at 10:00 in the morning, most parts of the courtyards experience PET values higher than 41 °C, which is indicated as extreme heat stress (Matzarakis et al., 1999). For the Perimeter pattern, the lowest share of the courtyard experiences extreme heat stress (53.2%) as compared to the Clustered Double Row pattern for which the highest share of the courtyard experiences extreme heat stress (57.1%). It is interesting to note that the Perimeter planting pattern therefore results in the lowest share of the courtyard that experiences extreme heat stress of above 41 °C but that it is also one of the patterns that has the largest area of PET values above 57.0 °C. On the other hand, the Clustered Double Row pattern has the highest share of the courtyard that experiences extreme heat stress, whilst it is one of the patterns that has the least occurrence of the maximum values of above 57 °C. The mean share of the courtyard that experiences extreme heat stress at 10:00 is 54.9%. In the Figure, extreme heat stress is experienced for the areas that are indicated with the colour range from yellow to purple.

Relative humidity - morning

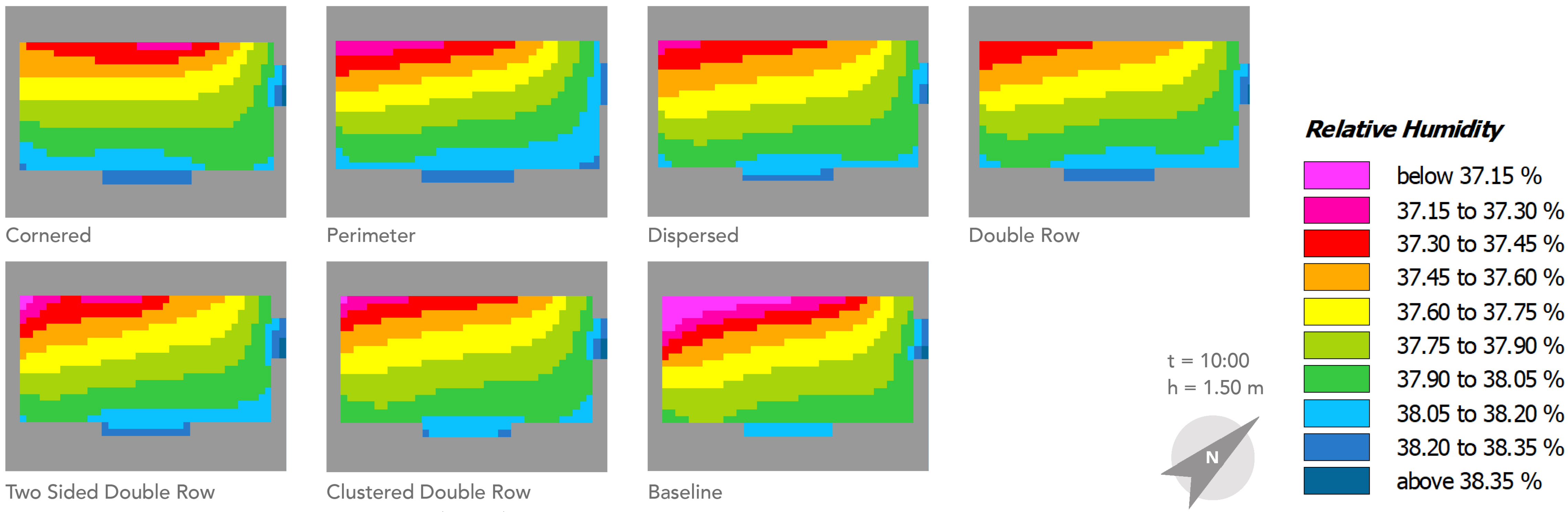


Figure 35. Simulation output of relative humidity in the morning (t = 10:00)

PET - morning

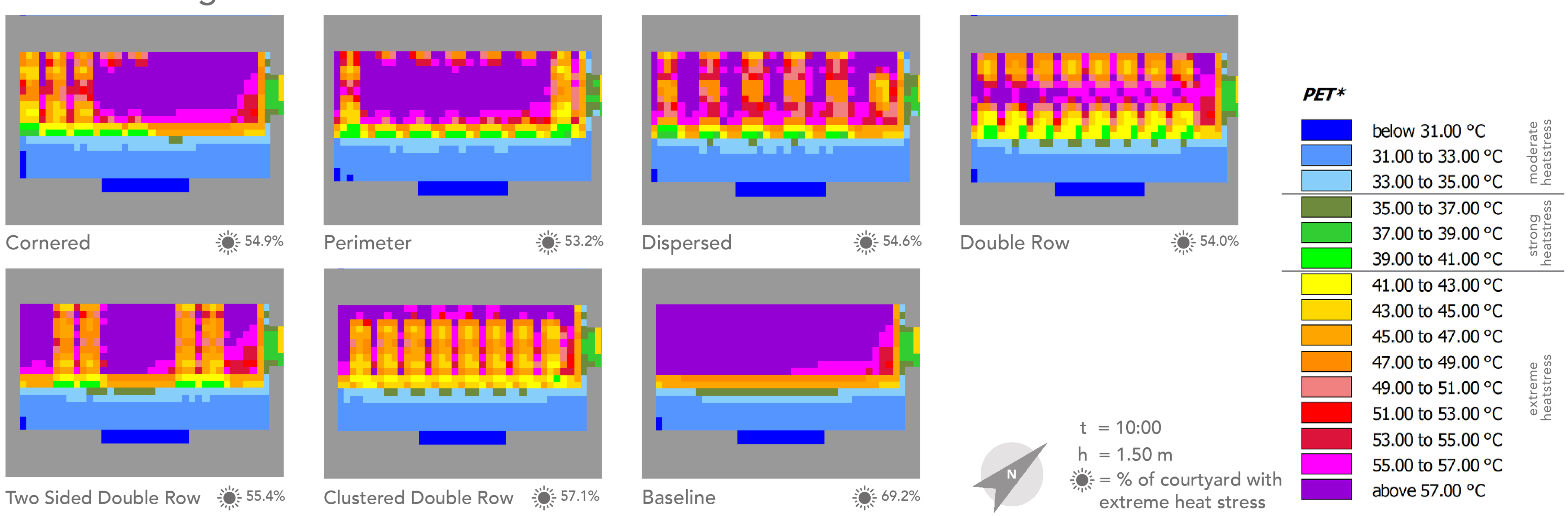


Figure 36. Simulation output of PET in the morning (t = 10:00)

6.2.2 Afternoon simulations

Air temperature

Figure 37 shows the air temperature levels for the different patterns at 14:00 in the afternoon, which was the hottest moment of the day and the climatic boundary air temperature was 35.4 °C. The air temperature levels are the lowest in the southern corners of the courtyard for all patterns. For this corner, the Clustered Double Row and Two Sided Double Row patterns have a larger area of higher values that range from 36.50 °C - 36.60 °C as compared to the other patterns making them the least effective in reducing highest air temperatures. In the opposing corner, higher temperatures are measured for all patterns with the highest temperature measured for the Clustered Double Row above 37.1 °C. When considering the other patterns, the Perimeter pattern has the lowest maximum temperature (at 37 °C) and lowest overall temperatures followed by the Dispersed pattern.

Mean radiant temperature

Figure 38 shows the MRT values at 14:00 in the afternoon. As was seen in the morning, MRT levels are highest in the open spaces in the Cornered pattern. With the Cornered pattern, 9.8% of the courtyard has MRT values above 83.0 °C. With the Clustered Double Row pattern, 3.0% of the courtyard has values of above 83.0 °C making these two patterns the least effective in preventing the highest MRT values. It should however be noted that the Clustered Double Row pattern has a relatively large occurrence of values above 83 °C, but smaller occurrences of values between 80.0 °C and 83.0 °C as compared to the Two Sided Double Row and Perimeter pattern. When looking at the Dispersed and Double Row patterns, maximum MRT values are lower and are between 80.0 °C and 83.0 °C. For the Dispersed pattern, 3.3% of the courtyard experiences these values between 80.0 °C and 83.0 °C. For the Double Row pattern, this percentage is 4.9%. This means that the Dispersed pattern creates a courtyard in which there is the least occurrence of the highest measured MRT values across the different patterns, followed by the Double Row pattern.

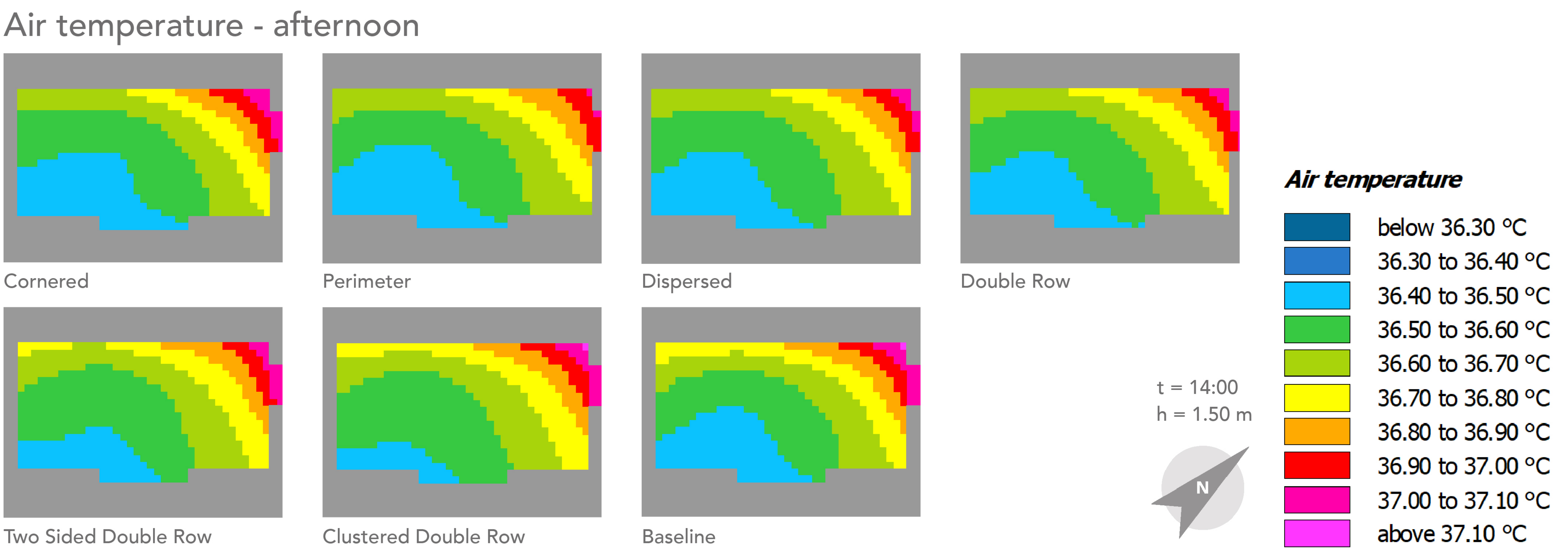


Figure 37. Simulation output of air temperature in the afternoon (t = 14:00)

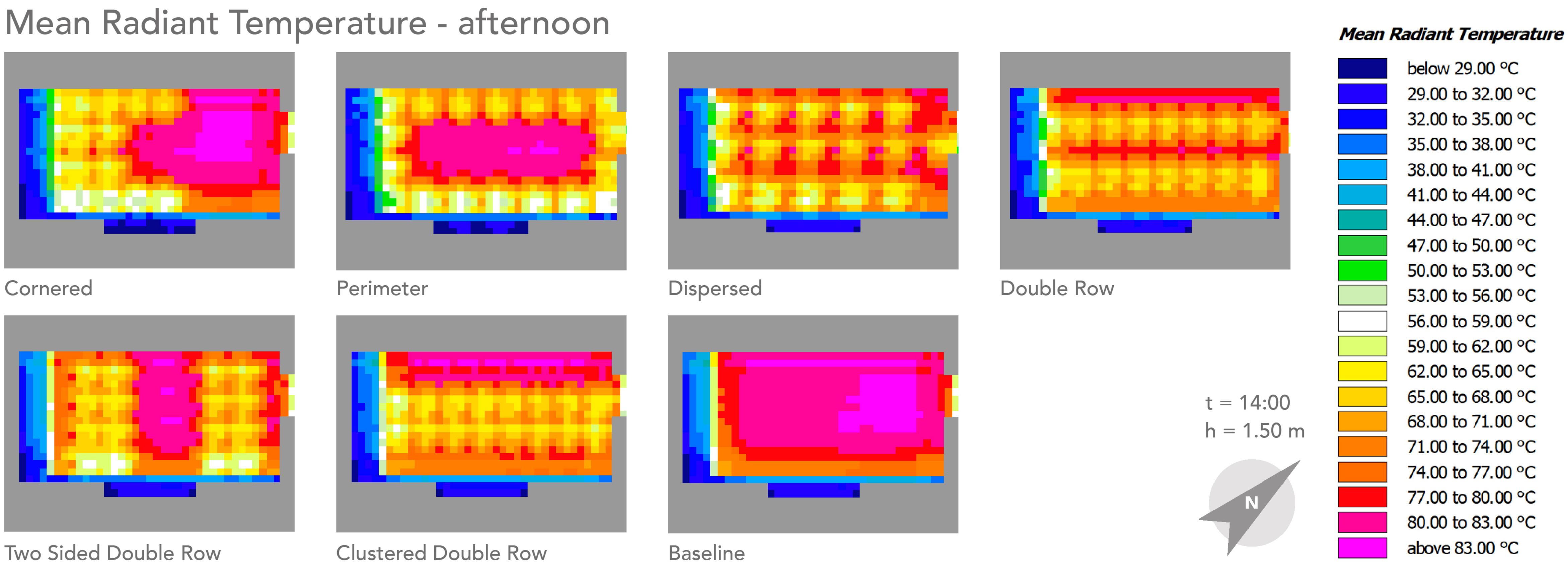


Figure 38. Simulation output of mean radiant temperature in the afternoon (t = 14:00)

Wind speed and direction

The wind speed and direction is shown in Figure 39. Similar to the morning simulation output, the presence of trees does not influence wind flows and speed considerably at a height of 1.5 m. The wind boundary conditions at this time have changed in direction slightly (140 degrees) and increased in speed up to 2.9 m/s. Higher wind speeds are therefore also visible within the courtyard. The wind enters the courtyard along the western wall and accelerates northwards.

Relative humidity

The distribution of relative humidity values is shown in Figure 40. General levels are very low and range between 23.01% and 23.49% for all courtyards. The northern corner and western facade experience the lowest relative humidity levels with large parts being below 23.01% for all the patterns. In general, the relative humidity in the whole courtyard is below 30% which is considered an uncomfortable level with dry air that causes mouth, skin and throat to dry out (Pijpers-van Esch, 2015). Therefore, the lower humidity levels are associated with worse performing patterns here. The Clustered Double Row pattern followed by Two Sided Double Row have the lowest overall relative humidity levels when considering both this northern corner as well as the southern corner in which lower relative humidity levels are experienced as compared to the other patterns. Higher relative humidity levels are found for the Cornered, Perimeter, Dispersed and Double Row patterns.

PET

Figure 41 shows the simulated output for PET at the hottest point of the day. For most of the courtyard, PET levels are above 57°C. A raster analysis of the different patterns shows that for the Cornered pattern, 40.8% of the courtyard has values above 57°C, followed by the Perimeter pattern (36.7%). The Dispersed pattern shows the smallest share (27.8%) of the courtyard with values of above 57°C followed by the Double Row pattern (32.2%) and the Two Sided Double Row pattern (32.5%). Considering PET values in the whole courtyard, extreme heat stress with PET values above 41°C is experienced in the largest part of the courtyard for all the patterns. In the Clustered Double Row pattern, 81.8% of the courtyard experiences extreme heat stress followed

Wind speed and direction - afternoon

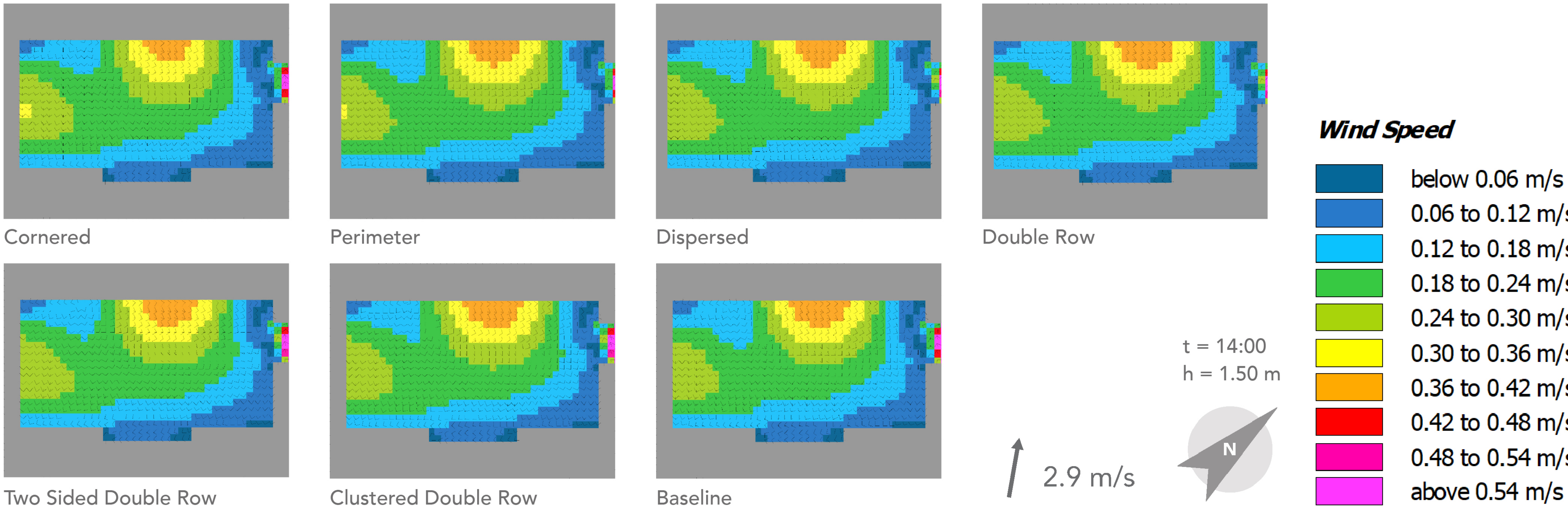


Figure 39. Simulation output of wind speed and direction in the afternoon (t = 14:00)

by the Two Sided Double Row pattern (81.5%). The tree planting patterns that result in the smallest share of the courtyard that experiences extreme heat stress are the Cornered and Perimeter pattern (both 79.1%). The mean share of the courtyard that experiences extreme heat stress at 14:00 is 80.4%.

To get a deeper understanding of the effect of the tree planting patterns at the hottest moment of the day, the absolute difference maps are also added for the six different patterns in which the difference compared to the baseline is given (Figure 42). From the figure, it can be seen that the Cornered pattern leads to one of the largest area in which the absolute difference is highest, below 7 K. On the other hand however, it is also the pattern that has the largest area in which an increase of PET is experienced as compared to the baseline case.

When looking at the Dispersed pattern, 38.6% of the courtyard has a reduction between 0.0 K and 1.0 K, which is the lowest reduction possible compared to the baseline case. For the Perimeter pattern, 38.1% of the courtyard has a reduction between 0.0 K and 1.0 K, making it a slightly better performing pattern compared to the Dispersed pattern. This is because the reduction between 0.0 and 1.0 K is the lowest reduction step, so the lower the share of this reduction, the higher the share of larger reductions and thus a cooler courtyard. Also when it comes to the share of the courtyard that has reductions of below -7 K, the Perimeter pattern is best performing. The Perimeter pattern has 3.6% of the courtyard with reductions lower than -7 K followed by the Cornered pattern that experiences reductions in PET of below -7 K in 3.0% of the courtyard. When looking at the absolute difference in PET for the different patterns, the Perimeter pattern is therefore better performing in reducing PET levels during the afternoon than the Dispersed pattern. This seems to be a conflicting result given that for absolute PET values, the Dispersed pattern leads to considerably lower shares of the courtyard that experience maximum PET values as compared to the Perimeter pattern (27.8% for the Dispersed pattern as compared to 36.7% for thePerimeter pattern). This could possibly be explained by the shading in the courtyard. The largest PET reductions in absolute differences are observed in the southern and western corner as well as along the eastern facade which are partially shaded. The trees that are placed close to that shading, as is the case for the Perimeter pattern, seem to have an extra cooling effect compared to trees that are placed in full sun exposure in the

Relative humidity - afternoon

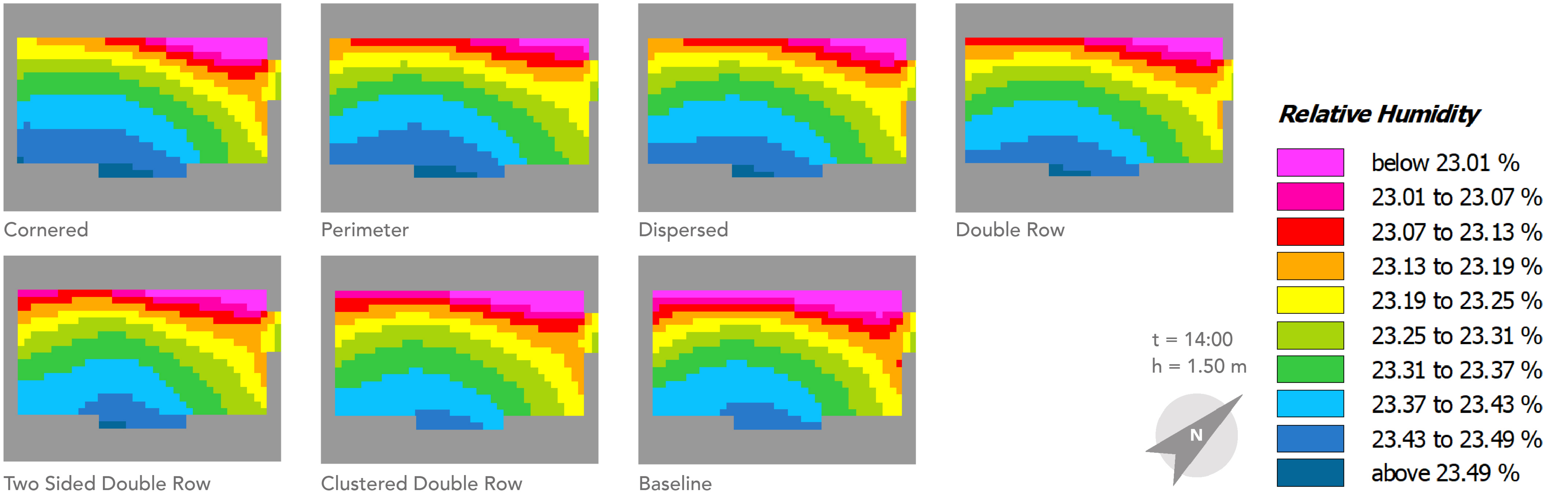


Figure 40. Simulation output of relative humidity in the afternoon (t = 14:00)

centre of the courtyard, as is the case for the Dispersed pattern. In comparison to the baseline case, the reductions along the shaded facades are therefore larger as the effect of the trees is larger. When considering the absolute PET values however, the Dispersed pattern is performing significantly better in reducing maximum PET values in the courtyard.

PET - afternoon

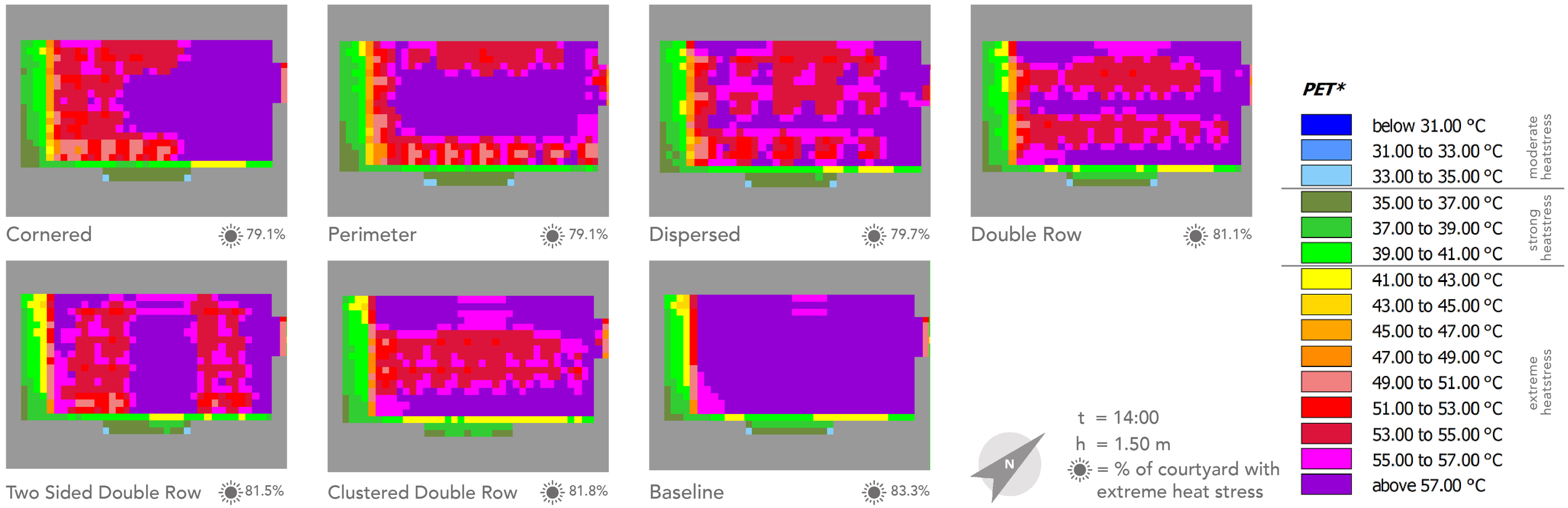


Figure 41. Simulation output of PET in the afternoon (t = 14:00)

Absolute difference PET - afternoon

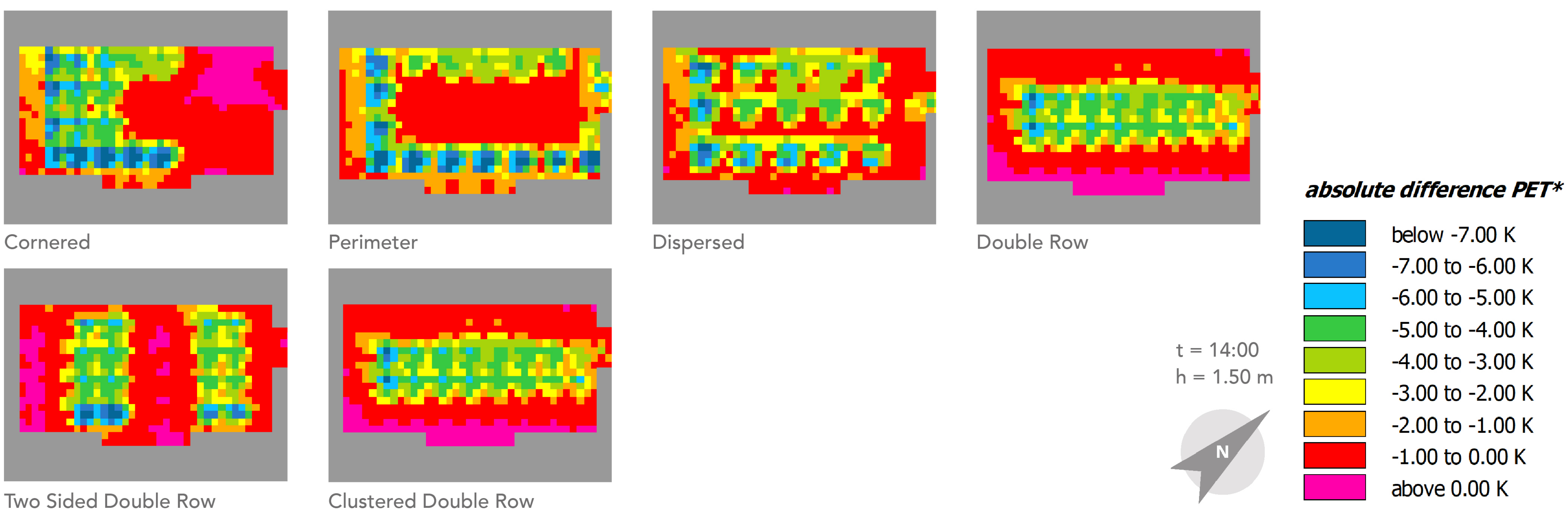


Figure 42. Absolute difference in PET for the different patterns compared to the baseline case in the afternoon (t = 14:00)

6.2.3 Late afternoon simulations

Air temperature

As can be seen in Figure 43, air temperature levels are quite equal among the different patterns. The climatic boundary condition air temperature was 32.9 °C. In the western and southern side, temperatures are lower. Highest temperatures are in the eastern corner and are highest for the Cornered pattern in which temperatures reach up to 33.66 °C followed by the Clustered Double Row and Two Sided Double Row patterns. The best performing pattern with lowest air temperatures in this case is the Perimeter pattern followed by the Double Row and Dispersed pattern

Mean radiant temperature

The MRT shows large variations among patterns as shown in Figure 44. In the southern and western part of the courtyard, MRT values are relatively low as they are shaded for most part. The patterns in which no or some trees are positioned along the eastern corner and facade, which are the Cornered, Two Sided Double Row and Perimeter patterns, MRT values are highest. For the Cornered pattern, MRT values reach up to above 71.80 °C. For the Two Sided Double Row pattern, values reach up to 69.60 °C and for the Perimeter pattern, maximum MRT values are 67.40 °C. Therefore, the Cornered pattern is the least effective pattern in reducing the share of maximum MRT values, followed by the Perimeter and Two Sided Double row pattern. The Clustered Double Row pattern is most effective in lowering MRT values with the largest part of the sun exposed courtyard experiencing MRT values between 36.60 °C and 45.40 °C. The second best performing pattern is the Double Row pattern.

Wind speed and direction

The slightly altered wind direction of 2.4 m/s coming from a 119 degrees angle in the late afternoon causes the wind to enter the courtyard in the area of the northern corner and fan out into a western, southern and eastern direction as can be shown in Figure 45. Along the western facade, wind speeds accelerate again. Similar to what was seen in the situation in the morning and afternoon, there are no large effects among patterns. In the Cornered pattern and the Baseline case, in which the northern part of the courtyard

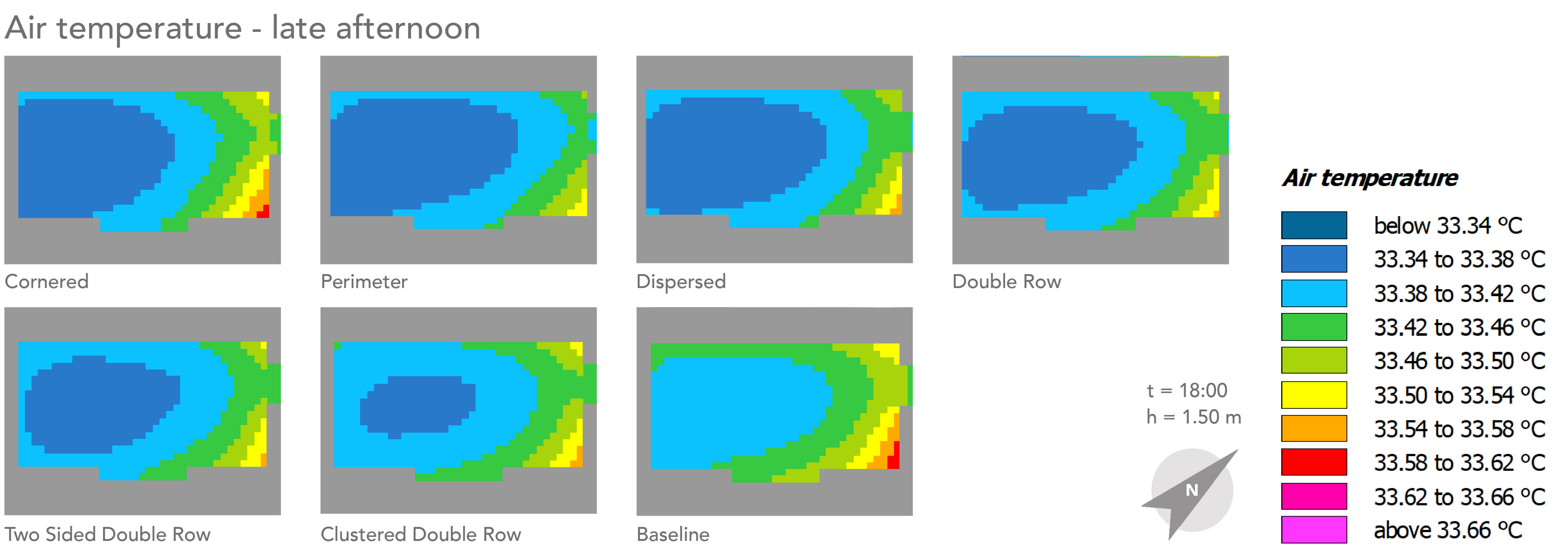


Figure 43. Simulation output of air temperature in the late afternoon (t = 18:00)

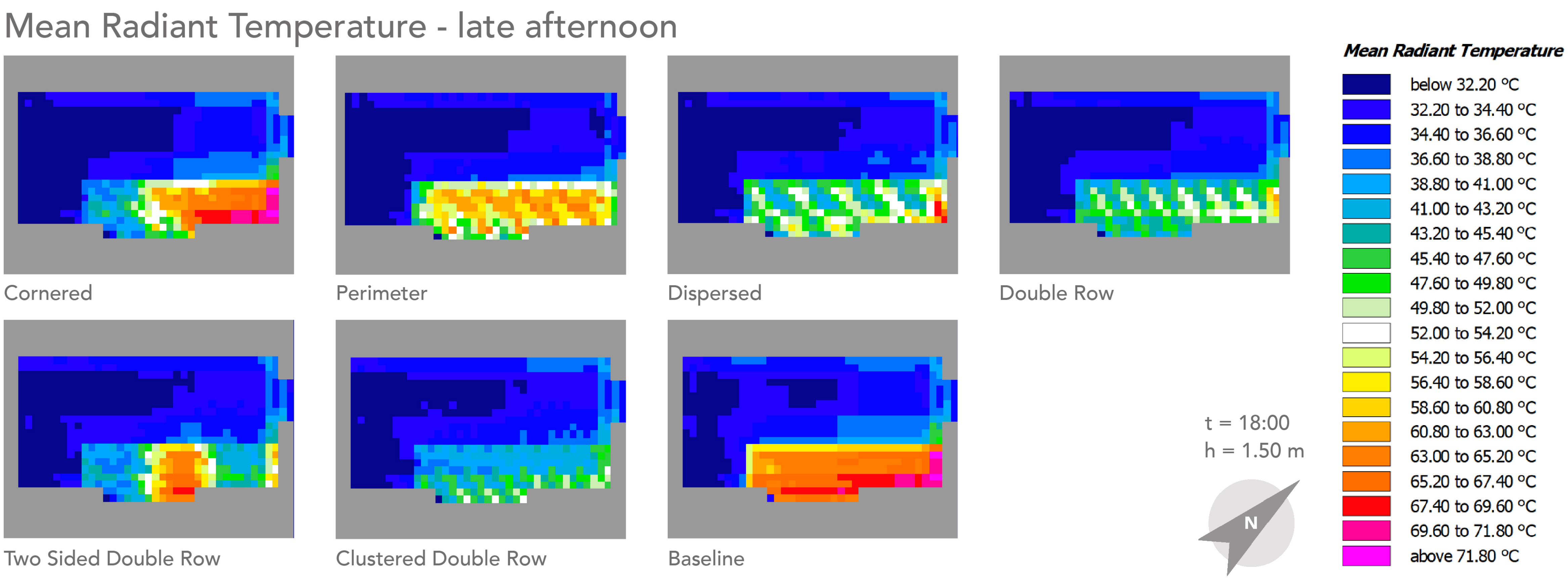


Figure 44. Simulation output of mean radiant temperature in the late afternoon (t = 18:00)

is clear, wind speeds are slightly lower compared to the other patterns.

Relative humidity

The relative humidity levels are shown in Figure 46. In general, the levels are relatively equal among patterns and vary from below 30.5% to 30.7% which is at the border of uncomfortable (Pijpers-van Esch, 2015). Towards the courtyard opening, relative humidity levels are higher and reach values of above 31.3%. Lowest overall levels are observed in the Clustered Double Row pattern followed by the Two Sided Double Row and Cornered patterns. The highest overall relative humidity levels are found for the Perimeter pattern followed by the Dispersed pattern. As higher relative humidity levels make it more difficult for a body to cool down through sweating, the Perimeter and Dispersed pattern are the least effective patterns in creating comfortable relative humidity levels.

PET

PET levels vary considerably across the different patterns as can be seen in Figure 47. Extreme heat stress is experienced in the parts of the courtyard that are still exposed to sun, which is along the eastern facade and in the eastern corner. The Perimeter pattern leads to the largest area (26.2%) of the courtyard in which extreme heat stress with PET values above 41 °C is experienced, followed by the Dispersed pattern (23.9%). Looking at the values of PET for the areas that are sun exposed however, the Cornered pattern has the highest share of PET values above 51 °C and is therefore the least effective pattern, followed by the Perimeter pattern. The Clustered Double Row pattern leads to the smallest area in which extreme heat stress is experienced (13.3%), followed by the Two Sided Double Row pattern (19.1%). From Figure 47, it becomes visible however that in terms of overall temperatures, the Double Row pattern is better performing than the Two Sided Double Row pattern. For the Double Row pattern, PET values are lower and range from 41 °C to 49 °C in most parts of the sun exposed courtyards. The Two Sided Double Row pattern might have a lower area in which values are above 41 °C (the threshold for extreme heat stress), but for these areas the PET values reach above 57 °C. Therefore, the pattern that leads to overall lowest PET

Wind speed and direction - late afternoon

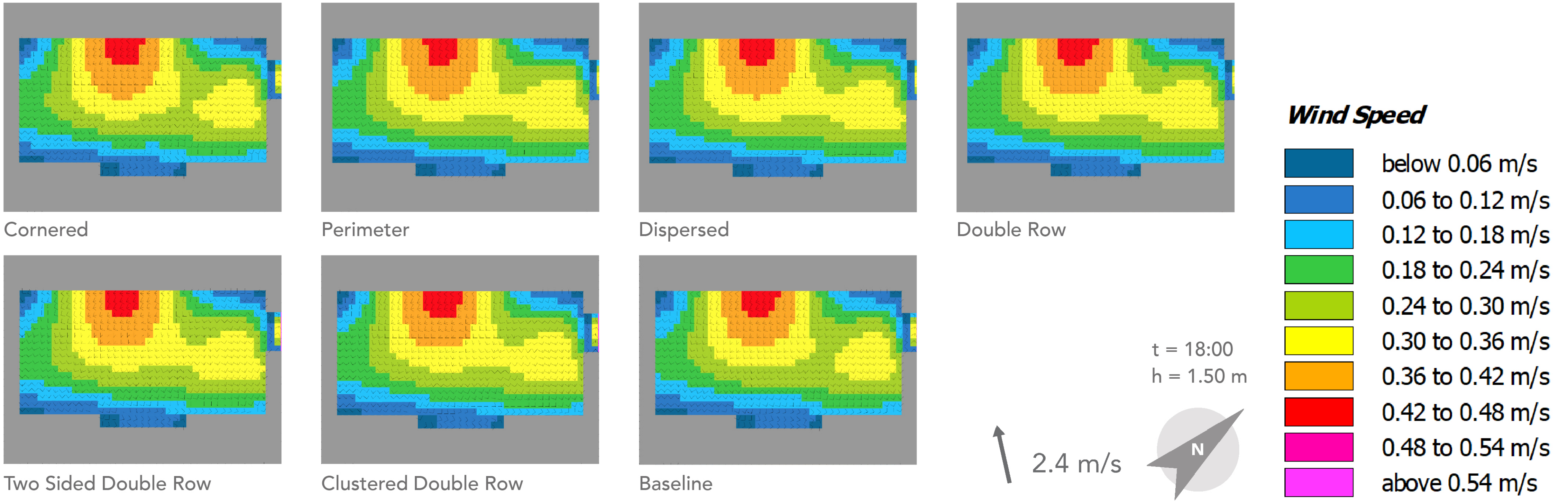


Figure 45. Simulation output of wind speed and direction in the late afternoon (t = 18:00)

levels and lowest share of the courtyard that experiences extreme heat stress is the Clustered Double Row pattern. The second best pattern in reducing extreme PET values is therefore the Double Row pattern. The mean share of the courtyard that experiences extreme heat stress at 18:00 is 21.2%.

Relative humidity - late afternoon

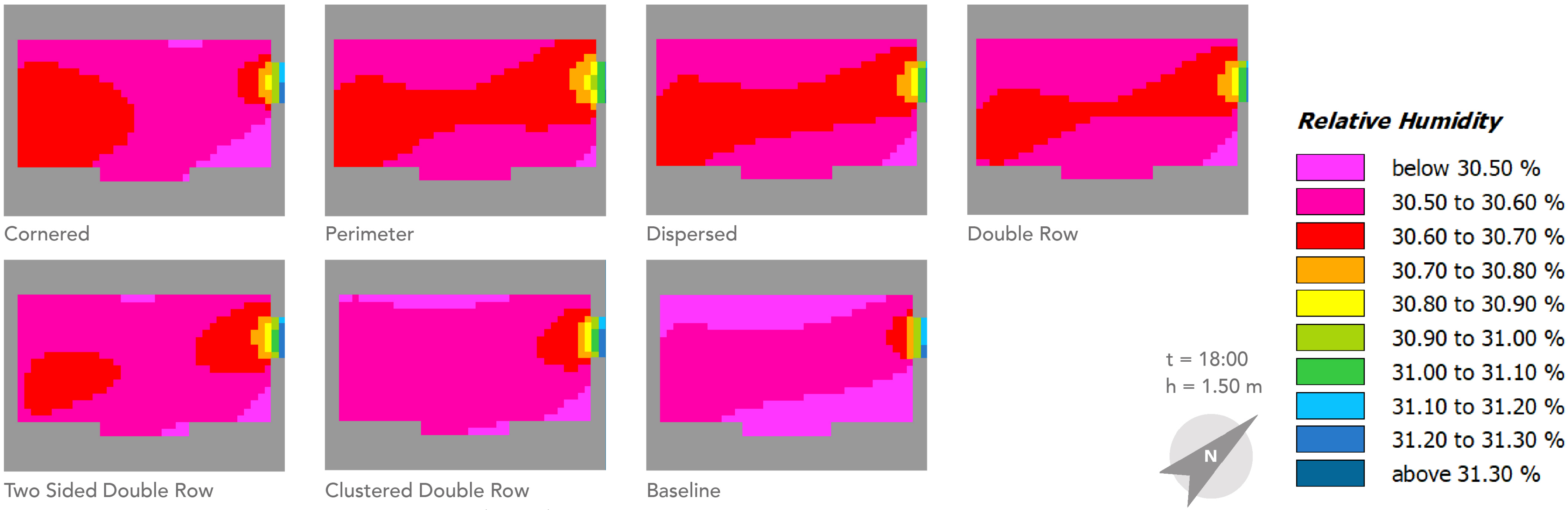


Figure 46. Simulation output of relative humidity in the late afternoon (t = 18:00)

PET - late afternoon

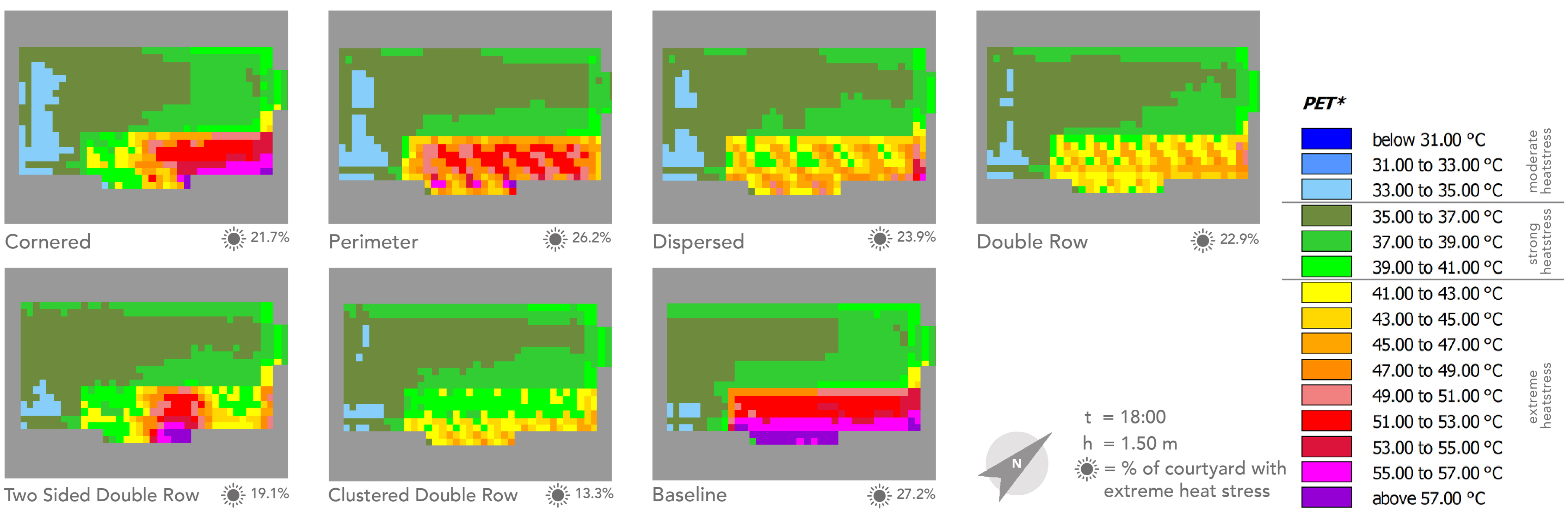


Figure 47. Simulation output of PET in the late afternoon (t = 18:00)

6.3 Interpretation of the results

In this section, the results of the simulation output that is presented in the previous section will be further explained. Per climatological parameter, an interpretation and further explanation of the results will be given.

Air temperature

Air temperatures in the courtyard vary considerably between morning, afternoon and late afternoon. Additionally, it is important to note that in general, the climatic boundary condition air temperatures varied between 31.5 ˚C and 35.4 ˚C as it was an extremely hot day for the Dutch climate. In the sun exposed corners air temperature is highest, which is the western corner and facade in the morning. The incoming radiation that is absorbed and reflected back into the courtyard causes this increase in air temperature in these areas. The shading of the building therefore has a large influence on the air temperatures in the courtyard. Next to the building, the trees also have an effect. As explained in Section 2.3, trees cool down their surrounding environment through evapotranspiration and shade. The air temperature reduction due to shading is visible for all tree planting patterns when compared to the baseline in the morning. The Dispersed and Double Row patterns result in the lowest air temperatures in this corner as they are the only patterns that do not experience maximum air temperature values of above 32.04 ˚C, making them the most effective patterns in reducing air temperature maxima. This can be explained by the fact that they have a higher density of shade along the western facade and corner as compared to the other patterns. This effect is also visible in the Cornered pattern on the side of the courtyard where trees are planted densely. In the afternoon and late afternoon, a similar effect is visible in which the northern corner has the highest air temperature because of the sun exposure. The various tree patterns exhibit slight differences in their effects on air temperatures. Patterns with densely planted trees in sun-exposed areas of the courtyard tend to result in lower air temperatures. Regarding evapotranspiration, the effect of trees is especially visible in the late afternoon. Even in the shadowed parts of the courtyard, the mere presence of trees slightly reduces the temperature as compared to the baseline case.

Mean radiant temperature

The largest effect among different patterns is visible when analysing the MRT. In general, MRT is very high for all the different tree configurations simulated on this specific day and reached up to above 83.0 ˚C. An important influencing factor in these high levels of MRT could be the materials of which the Lab courtyard is made. A possible explanation could be found in the thermal admittance of the material. The thermal admittance refers to how easily a material exchanges heat with its surroundings and a high thermal admittance means the material can heat up fast and cool down fast. Steel has a thermal admittance of 14 W/(m^2K) compared to for example 2 W/(m^2K) of concrete (Pijpers-van Esch, 2015). Next to that, the albedo of the material is very low and lies around 0.18 and indicates that a large portion of the incoming solar radiation is absorbed by the material. Within courtyards, the effect of the level of albedo and its effect on MRT is intricate. Research in a low aspect ratio courtyard by Lopez-Cabeza et al. (2022) showed that the different albedo levels of the floor material did not influence air temperature and MRT that much, but that the albedo of the surface materials did significantly influence MRT values within the courtyard as heat that is reflected by surface material cannot escape the courtyard easily but reflects off to different courtyard surfaces and is therefore trapped. A higher albedo of the material of courtyard facades generally leads to higher MRT levels, which is also confirmed in research by Haseh et al. (2018) and Taleghani (2018). From the simulated results in this thesis, it is not possible to say something about the different MRT for different albedo levels. Although the albedo is low, the heat that is reflected off the material of the facade is trapped within the courtyard space. Also, as heat is absorbed by the material and the material heats up, the emitted heat could be trapped according to the same logic which could explain the high levels of MRT. Figure 48 illustrates the high surface temperature levels resulting from the combined factors of the material's thermal admittance and low albedo. The Double Row pattern serves as an example in this case. Throughout the day, the surface temperatures vary quite significantly because of the high thermal admittance. In Figures 33, 38 and 44 this is also visible. In these figures, the blue areas represent the shaded regions of the courtyard, which are noticeably cooler than the sun-exposed areas. This high thermal admittance in combination with the low albedo levels, built up structure of the courtyards and low wind speed could be the explanation of high MRT levels. In the morning and late afternoon, the Clustered Double Row and Double Row patterns are most effective in reducing maximum MRT values. This could be attributed to the fact that the double row of trees with a low and perpendicular incoming solar radiation results in higher shade densities. This shade prevents solar radiation from reaching the surfaces and therefore lowers the MRT values significantly. In the afternoon, with almost the complete courtyard exposed to solar radiation, the dispersed shading of the Dispersed pattern resulted in the lowest area in which maximum MRT values are experienced.

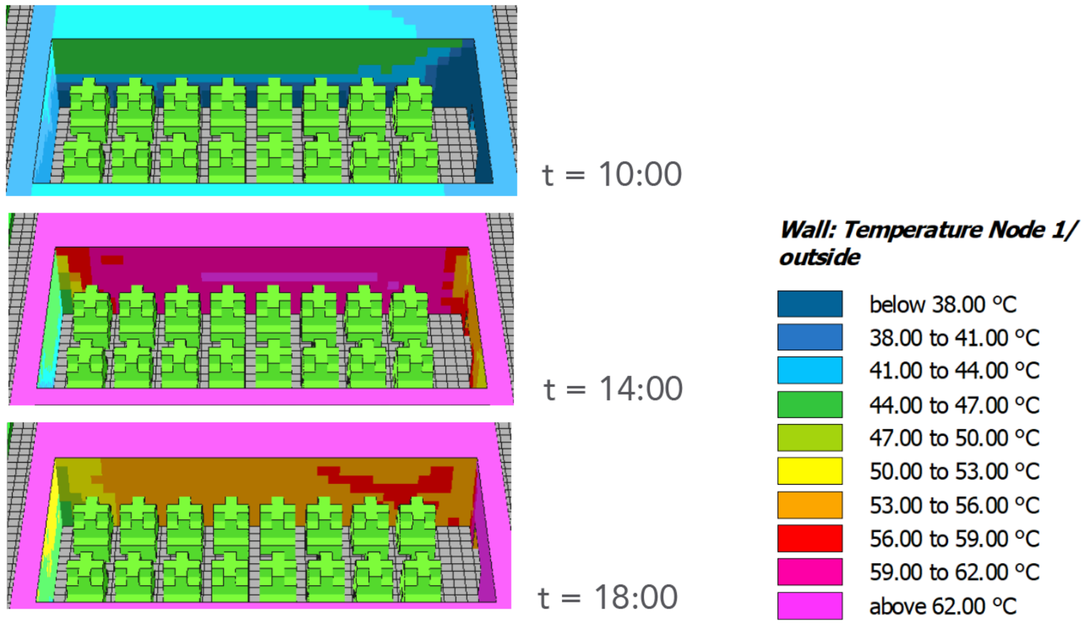


Figure 48. The different surface temperatures for the Double Row pattern for morning, afternoon and late afternoon

Wind speed and direction

Throughout the day, wind speeds within the courtyard varied between 0 m/s and 0.54 m/s, indicating a significant reduction from the climatic boundary condition of 2.4 m/s to 2.9 m/s. This reduction had an important negative influence on thermal comfort and can be mostly attributed to the courtyard building. When analysing the effect of tree planting patterns on wind speed and direction at 1.5 metres height, it appears that this specific type of tree has little to no impact, despite trees typically influencing wind flow significantly. In research by Zhang et al. (2018), it was found that placement of trees can often lead to obstruction of wind. However, it should be noted that the wind speeds simulated by Zhang et al. (2018) were 1 m/s, which is higher than the wind observed in these courtyard simulations and may have different influences. Also, research by Li et al. (2019) found that having tree planting patterns within a courtyard with open spaces (as was the case for the Cornered, Perimeter and Two Sided Double Row patterns) leads to wind being able to flow around more easily. These effects were not observed in this research. The most significant impact on wind flow was attributed to the courtyard building itself, acting as a crucial roughness element that obstructed wind and reduced its speed within the courtyard. This effect is confirmed when examining a vertical section (X-Z) of the courtyard simulation. For illustration purposes, Figure 49 compares the wind speed and direction for two of the six patterns. From this, it is visible that wind speeds do not vary considerably inside the courtyard, but that the wind direction is influenced by the different tree configurations at a higher level. Next to that, ENVI-met does not model the tree trunks and therefore there is no effect of the trees at 1.5 metres height on which the simulation has been executed.

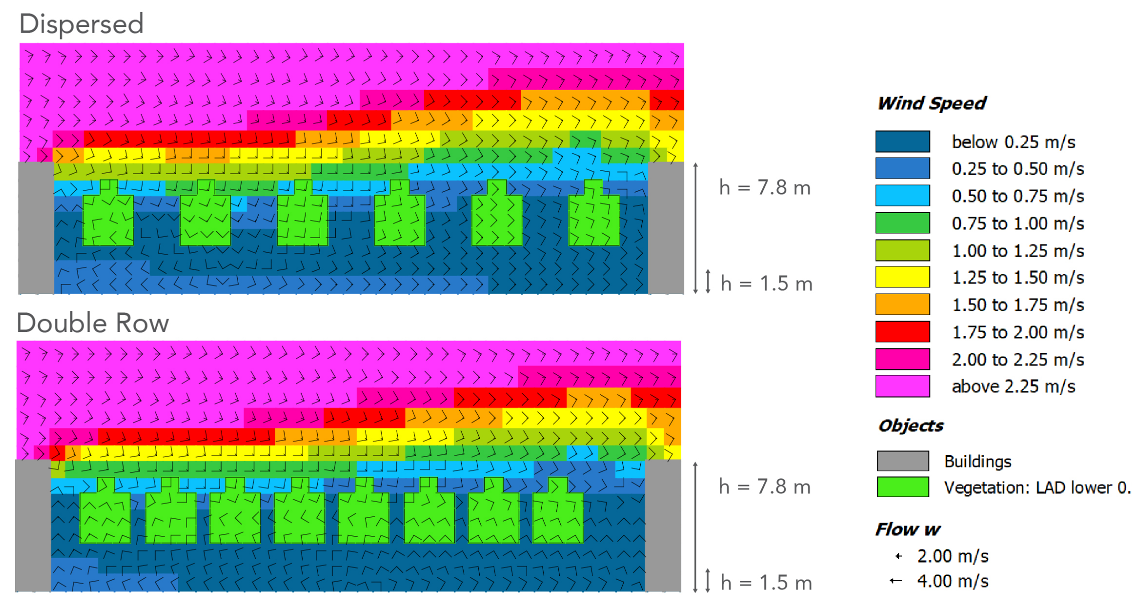


Figure 49. A vertical section of the Dispersed and Double Row pattern indicating the different wind speeds and directions.

Another noticeable aspect regarding the wind direction is that the wind in the courtyard flows in almost an opposite direction as compared to the outside environment. This can be explained by the direction changing effect of the building as explained by Oke (1988). As wind blows over, the wind blows onto the windward facade which pushes the wind downward into the courtyard therefore creating a flow of wind that is opposite to the wind direction in the simulation.

Relative humidity

Relative humidity levels vary during the day, but within the different time periods there are no large differences among patterns. An important influencing factor is the relative humidity level that was used as the boundary condition. In the morning, the relative humidity levels were slightly higher (between 37.15% and 38.35%) as compared to the boundary condition (37%). In the afternoon, relative humidity levels were slightly lower in the courtyard (between 23.01% and 23.49%) as compared to the boundary condition (24%). The same holds for the late afternoon where most parts of the courtyard experienced relative humidity levels between 30.50% and 30.70% as compared to the boundary condition of 31%.

The limited variation among patterns in relative humidity levels might be attributed to the low wind flows, as previous research by Li et al. (2019) has shown a relationship between moisture distribution and wind speed/direction. In general, lower relative humidity levels are favourable until 30%, as it allows the natural cooling process of the body to happen. For the morning and late measurements however, relative humidity levels are considered low and even at the border of uncomfortable with levels around 37% and 30% respectively. In the afternoon, the relative humidity level of 23% is considered very low and uncomfortable (Pijpers-van Esch, 2015). The simulation output shows that at 10:00, relative humidity levels in the sun-exposed parts of the courtyard are lower than in shaded areas. There is a slight increase in relative humidity in patterns where trees cast overlapping shades in these sun-exposed areas, such as the Cornered, Dispersed, Double Row, and Clustered Double Row patterns. At 14:00, low relative humidity levels are again most visible in the sun-exposed corner (the northern corner in this case) and the same effect of trees is visible. In the late afternoon at 18:00, lower levels of relative humidity are again visible in the sun-exposed corners, but the lower levels also seem to conglomerate according to the tree patterns in shaded areas. This could be caused by the lacking wind and the trees keeping the lower levels in place. However, the variations are very slight with a 0.10% difference.

The transpiration effect of trees is therefore not very noticeable in these simulation outputs although it showed to increase relative humidity in other courtyard research (Li et al. 2019). Several factors may explain this effect, including stomatal conductance in response to environmental conditions, the morphological characteristics of trees, and the properties of the surrounding soil or pavement (Winbourne et al., 2020). Little is known about the response of urban trees in relation to extreme heat such as the case in the simulated days, with some models assuming a decrease or stop in transpiration during a period of drought and warm weather (Teskey et al., 2014). Other research however suggests that this response is dependent on species and available water levels in the soil (Pataki et al., 2011). Also the area in which the tree is planted is an important influencing factor for the transpiration effect of trees. In research by Rahman et al. (2020), trees planted on a grass surface had transpiration rates ten times higher as opposed to trees planted in a paved environment as is the case in this model. These various factors may contribute to the limited impact of planted trees on relative humidity. However, as this is a simulation output, it is unclear which specific interactions among tree morphology, physiology, and environmental factors ENVI-met assumes and considers. ENVI-met has shown to underestimate relative humidity levels around trees in previous research, especially in hot conditions (Liu et al., 2018).

PET

When considering PET, extreme heat stress with PET values above 41 °C is experienced for large parts of the courtyard throughout the day. In the morning, the mean share of the courtyard that experiences extreme heat stress is 54.9%, in the afternoon 80.4% and later afternoon 21.2%. Additionally, PET values are above 57 °C for the largest parts of the courtyards throughout the day. These extremely high PET values can be explained by different reasons. One of the most important explanations is the fact that it was an extremely warm day considering the Dutch climate, with temperatures reaching up to 35.4 °C. Next to that, PET is based upon the different climatological parameters that are discussed above (Section 2.2). Some studies have found that air temperature is one of the main driving factors of PET (Song, 2011). In this simulation however, air temperatures vary slightly, but MRT values show clearer results in line with PET values, indicating it to be the most influential factor. This is because in warm conditions with minimal wind, the impact of MRT on the heat balance of the human body is approximately equivalent to that of air temperature (Höppe, 1999; Matzarakis et al., 1999). However, from comparing the simulation outputs of PET and MRT, it is evident that PET values are significantly lower than MRT values. MRT values exceed 83 °C, while PET values reach above 57 °C. MRT values reach up to above 83 °C and PET values up to above 57 °C. Therefore, the other climatological parameters influence PET as well. To get a deeper understanding of the influence of the different climatological parameters on PET, Table 4 gives an overview of the most and least effective patterns per parameter. The parameter of wind speed and direction has been omitted due to the minimal differences observed across patterns, which made it challenging to determine the most and least effective patterns. As the simulated output often showed values that were very close to each other, the several most and least effective patterns are noted in the table. A pattern is considered most effective when it leads to the lowest share of maximum values for a specific climatological parameter. On the other hand, a pattern is least effective if it results in the largest share of maximum values for the climatological parameter.

	Parameter	Most effective	Least effective
Morning, t = 10:00	Air temperature	Double Row, Dispersed	Two Sided Double Row, Perimeter, Clustered Double Row
	MRT	Clustered Double Row, Double Row	Cornered, Perimeter
	Relative humidity	Two Sided Double Row, Clustered Double Row	Double Row, Dispersed, Cornered
	PET	Double Row, Clustered Double Row	Perimeter, Cornered, Two Sided Double Row
Afternoon, t = 14:00	Air temperature	Perimeter, Dispersed	Clustered Double Row, Two Sided Double Row
	MRT	Dispersed, Double Row	Cornered, Clustered Double Row
	Relative humidity	Cornered, Perimeter, Dispersed, Double Row	Clustered Double Row, Two Sided Double Row
	PET	Dispersed, Double Row	Cornered, Perimeter
Late afternoon, t = 18:00	Air temperature	Perimeter, Double Row, Dispersed	Cornered, Clustered Double Row, Two Sided Double Row
	MRT	Clustered Double Row, Double Row	Cornered, Perimeter, Two Sided Double Row
	Relative humidity	Clustered Double Row, Two Sided Double Row, Cornered	Perimeter, Dispersed
	PET	Clustered Double Row, Double Row	Cornered, Perimeter

Table 4. An overview of the most and least effective patterns for the different climatological parameters

In the morning situation, the Double Row pattern shows the lowest share of the highest PET values, closely followed by Clustered Double Row making them the most effective patterns. When considering the other parameters apart from PET, the Double Row pattern is also the most effective pattern when considering air temperature as it leads to the lowest share of maximum air temperatures. Also the effectiveness of the Double Row pattern is visible when considering MRT, as it is the second most effective pattern in reducing maximum MRT values. The Clustered Double Row pattern is the best performing pattern for MRT, and the second best performing pattern for PET. As air temperature and MRT are the most influential factors for PET, it is therefore clear why these two patterns have lowest PET levels. Also, the Clustered Double Row pattern is the second most effective pattern concerning relative humidity as it ensures lower relative humidity levels. This influenced the PET levels for this pattern in a heat stress reducing way. In the afternoon, when temperatures rise to the maximum of 35.4 °C for that day, the influence of MRT on PET seems to increase. Considering the most and least effective patterns for MRT and PET, they are closely aligned. Overall, the Dispersed pattern performs best in reducing PET levels, followed by the Double Row pattern. In some areas of the courtyard, a decrease of 7 K in PET levels is observed compared to the baseline case. The Dispersed pattern is also the second best performing pattern for air temperature, which again indicates the influencing effect of air temperature on PET. The impact of MRT on PET is further evident when examining the least effective patterns, which result in larger proportions of the courtyard experiencing maximum MRT and PET values. The least effective pattern for MRT, the Cornered pattern, is also the least effective pattern for PET. Also the influence of the presence of wind is visible in the PET simulation output. Even though it is difficult to make inferences about the least and most effective patterns on wind speed and direction, the mere presence of wind reduces PET levels. This is visible in the middle of the western facade where the wind speed increases for all patterns as the PET levels are slightly lower there. In the late afternoon, PET follows MRT completely considering the most and least effective patterns indicating that the influence of MRT on PET is increasing throughout the day. Also, similar most and least effective performing patterns are visible for air temperature and relative humidity and PET.

The distribution of PET values in the courtyard follows the distribution of MRT closely, especially in the afternoon and late afternoon. For the other climatological parameters, the difference between patterns per parameter is not significantly large. Because of this lack of significant variations, there is little influence of the different parameters on the distribution of PET levels. However, this does not entail that they are not influential. For example for air temperature, the lower courtyard air temperatures compared to the MRT values do influence PET in a way that PET values are lower compared to MRT values. Also, the lower wind speeds in the courtyard have caused higher PET values. Similar logic holds for the other climatological parameters. During the morning and afternoon when some parts of the courtyard are covered by the shade of the building, the Double Row and Clustered Double Row patterns with more densely planted trees in the centre are most effective. However, during maximum sun exposure in the afternoon, the Dispersed pattern is most effective. This could be related to the shading density. During the morning and afternoon when the sun enters the courtyard at an angle, the densely planted trees in the centre have overlapping shades. This effect is enforced by the planting orientation of the trees (Liu et al., 2020), which is NE-SW. This could have resulted in solar radiation having to enter through two canopies of leaves increasing the amount of solar radiation that is absorbed by the leaves. This results in a denser shade and thus less heat absorption and warming of the environment (de Abreu-Harbich et al., 2015). During the afternoon, the most evenly dispersed shading created by the Dispersed pattern is most effective in decreasing PET levels.

Next to the influence of different climatological parameters on PET, the greenery coverage ratio (including trees) could be a possible explanation for the fact that extreme heat stress is experienced in most parts of the courtyard throughout the day. Based on the analysis of the historic hofjes in Amsterdam, a 30% tree coverage ratio was chosen to fit the Amsterdam urban context. As more extreme weather events with increasing heat are expected in the future, the prevalent tree coverage ratios might not be sufficient anymore. In research by Haseh et al. (2018), the study found that for a courtyard in Iran, a minimal greenery coverage ratio (including grass and trees) of 50% is advised to ensure thermal comfort in courtyards. Although the general greenery levels (including trees) in hofjes is 48.9%, only trees and their patterns were part of this research scope. Either increasing this ratio to 50% or adding other types of vegetation up to 50% could potentially increase thermal comfortability.

7. Discussion and Conclusions

This chapter starts with a summary of the main findings of the three different sub questions of this thesis, a reflection on their findings and a discussion of the limitations. After, the main research question is addressed and the scientific and societal relevance of these research findings are discussed.

7.1 Tree configuration literature research

The first sub question of this research aimed to discover optimal configurations of trees to reduce heat stress in a courtyard setting according to existing literature. Although research on tree patterns has seen an increase in interest over the past decade, research remains relatively scarce and even more scarce when considering courtyards specifically. In this thesis, studies on different tree planting patterns have been reviewed, both for the general urban context as well as courtyards. In the general urban context, density plays a crucial role, and planting trees at a distance from each other equal to their crown has been shown to be most effective regardless of the pattern. As a rule of thumb, the distance between two trees should be smaller than two times the height of the trunk. Next to density, orientation also plays an important role with a north-south orientation resulting in shade maximisation. Additionally, planting in the shade of the building offsets the cooling effect of trees.

Regarding the effect of different planting patterns on reducing heat stress in the general urban context, the existing literature showed that three tree planting patterns are most commonly researched. These are: a rectangular tree planting pattern with trees planted in different densities, double row tree planting pattern and a clustered tree planting pattern. The rectangular and double row tree planting patterns were often found to be effective, but the results for clustered tree planting patterns were often very ambiguous. When looking more specifically at the scarce literature that is available on tree planting patterns in courtyards, trees planted in the sun facing corner and trees planted along the perimeter were most researched. Based on these findings, four tree planting patterns were identified for this research: the Cornered pattern, Perimeter pattern, Dispersed pattern, and Double Row pattern.

Reflection and limitations

The methods used to address this sub question are subject to several limitations. For doing the literature research, first Google Scholar has been used to get a basic understanding of the important terminology after which a boolean search consisting of different keywords has been conducted on Scopus. Limitations of the literature search include the exclusive use of Scopus, which may have resulted in the omission of relevant literature from other databases. Also, the combination of the keywords used (see Section 3.1.1) could have resulted in a non-extensive find of research articles that were considered for this study as more or different keywords would have yielded different results. Next to that, this part of the research has gathered input from studies conducted in all parts of the world because of the scarcity of literature. Microclimates are however very context specific, so general guidelines that have been derived based on literature in a certain context might not apply to other contexts.

7.2 Hofjes Analysis

The second sub question of this research focused on whether prevalent tree planting patterns could be derived from a qualitative and quantitative analysis of hofjes in Amsterdam. This was done by quantitatively and qualitatively analysing hofjes' geometries and their tree planting patterns. After, these patterns were mapped. This qualitative and quantitative analysis was performed by looking at the tree and greenery coverage ratio, planting distance of trees to building, number of trees, height to width ratio, width to length ratio, orientation and their shape. The mean tree coverage ratio of courtyards is 24% with a standard deviation of 18%. The mean greenery coverage ratio (including trees) is 48.9% with a standard deviation of 19.9% and the mean planting distance of trees is 3.5 metres with a standard deviation of 1.8. The mean height to width ratio is 1.1 with a standard deviation of 0.6 and the mean width to length ratio is 0.6, with a standard deviation of 0.4. The most common orientations are east to west and north to south. Per hofje, the quantitative parameters have been qualitatively assessed with established labels.

After, the tree planting patterns have been analysed by using a method that has been developed in this research, based on the study by Yang et al. (2018). For this analysis, the hofjes were considered as two canyons, with one referred to as the long canyon and the other as the short canyon. From the perspective of each canyon, a ratio was derived which was the mean distance between the building and the tree trunk (indicated by ds for the short canyon and dl for the long canyon) to half the width of the canyon (indicated by DS for the short canyon and DL for the long canyon). To classify the tree placement, half the canyon width was divided into three in which the part closest to the building was marked as the perimeter, the part closest to half the canyon was indicated as the centre and the part in between as the midway. All different combinations of the two different ratios per hofje have been plotted in a scatterplot. From the scatterplot analysis, it became apparent that 62.9% of the hofjes have a tree planting pattern in which the average tree is planted within the midway area from the perspective of the shorter canyon and in the midway or centre area from the perspective of the longer canyon. 44.1% of the hofjes have a tree planting pattern in which the trees are planted in the centre along the long canyon and midway and centre of the short canyon.

Based on these findings and the earlier classification of hofjes, nine different hofjes have been selected with similar geometries and mapped to get a better understanding of their tree configurations. Based on the findings of this sub question, the exact placement and number of trees for the different earlier established planting patterns were established and two patterns were added based on the tree pattern analysis of hofjes. These patterns were called Two Sided Double Row and Clustered Double Row.

Reflection and limitations

There are some limitations to the methods adopted in this chapter. The ratios used in this analysis focus on the distance between the building and half of the courtyard's width, providing information about only one side of the courtyard. Symmetry in tree planting patterns is not implied, but the ratio does not say something about on which half of the courtyard the tree is placed. This was especially of influence for courtyards in which only one tree was planted. However, since the mean number of trees planted is 4 - 5 trees, there were only a few cases with one tree and therefore the results are only slightly influenced. Next to that, the ratios are based on the mean tree planting distance and therefore overlooks individual distances of trees. The mapping of hofjes with similar classifications in this sub question revealed that the method used is generally valid for most patterns. However, for highly dispersed tree planting patterns, the fact that the ratio is based on the mean tree planting distances yielded somewhat skewed results. For dispersed planting patterns, the method favours the midway output because it looks at the mean distances to buildings. Suggestions for future research and development of this method are therefore made in the next chapter.

Additionally, the calculation of tree coverage ratios and distances to buildings involved overlaying Google Earth imagery and utilising downloaded OBJ files from 3Dbag. These files were then used for calculations in Rhino with the assistance of the Grasshopper plugin. However, the building outlines in the OBJ files occasionally deviated slightly from the actual outlines observed on Google Earth. Additionally, determining the precise location of the hofje's plot border posed challenges, especially when the hofje had a U or L shape rather than a full courtyard shape. Google Earth imagery is not always captured from directly above but at an angle, making it difficult to determine exact borders. These borders were also sometimes visually blocked by tree canopies. This potentially resulted in slightly different tree coverage ratios then the real world environment. When it comes to the trees, not all hofjes had extensive imagery available online nor were they all publicly accessible which may have resulted in trees being overlooked.

7.3 Microclimate simulation of courtyards and tree patterns

In the third sub question, the established tree planting patterns were modelled in ENVI-met 5 to determine their effect on air temperature, mean radiant temperature, wind speed and direction, relative humidity and PET. The objective was to determine which pattern was most effective in reducing heat stress at three moments of the day, being the morning (t = 10:00), afternoon (t = 14:00) and late afternoon (t = 18:00). The modelled day was the 19th of July, 2022 which was the hottest day of the year with temperatures reaching up to 35.4 °C. Throughout the day, extreme heat stress with PET values of above 41 °C was measured in most parts of the courtyard. In the morning, the mean share of the courtyard that experienced extreme heat stress across the different patterns was 54.9%. In the afternoon, this value increased to 80.4% and decreased to 21.2% in the late afternoon. The Dispersed, Double Row and Clustered Double Row patterns were the most effective patterns in creating the smallest area in which maximum PET values were experienced. In the morning and afternoon situation with parts of the courtyard covered by the shade of the building, the Double Row and Clustered Double Row pattern were most effective in reducing the share of maximum PET values in the courtyard. These are patterns in which trees are planted more densely in the centre of the courtyard on a NE-SW orientation. These two factors resulted in shade maximisation and therefore highest effectiveness. The Double Row pattern was most effective in the morning and the Clustered Double Row pattern was most effective in the afternoon. In the afternoon, during the hottest part of the day, the dispersed pattern with more evenly spread shade was most effective and temperature reductions of up to 7 K were experienced as a result of planting the trees.

The observed PET levels are based on air temperature, wind speed and direction, relative humidity and mean radiant temperatures experienced in the courtyard. For air temperature, wind speed and direction and relative humidity, little differences were observed between patterns at the three different moments of the day. The arrangement of trees had minimal impact on wind speed or direction, as the courtyard itself played the primary role in reducing wind speeds. The wind speed in the courtyard was below 0.54 m/s throughout the day although the climate boundary wind conditions varied between 2.4 m/s and 2.9 m/s for the different moments of the day. Similarly, there was minimal variation in air temperature among the different patterns. Compared to the baseline case, air temperatures were slightly lower because of the evapotranspiration of trees, but the largest effect on air temperature also came from the shadow caused by the courtyard building. When it comes to relative humidity, general levels throughout the day are low and vary between 23% and 38%. Although slight variations with higher relative humidities were observed in densely planted areas, no significant differences were observed between the patterns. A possible explanation could be related to the fact that the trees were planted in a paved environment which hinders their transpiration flow. Another possible explanation could be that the tree's transpiration is influenced by extreme heat, although large uncertainty remains regarding the calculation processes in ENVI-met to be able to make strong inferences. Mean radiant temperature exhibited significant variations between the patterns during the three different moments of the day, with maximum values exceeding 83 °C. The high mean radiant temperatures are explained by the high temperatures on that day and the material of which the courtyard in the Lab is built. The steel has a very high thermal admittance, low albedo and therefore high surface temperatures which are reflected off into the courtyard. Also, because of the courtyard shape and low wind speeds this emitted heat stays trapped increasing mean radiant temperature levels.

When considering the influence of various climatological parameters, mean radiant temperature had the most pronounced effect, with PET simulation output closely reflecting the variations in mean radiant temperatures. The other climatological parameters did have an overall effect on PET levels as well, but no pattern specific effects.

Reflection and limitations

Linking these findings back to previous research regarding tree planting patterns in courtyards, the effectiveness of the Dispersed pattern was also found in research by Li et al. (2019). The study did not consider PET however, but found that a dispersed pattern resulted in the largest decrease in air temperature in certain parts of the courtyard. Although this effect was not visible in this research, the effectiveness of a dispersed pattern was confirmed as well. In their research, the pattern that created the overall largest average decrease in air temperature was a pattern similar to the Cornered pattern of this research. This effect was not seen in this research, which could be related to different wind conditions. In their research, wind speed within the courtyard varied between 0 and 2 m/s and the courtyard opening was directly aligned with the direction of the wind. In the courtyard study by Manneh & Taleb (2017), a more evenly dispersed tree planting pattern resulted in lowest PMV levels (which is another bio-climatological index like PET). However, no other similar patterns to the ones in this research were considered. The same counts for research by Mundra & Kannamma, where different variations of a perimeter planting pattern have been tested. In this research, the Perimeter pattern was among the least effective patterns in reducing heat stress. The effectiveness of a double row tree planting pattern, as observed in previous research by Atwa et al. (2020), Morakinyo & Lam (2016), and Zhao et al. (2018), is confirmed in the courtyard setting. In the aforementioned research, the balancing act between the double row pattern and its effect on wind speed was mentioned as an important factor but as wind speeds were hardly influenced in this research, this effect did not happen in this research. With regards to the general ambiguous effect of clustered tree planting, this research positively confirms the effect of a more clustered tree planting pattern (which is the Clustered Double Row pattern) (De Abreu-Harbich et al., 2015; Rahman et al., 2020; Zhao et al., 2020).

This part of the research also comes with several limitations. An important limitation is the use of the ENVI-met simulation software. ENVI-met is one of the most widely adopted programs for outdoor microclimate simulations and has proven to have high accuracy in different urban settings (Fu et al., 2022; Morakinyo & Lam, 2016). In courtyard settings however, important limitations of the accuracy of ENVI-met have been highlighted in research by Lopez-Cabeza et al. (2018). Three different courtyards were tested in which the model was validated with real life measurements. The modelled output had high R-squared values ranging from 0.84 - 0.93, but the study concluded that for small sized courtyards (ranging from 7-13 metres in length and width in their research) and especially deep courtyards (H/W > 1.3), air temperature was not accurately modelled. As the modelled courtyard in this research is at least twice the size and has a considerably lower height to width ratio (0.43), these limitations do not apply. Also in different courtyard studies with similar courtyard dimensions, high accuracy has been established between ENVI-met and real world data (Ghaffarianhoseini, 2015; Taleghani et al., 2014). Next to that, the model used in this research has been validated for the baseline scenario but not yet for trees (Wuite et al., 2023). Due to time constraints and a planned validation in July 2023, the validation of the model with trees still needs to happen. This negatively influences the reliability of these research findings up to a certain degree as the model holds validity to a certain degree because of the validation of the bare courtyard. Whether the chosen trees in the model result in modelled effects equal to the real world requires validation however. In addition to the model's accuracy the method used to determine the effectiveness of the patterns has certain limitations. A pattern was deemed most effective when it resulted in the smallest area in which the highest value of the climatological parameter was present. This is however a simplified way of considering effectiveness as other assessment methods were out of scope for this research. Additionally, the simulated weather conditions were exceptionally warm. There were extreme temperatures and the wind was blowing from an uncommon direction (east/south east) as the prevailing wind in The Netherlands comes from the southwest. This could have potentially influenced simulation results as wind is often mentioned as a crucial factor. Also, the material of the courtyard is an important limitation to this study. The courtyard in this lab was constructed with metal shipping containers with specific properties that influence the thermal comfort within the courtyard. Although the influence of trees was still measurable, extreme mean radiant temperatures were observed as a result of the material. This could potentially have influenced the effectiveness of trees. Also, the courtyard was located in a rural environment and not a densely built urban environment. The material and location of the courtyard therefore make it harder to generalise the findings of this simulation.

7.4 Addressing the main research question

This research addressed the question: "*What configuration of trees is most effective in reducing heat stress in courtyards in the Amsterdam Metropolitan Area?*". From this research, six different tree planting patterns have emerged. Four of these patterns were derived from literature and were the Cornered, Perimeter, Dispersed and Double Row pattern. From an analysis of the tree planting pattern of hofjes in Amsterdam, two more patterns called the Two Sided Double Row and clustered Double Row patterns were chosen because of their prevalence in hofjes. The planting distances and tree coverage ratios of all patterns were based on this hofjes analysis, resulting in six tree planting patterns fitting to the Amsterdam Metropolitan context. Through simulations, the Dispersed, Double Row and Clustered Double row patterns have shown to be most effective in reducing heat stress at different times of the day with reductions up to 7 K as compared to the scenario without trees. At 10:00 in the morning, the Double Row pattern was most effective and resulted in the lowest share of the courtyard that experienced maximum PET values. At 14:00 in the afternoon, the Dispersed pattern was most effective and in the late afternoon at 18:00, the Clustered Double Row pattern was most effective. The Double Row and Clustered Double Row are similar patterns with two rows of trees along the length of the courtyard and in this scenario, they were planted in a NE-SW orientation. This type of pattern with two rows of trees (with different distances between the rows) has shown to be most effective with lower incoming solar radiation in the morning and afternoon as this creates dense shade. The Dispersed pattern is however most effective in reducing maximum PET values at 14:00 during the hottest part of the day with maximum sun exposure and can therefore be considered the most effective tree configuration to reduce heat stress in the Amsterdam Metropolitan Area.

7.5 Scientific and societal relevance

There are different scientific and societal relevances pertaining to the different parts of this research. The literature review provides an overview of the available literature on tree planting patterns and more specifically in a courtyard setting. This overview can be used as a basis for researchers as a starting point for other research into the effect of tree configurations on heat stress. This part of the research can also provide an overview of anyone trying to get an understanding of the effect of trees in different urban settings. Therefore, urban designers and municipalities can use this information in their pursuit of creating liveable and healthy cities.

The analysis of the hofjes and their tree planting pattern provides a method to analyse tree planting patterns in courtyard that has been developed based on a method adopted in a canyons study by Yang et al. (2018). The method established in this study is an integrated qualitative and quantitative analytical method and can be used and further developed in different courtyard studies. Additionally, the extensive analysis of hofjes in Amsterdam provides insights into the characteristics of hofjes in Amsterdam and could potentially be used by the municipality, city planners or architects when designing new courtyards fitting the Amsterdam urban context. The analysis of hofjes also contributes to the preservation and promotion of traditional urban design which fosters a sense of culture and identity specific to the Amsterdam Metropolitan Context. The findings allow for this cultural and contextual significance to be integrated into the design of courtyards whilst also providing effective tree planting patterns in reducing heat stress, as the Clustered Double Row planting pattern was both prevalent and effective in reducing heat stress.

Next to the aforementioned contributions, this research contributes to the scarce knowledge currently available on the influence of different tree configurations on heat stress in courtyards. The increase in expected heat extremes in the Netherlands comes with potential major health concerns and increased urban heat island effects and therefore, it becomes increasingly important to expand this knowledge. Although the findings of this thesis are contextual to the climatic region, material and courtyard geometry, the findings do create more insight into the effectiveness of different tree planting patterns. These findings have a twofold value. On the one hand, they can help to raise awareness among municipalities, city planners and citizens regarding the level of extreme heat stress that is experienced and is expected to be experienced in the coming decades. On the other hand, the findings provide insight for municipalities, city planners and architects on tree planting patterns in courtyards. When designing courtyards, different patterns can be considered based on their effectiveness to reduce heat stress. The Dispersed, Double Row and Clustered Double Row can be considered based on their effectiveness in this study. These findings on effectiveness of patterns can be combined with other factors such as the use of the courtyard space to create climate resilient and sustainable urban environments with comfortable microclimates that foster social cohesion. These cooler microclimates can also play an important role in reducing the energy demand of buildings for active cooling systems during heat waves and therefore the total energy consumption of cities. Additionally, the findings of this research identify other important factors that could be taken into account and their interrelation with trees, such as orientation to the sun and wind, and height to width ratio of the courtyard.

8. Suggestions for Future Research

This thesis studied the effect of different tree configurations on heat stress in a courtyard. Through a literature review, analysis of hofjes in Amsterdam and a model simulation, the effectiveness of six different patterns has been assessed. Based on the findings of these different research steps, suggestions for future research are made in this chapter.

Regarding the literature review, a more extensive analysis of the existing literature could be done by including more databases from which scientific articles can be retrieved. Also, the scope of the literature study could focus specifically on the Dutch climate, certain tree species or specific tree configurations.

Additionally, the proposed method in this research for analysing tree planting patterns could be further developed to increase the accuracy. As a suggestion for further adaptations of the method, individual planting distances of trees to buildings could be considered instead of the mean distances. Also, instead of taking the ratio of the planting distance of the tree to half the width of the long or short canyon, the full length or width could be considered. Based on individual planting distances, a scatterplot per courtyard could be made which could all be overlaid to derive certain hotspots for planted trees. Next to that, more advanced methods for the analysis of hofjes could be considered to increase accuracy in tree and greenery coverage ratios.

Regarding the courtyard simulations, there are numerous future research possibilities. The impact of different building materials, for example bricks, should be further explored to determine the influence of the steel material in this research and to increase generalisability of the findings. Moreover, a different setting closer to the Amsterdam urban environment could be modelled as opposed to the rural environment the Lab is currently in. Also, the different tree planting patterns could be further explored by for example increasing the coverage ratio of the trees, testing different densities or different types of trees. Especially different tree characteristics such as crown shapes and diameters and trunk heights are aspects that have been mentioned in research to influence the effectiveness of trees to reduce heat but have been out of scope in this research. Next to trees, the effect of adding different vegetational types such as grass and shrubs could be further explored as well.

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Appendix

Appendix A

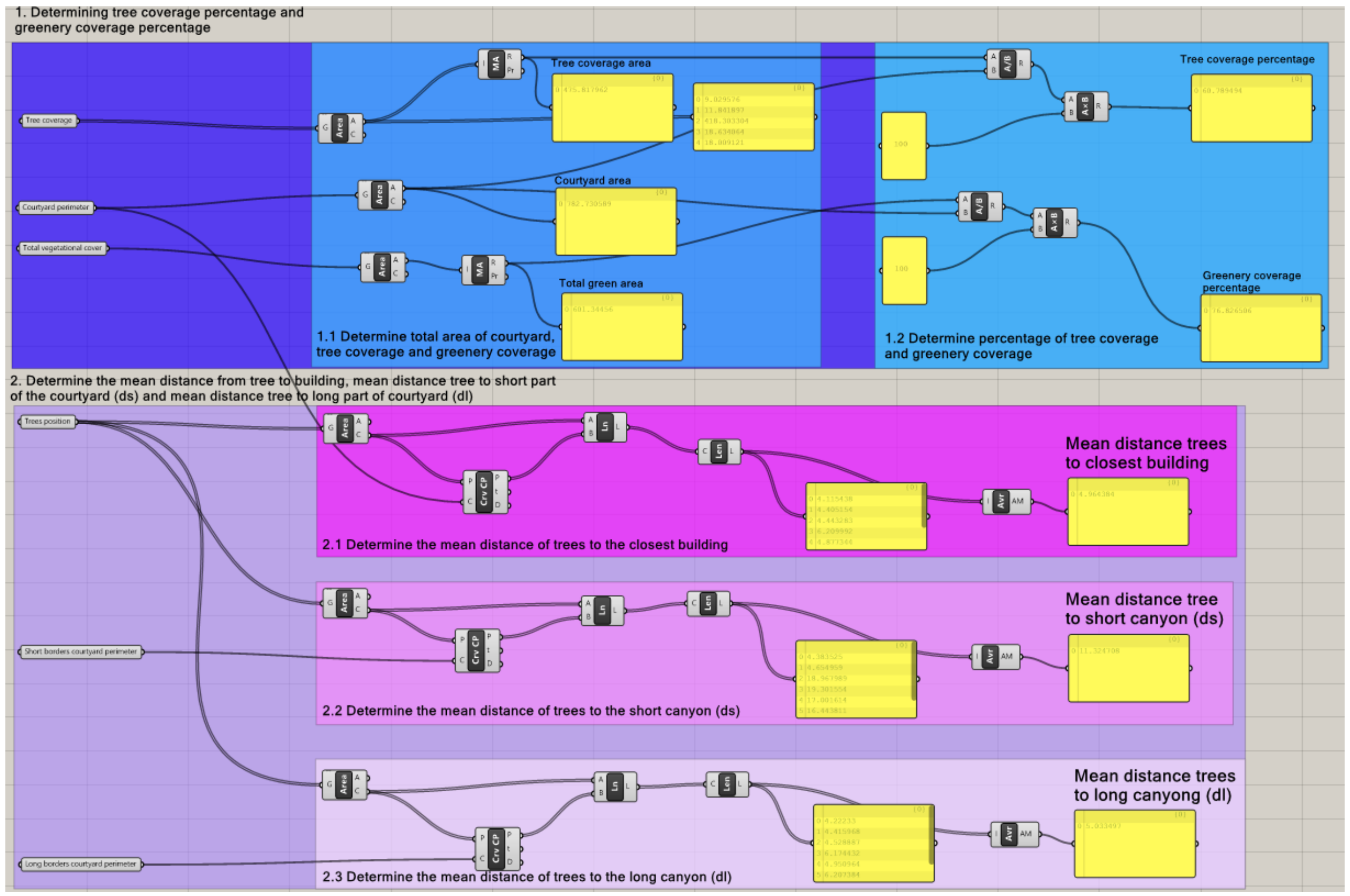

Figure 50. The Grasshopper workflow

Figure 50 gives a full overview of the workflow in Grasshopper. The workflow was divided in two parts and as an illustrative example, the workflow of Rhino 7 and Grasshopper for one of the hofjes is given. The Grasshopper workflow is divided into two steps. To link the Grasshopper to the Rhino 7 file, the Rhino file has to be created first and different polygons have to be drawn.

To prepare the Rhino file, the OBJ file from 3DBag is downloaded and cleaned to get the outline of the needed hofje. A screenshot from Google Maps is then laid under this outline and aligned. Next, the inner courtyard perimeter/boundary is drawn within the map (in orange in the example). Next, the outline of all the different tree coverages is created (in red in the example). For trees that have large and overlapping coverage, the position of the trunk is indicated with an extra circle in the tree coverage as this is of importance to determine the distance to the building. Next, the total greenery coverage is outlined (using green in the example). Also, the long and short side of the courtyard are indicated with the magenta lines in the example. Figure 51 gives an example of such a prepared Rhino file.

Figure 51. An example of a prepared Rhino file of a hofje (Karthuizerhofje)

Moving to the Grasshopper workflow, there are 2 steps. The first step pertains to determining the tree coverage ratios, greenery coverage ratios and total courtyard areas of all the hofjes. In step 1.1, the tree coverage component is linked to the tree coverage outline (in red) in the Rhino file. The total are is then calculated with the 'Area' function, after which the 'Mass Addition' (MA) function calculates the total tree area. Similar steps are performed for the courtyard perimeter and total vegetational cover. In step 1.2, the different ratios are calculated by dividing the total coverage area of trees or greenery by the total courtyard are by using the 'Division' (A/B) function. Next, the output of this function is multiplied by 100 through the 'Multiplication' (AxB) function. This step is repeated for both the trees as well as the total greenery area.

In step 2 of the workflow, the mean distance to the building, mean distance of trees to short side of the courtyard (ds) and mean distance of trees to long side of the courtyard (dl) is given. First, for the mean distance of trees to buildings in step 2.1, the tree position is linked to the 'Area' function. From the area function, the C (which stands for the centre of that area) is linked to the P of 'Curve Closest Point' (CrvCP) function, which indicates the point. The CrvCP function is linked to the courtyard perimeter. The output of this function is then linked to the 'Line' (Ln) function to draw a line from the centre of the tree to the building and with the 'Length' (Len) function, the length is determined. As a last step, the 'Average' (Avr) function determines the mean distance. This step is repeated for 2.2 and 2.3. The difference for those steps is that the 'Closest Point to Curve' function is not linked to the courtyard perimeter, but to the long and short canyon of the courtyard.

Appendix B

Name	tot. m2 tree coverage	tot. m2 greenery coverage	tot. m2 courtyard surface	% tree coverage	% greenery coverage	ds	dl	Mean dist. tree to building	dl:DL	dl:DL class.	ds:DS	ds:DS class.
Begijnhof	508.5	1697.3	2577.9	19.7	65.8	19.6	6.6	6.1	0.33	Perimeter	0.46	Midway
Bossche Hofje - Het Raepenhofje	3.9	39.5	137.7	2.8	28.7	7.8	3.8	3.8	0.95	Center	0.92	Center
Catharinahofje	31.4	110.0	203.8	15.4	54.0	6.7	2.9	2.9	0.84	Center	0.67	Midway
Claes Claeszhofje (Anslo + Zwaardvegershofje)	9.0	22.7	97.3	9.2	23.3	7.6	2.2	2.2	0.90	Center	0.90	Center
Claes Reinierszhofje	22.2	78.6	326.9	6.8	24.0	6.5	6.1	5.3	0.77	Center	0.65	Midway
Concordiahofje Noord	156.6	395.0	527.5	29.7	74.9	10.1	4.2	3.0	0.70	Center	0.52	Midway
Concordiahofje Zuid	220.2	520.2	682.8	32.3	76.2	6.3	5.2	4.4	0.69	Center	0.36	Midway
Constantia Hofje	263.8	264.5	374.4	70.5	70.6	7.0	3.5	3.2	0.47	Midway	0.63	Midway
Deutzenhofje	154.2	383.9	685.5	22.5	56.0	9.8	6.2	5.4	0.59	Midway	0.65	Midway
Elisabeth Otter-Knoll Stichting	98.1	224.1	393.2	25.0	57.0	3.9	5.6	3.5	0.56	Midway	0.39	Midway
Everdina de Lanoyhof	45.8	117.2	277.7	16.5	42.2	7.5	4.6	4.7	0.77	Center	0.69	Center
Fontainehofje	151.7	268.0	410.8	36.9	65.2	10.3	2.4	2.4	0.37	Midway	0.69	Center
Hilmanhofje	27.7	27.7	82.4	33.7	33.7	2.7	2.5	2.5	0.83	Center	0.36	Midway
Hodshon-Dedelhof	34.9	173.8	341.3	10.2	50.9	6.4	2.8	2.5	0.47	Midway	0.47	Midway
Hofje de Kalverengang	57.3	84.7	121.2	47.3	69.9	5.4	1.7	1.5	0.68	Center	0.54	Midway
Hugo de Groothofje	290.2	420.2	505.3	57.4	83.2	8.1	3.5	3.4	0.53	Midway	0.54	Midway
Karthuizerhofje	475.8	601.3	782.7	60.8	76.8	11.3	5.0	5.0	0.59	Midway	0.53	Midway
Lindenhofje	27.4	46.9	214.0	12.8	21.9	0.7	2.9	0.7	0.53	Midway	0.07	Perimeter
Magdalena Hodshonhof	6.8	20.8	101.8	6.7	20.4	4.6	3.5	3.5	1.00	Center	0.77	Center
Occohofje	185.0	914.0	1418.7	13.0	64.4	12.5	6.9	5.4	0.49	Midway	0.52	Midway
P.W. Janssenhofje	170.8	191.1	544.4	31.4	35.1	7.9	5.4	5.4	0.83	Center	0.66	Midway
Platanenhof	346.1	346.1	1013.7	34.1	34.1	13.8	4.8	4.7	0.48	Midway	0.61	Midway
Regenboogs-Liefdehofje	7.2	39.5	96.0	7.5	41.2	5.8	2.6	2.6	0.93	Center	0.65	Midway
Rijpenhofje	32.4	109.3	218.7	14.8	50.0	5.3	3.1	3.1	0.61	Midway	0.53	Midway
Rozenhofje	191.1	301.3	490.6	39.0	61.4	6.5	8.2	7.6	0.82	Center	0.54	Midway
Sint Andrieshofje	0.0	77.0	159.9	0.0	48.2	0.0	0.0	0.0	0.00	-	0.00	-
Staringhofje/Lutherhofje	46.8	168.4	416.4	11.2	40.4	6.1	5.2	5.2	0.57	Midway	0.61	Midway
Suykerhofje	105.2	247.7	359.7	29.3	68.9	8.7	4.3	4.3	0.66	Midway	0.72	Center
Van Brants Rus hofje	0.0	0.0	137.3	0.0	0.0	0.0	0.0	0.0	0.00	-	0.00	-

van Brienenhofje	175.2	263.4	519.8	33.7	50.7	9.6	5.5	5.5	0.69	Center	0.71	Center
Venetiaehofje	98.4	350.5	637.4	15.4	55.0	8.1	5.0	4.1	0.44	Midway	0.65	Midway
Vredenburgh hofje	0.0	16.4	79.0	0.0	20.7	0.0	0.0	0.0	0.00	-	0.00	-
Zevenkeurvorstenhofje	39.8	70.9	164.0	24.2	43.2	7.2	2.1	2.1	0.85	Center	0.56	Midway
Zon's hofje	120.2	142.4	260.3	46.2	54.7	4.0	2.9	2.8	0.59	Midway	0.50	Midway
Mean	120.7	256.9	451.8	24.0	48.9			3.5				
Standard deviation	131.8	322.2	475.4	18.0	19.9			1.8				

Table 5. The total m2 tree coverage, total m2 greenery coverage, total m2 courtyard surface, tree coverage percentage, greenery coverage percentage, ds, dl, mean distance of tree trunk to building, dl:DL, the classification of dl:DL, ds:DS and classification of ds:DS per hofje