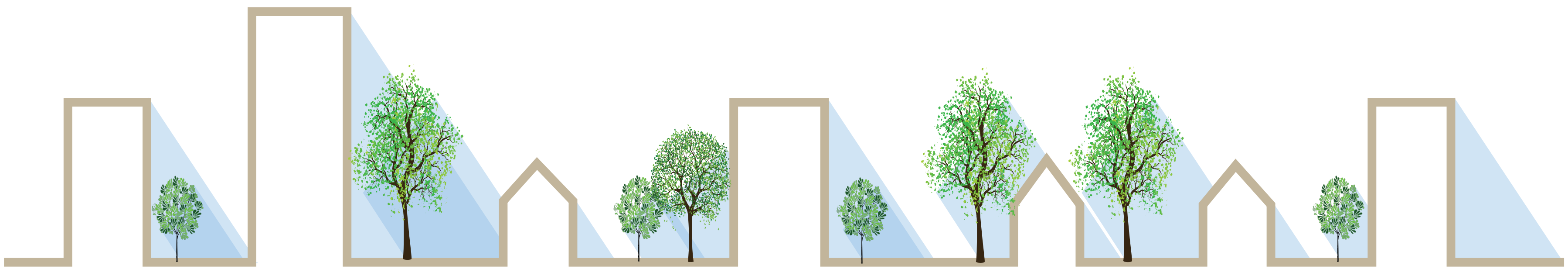
Green elements in street canyons

Research by design for heat mitigation and thermal comfort in urban areas.



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Thesis Report
Master of Landscape Architecture

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WAGENINGEN UR
For quality of life

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Abstract

Street canyon geometry has important effects in urban climate. Formation of urban heat within street canyons due to solar radiation gains, and limited wind access is one of them. Streets layouts are usually predetermined and hardly to change, nevertheless it is possible to find solutions within the existing layouts. Canyons aspect ratios and orientation towards the sun create diurnal patterns of solar exposure/ shade areas pointing out the overheated zones on the street. By combining the diurnal patterns with traditional street green elements it is possible to modify streets solar gains, reducing urban heat and providing comfortable thermal environments.

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1. Introduction

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1.1 Urban microclimate and urban heat effect.

In the last years the amounts of the people who live in urban areas become more than a half of the global world population. This is a global tendency and cities will continue to grow (Erell, Pearlmutter et al. 2011). This master thesis research will focus on one of the effects caused by urbanization – **urban heat island**.

Local effects of urbanization on climate have long been documented. The increase in surface and air temperatures over the urban areas compared to their rural surroundings is the best documented climatic modification. This condition is called urban heat island (UHI). Average urban temperatures may be up to 5 oC warmer, but in some particular areas of the cities difference in comparison with rural surroundings can reach even 12 oC (Roth 2009).

The reasons of such temperature difference are consequences of such design planning as rough and build up areas that forms urban fabric and resulted lack of open green spaces. Intensity of the UHI depends on thermal and radioactive properties of surface materials, anthropogenic heat production and urban geometry (Futcher 2008). City grids of buildings blocks, hard pavement surfaces, transportation systems and industrial areas transform local climate into variety of urban microclimates with increased intensity of radiation and lower wind speeds (A., Steeneveld et al. 2011). Those factors increase temperatures during days and slower heat losses during nights and as the consequence rise the problems with urban heat (Shahidan and Jones 2008).

The case study of this research is taking place in the city of Rotterdam. This city is one of the most industrial cities in the Netherlands and Urban Heat problems are very relevant there. The mean year UHI temperature of the city is 1.7 oC although in the warmest period of the year it can reach till 8 oC (Klok, Zwart et al. 2012). Municipality of Rotterdam is interested in climate condition improvement and the city itself for the last few years become a significant study case for various researches. The Bergpolder-Zuid area in Rotterdam in particular is a design case of the current research due to relevance of the problem, demand of improvements and data availability.

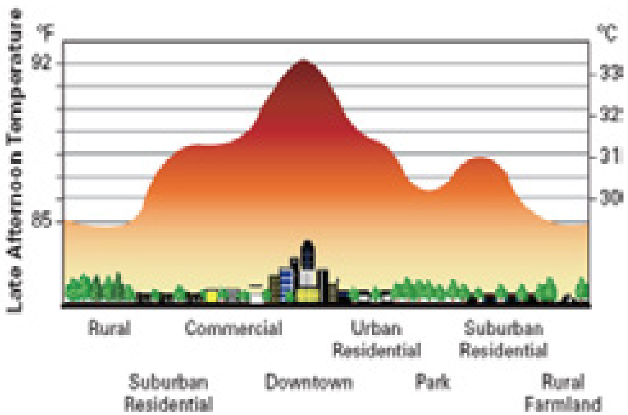


Figure 1.1 Urban heat island scheme.
Source: http://explow.com/urban_heat_island

1.2 Negative effects of urban heat.

Quality of the urban environment plays a huge role on people's health conditions. The impact of Urban Heat is significant and in most cases negative.

Summer heat waves in the combination with UHI effect can cause ***major public health crises*** in largely urbanized populations (A., Steeneveld et al. 2011). ***Mortality*** is known to increase in hot weather especially amongst the elderly people. Heat affects mortality and morbidity in indirect way as well, ***urban heat exacerbates other environmental health stressors*** like air and water pollution, summer smog and drought (Mills 2009).

In the past 3 decades, ***the number of overweight people increases sharply*** for both adults and children, causing the large variety of the health problems. Recent studies in the US showed that low level of the physical activities amongst city inhabitants is influenced by unpleasant conditions of the outdoor build environment. Unpleasant outdoor conditions according to the research group are high air temperatures, lack of vegetation and particularly street trees and parks, stony, paved and build up areas (Wolf 2008).

Moreover, warm external urban environments result an increasing number of air-conditioners use to cool the indoor environment and, as the result of this - i***ncrease of on energy demand,*** which in turn further increases the external temperature, which will cause even more energy demand to cool the internal environment (Futcher 2008). That is why the attention should be paid to the minimization or elimination of the Urban Heat generation reasons. Adaptation to the existing climate conditions by using the air conditioners or other cooling devices that consume energy will only make the whole situation worse.

The negative influence of UHI should be mitigated, creating cooler but still thermally comfortable outdoor environment. Growing concern with environmental degradation has reawakened interest in the use of ecological materials, processes and sources of energy. This led to a new approach of architecture as a bioclimatic architecture, which considers the building as a place of energy exchange between the indoor and outdoor, natural and climatic (Serghides 2010). This also caused additional interest for the use of traditional techniques of thermal control that were developed by centuries before the industrial revolution and fossil fuel expansion era. The traditional architecture principles are based on local climatic conditions and therefore differ in all climates and countries. In the globalization era nowadays together with the technology development allows to transform the successful heat mitigation principles used in one country to the other.

Nowadays urban layouts are very often predetermined, and, therefore it is important to work within the existing parameters of the urban framework. However within this framework there may be a possible solution to the problems of rising urban temperatures (Futcher 2008). Studies about the urban geometry proved that densification of urban areas can reduce the urban heat within the streets canyon due to the larger shadowed surfaces(Herrmann and Matzarakis 2012). At the same time cities should provide thermally comfortable and pleasant environment what requires open spaces, solar access and a good infrastructure. That is why **search for the right balance between heat mitigation within the urban layout and creating thermally comfortable and pleasant outdoor environment for city inhabitants is the main purpose of this research.**

1.3 Prior research on urban heat island and it's mitigation strategies

The prior knowledge in city microclimate started with the *investigation and invention of the Urban Heat island phenomena.* The evidence that air temperatures were often higher in a city than in its surrounding countryside was firstly provided in 1810 by Luke Howard (Erell, Pearlmutter et al. 2011). Although temperature differences are significant the comparison between rural and urban areas show that **UHI effects have little influence on global warming.** Nevertheless the global tendency of the urbanization and expansion of the cities together with the population aging and health crisis pointed out ***the importance of providing the comfortable and healthy environment in the cities.***

During the last decade the large variety of different social studies were done in order to understand what does ***the thermal comfort*** mean and which conditions are considered to be a comfortable.

Some of the studies were focused only on the temperature conditions in the different countries and human perception (Nikolopoulou and Lykodis 2006).

Some were taking into account the environmental qualities and weather conditions and its influence on human behavior and activities (Eliasson, Knez et al. 2007).

Finally, several studies were focusing on the design strategies for opens spaces and optimal temperatures for human behavior (Katzschner 2004).

Urban heat has negative impact on human thermal comfort during the hot seasons that is why strategies for heat mitigation have to be developed considering summer situation (Brown and Gillespie 1995; Erell, Pearlmutter et al. 2011).

The formation of urban heat islands reflects the sum effect of the multitude of man-made alterations to the natural environments that continually take place in the city. Cities differ from their natural surroundings in a multitude ways, many of which directly influence the surface energy balance and hence the formation of urban heat island. The most obvious characteristic of cities is the concentration of buildings in a fairly dense pattern in a given space. As buildings have raised along the city streets the spaces between them have come to resemble artificial canyons. This dense matrix of buildings/artificial canyons promotes the creation of urban heat islands by

- trapping and storing the solar energy as a heat due to multiple reflections and absorption within canyons during the day,
- reducing the heat release and therefore cooling urban canyons during the nights by low sky view factors of the deep and narrow canyons,
- and in the end, restrict ventilation cooling by blocking the air flows (Erell, Pearlmutter et al. 2011).

As it is possible to see urban heat island effect first occurs in *urban canyons – streets* during the day and night.

Various microclimatic studies consider the design of a street a key issue in bioclimatic urban design methodology because *street affects both outdoor and indoor microclimates*, and as result, influences the thermal sensation of people as well as the energy consumption in urban buildings.(Ali-Tourdert and Mayer 2006).

At the same time from the point of view of urban planning street is a *public easement, shared between all sorts of people.* It is a component of the build environment as long as an environment itself and sustains a range of activities vital for civilization (Carmona, Tiesdell et al. 2010).

The main microclimatic features of Urban street canyon have been clarified by studies of the energy balance, thermal and wind flow modifications within a street canyon and streets morphologies, especially height-to-with ratio and orientation towards sun position (Ali-Tourdert and Mayer 2006).

The relationship between height-to-width ratio and orientation with the respect to the sun were found to have a great influence on the thermal conditions due to overshadowing and sun exposed surfaces. The surface temperature is markedly lower for shaded areas and this way also the air temperatures for narrow and deep streets are few degrees cooler at the street level than in wider streets. Thus shadows prevent street heating, provide cooler environments and therefore contribute to the UHI mitigation (Ali-Tourdert and Mayer 2006; Futcher 2008; Herrmann and Matzarakis 2012).

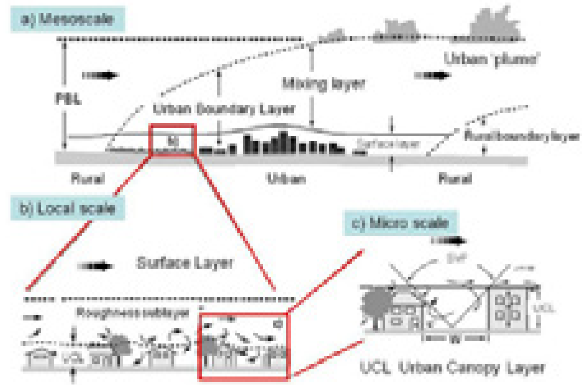


Figure 1.2 Urban heat island scales and layers
Source: Alterra, 2011

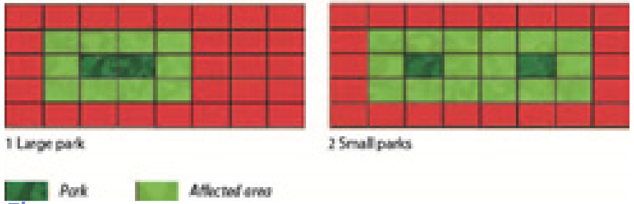


Figure 1.3
Source: Roo and Roozen 2011.

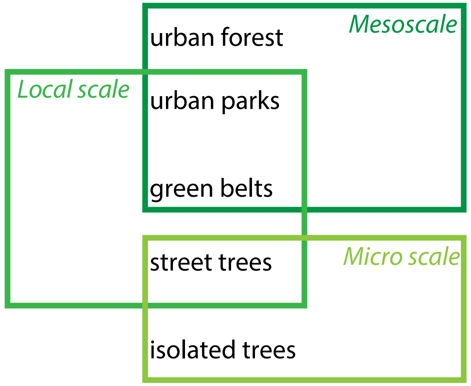


Figure 1.4 Green elements and UHI scale levels

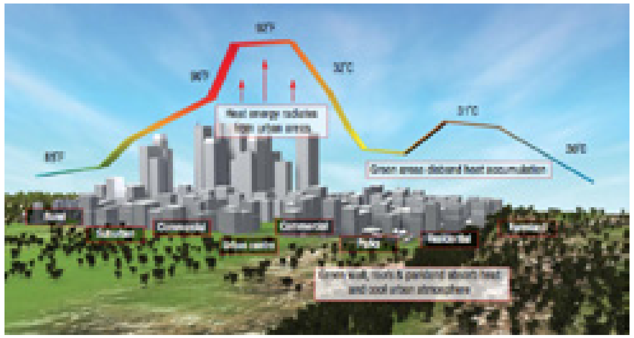


Figure 1.5 Role of green areas on city thermal conditions. *Source: http://www.sigmawaterproofing.com*

Besides canyon geometry, shadows on the streets can be provided by such landscape elements like street vegetation (trees and climbing plants), solar umbrellas, tents or other overhanging constructions, solid or transparent. *Vegetation, especially trees* bring the positive effects on aesthetical, ecological and environmental aspects of the urban environment (Jacobs 1995) (Bolund and Hunhammar 1999). In addition to this, there are other positive impacts of vegetation on microclimate like wind control and air moisturizing. Taking into account that vegetation has a number of functions that contribute to the urban environmental quality in general and to microclimate specifically it is decided to take a closer look on the role of green elements in the cities.

The role of vegetation in urban environment has long been studied. In 1991 special climatopes for urban area were defined and depicted characters concerning proportion of vegetation. Their comparison and analysis of examples from many experiments revealed the importance of green elements in town planning when aiming to optimized urban climate (Wilmers 1991).

Atmospheric interaction between vegetation and built urban environment take place in different scales, which are based on the Oke classification and described in report made by Alterra institute in 2011:

- Microscale or street canyon scale

Typical scales of urban microclimates relate to the dimensions of individual buildings, trees, roads, streets, courtyards, gardens etc.

- Local scale or neighborhood scale

Includes landscape features such as topography but excludes microscale effects. Mean climates of neighborhoods with similar types of urban development (surface cover, size and spacing buildings, activity).

- Mesoscale or city scale

The city elements in the microscale are affected by phenomena at the local scale. In their turn, the phenomena at the local scale or neighborhood scale are affected by the conditions and interactions the mesoscale (Oke 1988; A., Steeneveld et al. 2011).

According to this classification urban green areas are distinguished into:

- urban forest
- urban parks
- green belts
- street trees
- isolated trees (Oke 1988).

All types of vegetation are able to reduce the air and surface temperatures by controlling and modifying radiation (mostly solar) and evapotranspiration. Thus the urban heat effect is reduced in all described scales (Heisler 1986; McPherson and Muchnick 2005). At the same time the numbers of other eco-services like air filtering, noise provide reduction, rainwater drainage, sewage treatment and recreational and cultural values are provided (Bolund and Hunhammar 1999). The numerous of studies of the vegetated areas proved that even small interventions can affect the situation in a positive way and many small parks may provide the same or even larger effect than one big park (Figure 3) (Roo and Roozen 2011).

Revising the general parameters of Urban Heat island formation principles, it's scales, and vegetation elements that have Urban Heat mitigation potential it is decided to focus on the micro scale of Urban Heat Island phenomena and specifically on the thermal conditions in street canyons and green elements - trees for its improvement. Trees are important and most commonly used tool for street shadowing, especially in mid-latitude cities, because they provide dense shade during the summer when the urban heat problems are very relevant and allow the solar access during the winter time when city inhabitants actually need sun.

1.4 Knowledge gap in thermal effect of vegetation in street canyons.

Despite the numbers of researches on street canyons and studies about vegetation stating and proving that trees are probably the best tools for urban climate improvement in the streets while providing the number of other environmental services at the same time, there is still lack of practical advices of street trees allocation considering the street geometry to improve the amounts of shadows in the streets.

Vegetation impact on the urban environment has to be studied from the very different perspectives. The positive influence of trees on the quality of outdoor environment and thermal conditions due to solar radiation control, wind reduction an air moisturizing was already mentioned. But there are also a number of factors that naturally take place on the streets that in combination with rows of the trees may lead to undesirable effects. For example seasonal change of sun positions can bring a negative effect on the streets – to less shadow during the summer period – when it is necessary and too much in the winter time – when it is better to be avoided (Heisler 1986). In some cases of the street canyons with the heavy traffic the dense alleys of the threes may capture the CO2 emissions within the street canyon and significantly reduce the air quality (2012). Dense canopy of trees may prevent nocturnal cooling, due to heat capture by tree crowns. This factor in long perspective may neutralize or even oppose the initial purpose of the street vegetation – urban heat reduction.

It is evident that it is not enough just to place the trees along the streets. Careful and thoughtful analysis of street canyon geometry, its functional zones, and shadow patterns is re-

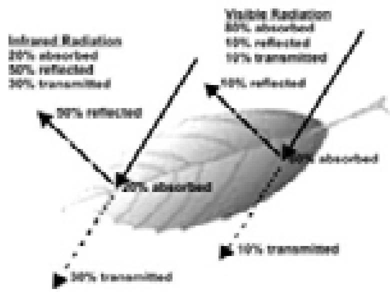


Figure 1.6 *Source: Shahidan and Jones 2008*

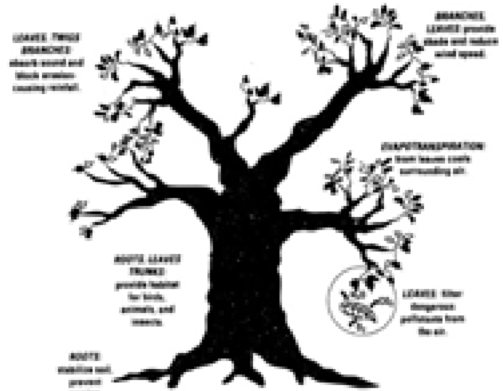
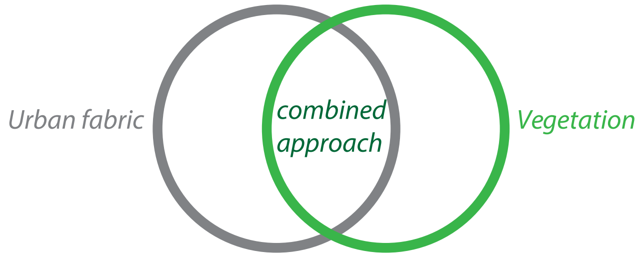


Figure 1.7 *Source: Shahidan and Jones 2008*



Urban element - ***Street canyon*** – urban heat generation source

Green element – ***Street trees*** as a tool to improve the situation

Figure 1.8

quired in order to understand its existing heat mitigation potential and thermal environment of the street itself. The combination of cooling potentials of streets and trees through shadows can be expressed in the number of design principles which could be applicable to the specific design case taking into the account the existing situation.

1.5 Research objectives

In order to formulate the main research question and the sub questions the main research objectives and goals need to be stated.

The purpose of this study is to find ways how to mitigate the urban heat in the street canyons and create thermally pleasant outdoor environment by providing shadows of the trees or other green elements.

It is important to understand *what does the thermal comfort mean*, which conditions are considered to be comfortable and how plant trees on the street in the most efficient and successful way for providing thermal comfort.

The pattern between street geometry parameters like H to W ratio and orientation towards the sun and temperature conditions need to be found. This analysis will make it possible to distinguish the most vulnerable canyon parts and their functions and to find the possible solutions for the heat mitigation. T*he influence of geometrical parameters of trees like sizes, crown shapes and diameters, arrangements and planting distances on the shadowing abilities needs to be studied as well.*

Finally the outcomes should be applied in the existing situation where the *whole research concept should be tested on its validity.* The design objective is not only to provide thermally comfortable environment, but also to create the aesthetically pleasant and functional space and improve street general qualitiesas well as microclimatic.

1.6 Research question and sub-questions

The main research question:

What is the strategy for urban heat mitigation and thermal comfort creation in the streets by using green elements?

Sub questions:

1. What is the influence of street canyon geometry (H to W ratio and orientation towards sun) in street thermal conditions? For which street types heat problems are more relevant, for which are less?
2. What is the role of street vegetation? Which parameters of vegetation contribute to street thermal environment and create thermal comfort?
3. How to find the optimal green elements for different street canyon types to mitigate urban heat and provide human thermal comfort?
4. How to implement the design principles for heat mitigation in the real site taking in account the existing situation?

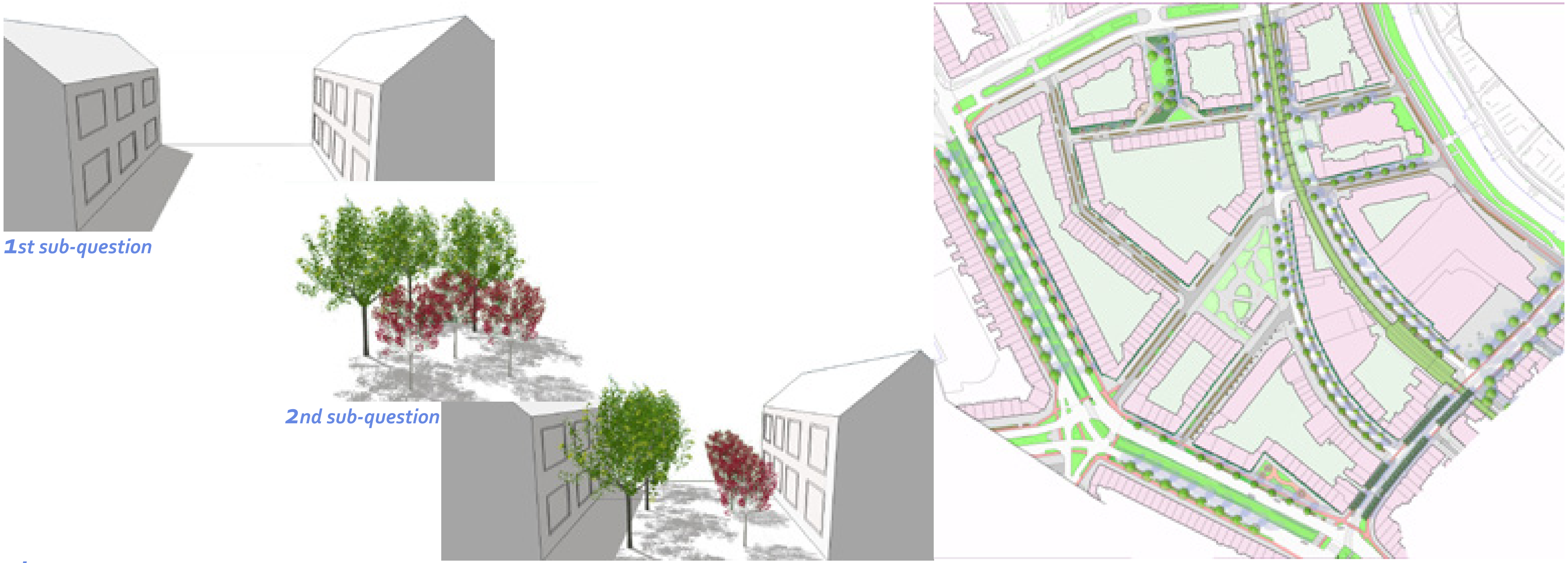


Figure 1.9

4th sub-question

1.7 Research methods

The contemporary landscape design needs scientific knowledge into decision making process. Any intentional change of the landscape pattern should respond to the purpose of sustainability providing ecosystem services but at the same time needs to meet societal needs and respect societal values. Collaboration between scientists and practitioners in many disciplines improves the impact of landscape science in society and enhances the saliency and legitimacy of landscape ecological scientific knowledge (Nassauer and Opdam 2008).

Between five distinct approaches to the incorporation of research into design according to Milburn and Brown the systematic model is the most suitable for the following studies. It reflects a pragmatic approach to design, where the research plays the central role in design (picture 7). The research (triangular forms) determines the concept (oval), and the concept is a tool for transmitting the integrated complexities of the site (triangle). The design approach tends to be formulaic: problems are identified, standard solutions are applied, and the problem is resolved (Milburn and Brown 2003).

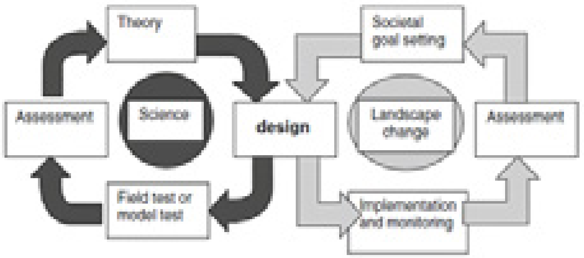


Figure 1.10 Design as a link between science and landscape change.
Source: Nassauer, Opdam, 2008

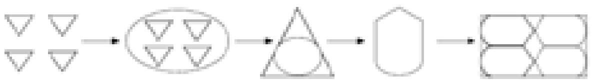


Figure 1.11 The model of the systematic model *Source: Milburn, Brown, 2003*

1. Literature research.

Literature provides all the necessary information for the topic, so called theoretical basement for the research. The main part of it refers to the prior knowledge on the topic but furthermore references to the literature will take part in all phases of the thesis to explain or prove the research concepts.

Most of studied literature that refers to the prior knowledge can be divided in 3 parts

- Human thermal comfort studies
- Urban geometry influence on climate conditions and thermal comfort in the cities.
- Vegetation influence on microclimate and thermal conditions.

2. Simulations and graphical design

The influence of street canyon geometry on the street shadow patterns and shadow patterns of the trees is simulated by graphical 3d program Sketch Up 8 from Google (available at http://google-sketchup.en.softonic.com/). This program allows calculating shadows of the objects for certain locations and times of the day and year in a fast simple way.

The shadow patterns will be simulated for the area of Rotterdam for the morning, noon and afternoon hours. After shadows are simulated by SketchUp they will be combined together in order to get the general overview of the diurnal shadow patterns of objects and their combinations. The graphical design software like an AutoCAD from Autodesk and Adobe Suit are the tools to solve this issue in the research and will be used to calculate shadow areas and find the best locations and arrangements of the trees in the streets.

3. Site analysis and data collection

The purpose of the research is to find the solutions for the existing problem and implement them in a specific site. Data collection and site analysis of Bergpolder-Zuid is crucial for the developing the relevant and accurate simulations for the research part and implementing the design principles in the final design of the area master plan.

4. Research design relationship

Research by design is taking place in all research part and final design step.

- To develop the design principles through the simulation of shadow patterns the certain design steps should be taken to specify the geometry of the streets and sizes of the trees.
- Later, when shadow patterns will be overlapped in order to overview the situation in general the design and following research will be necessary to find out the most suitable shadow patterns and design solutions for the existing situation.
- When design principles for street shading will be created, they will be applied to the existing situation. This will require the careful evaluation, certain changes of the principles, and search for better solutions through testing and critical review of the design parts. The whole concept may require adjustments or corrections and have to prove itself.
- The final design should reflect the response of the design concept to the actual site requirements and existing situation at the same time solving the main objective of the research – urban heat mitigation

1.8 Relevance and target group

The following thesis can be interested for the landscape architects, urban and spatial planners, and environmental scientists. Governmental organizations, municipalities and local communities who are interested in improving the quality of microclimate along the streets can get practical information about the Urban Heat mitigation in the street level.

The analysis and recommendations are provided for the streets in Rotterdam with different orientation towards the sun and different Height to Width ratio. The other municipalities of the Netherlands can also use the research outcomes; although there can be slight variations in the exact shadow patterns.

This research can be applied for the different locations of the world as well. To do this, the shadow patters have to be recalculated according to the exact sun position of the design case and requirements to urban heat mitigation should be modified according to the local climate but the other research methods remains similar.

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2. Urban microclimate

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2. Urban microclimate

The climate of a location is usually understood as comprising a number of physical aspects e.g. temperature, moisture content of the air, rain, wind, fog, snow, insolation, cloudiness and general air quality. Humans by various means are able to inhabit almost all of the climate conditions on Earth (Erell, Pearlmutter et al. 2011). When the prevailing climate of the area interacts with objects in the landscape it creates microclimates. Microclimatologists describe these interactions in terms of the effects on the air temperature, wind velocity, solar radiation, relative humidity and so on. Landscape architects determine locations of objects in the landscape through design, and consequently can have a significant impact on microclimates. Microclimates in turn strongly influence the thermal comfort of people within a landscape, and can significantly affect the energy required to heat or/and cool buildings in the landscape (Brown and Gillespie 1995).

Much of the literature dealing with climate and design focuses on the effect of climate on the built environment and in particular on creating comfortable indoor conditions. Starting from 1818, when Luke Howard introduced urban heat island phenomena in London, a lot of studies about climatic conditions in urban environment were made, evolving the discipline into a distinct branch of meteorology (Erell, Pearlmutter et al. 2011).

Right now when the world is undergoing the largest wave of urban growth in history the main contemporary goal is to provide sustainability of city expansion. For example - reversing the loss of environmental resources, reducing biodiversity loss, providing access to safe drinking water and basic sanitation, and overall, creating a significant improvement in the lives of slum dwellers.

In the conversations about sustainable cities very little is said about the urban development necessary to promote human health and well-being, although there is a clear link between the climate of a settlement and its potential sustainability. Poor climatic conditions result lack of movement, health issues and increase of mortality, especially during the heat waves(Wolf 2008; Mills 2009; A., Steeneveld et al. 2011). It also cause seasonal a weekly migration of population from cities to the countryside or seaside for the recreational purposes, which in the end result higher CO_2 emissions (Katzschner 2004). Therefore, providing the pleasant environmental conditions in the cities is extremely important.

The certain climate conditions provide opportunities for energy gathering and help to conserve energy. Urban design and landscape decisions are able to create microclimates that either accentuate or moderate the properties of background climate. Thus, there is a clear role for an applied urban climatology in urban design, architecture and landscape architecture practice in planning sustainable settlements (Erell, Pearlmutter et al. 2011).

2.1 Urban Heat Island levels and formation

Levels

One of the most significant and problematic aspects of the urban climate is the urban heat island (UHI). Under certain weather conditions a substantial difference in temperature may be observed between city and its surrounding rural areas - city area is always warmer that the rural surroundings (Erell, Pearlmutter et al. 2011). The maximal temperature difference between urban areas and its rural surroundings occurs during the nights and near the densest part of the urban area. UHI may be observed both, at the surface (surface heat island SHI) and in the atmosphere in and above the city (atmospheric heat island). The later type may be subdivided into canopy-layer heat island and boundary-layer heat island (Erell, Pearlmutter et al. 2011).

- ***A surface heat island (SHI)*** forms when the temperature of urban surfaces is greater than that on the surrounding rural (natural) surfaces. This type of heat island is common where the city is surrounded by moist soil or by vegetated areas, which tend to be cooler than dry impervious surfaces of cities (Klok, Zwart et al. 2012). This characteristic is applicable for most of the middle latitude cities, Rotterdam – the study case of this research is not exclusion. However, it needs to mention that in desert surroundings, the dry rocky or sandy soil may actually be warmer than many urban surfaces.
Urban SHIs are largest during the daytime, especially in sunny conditions with little wind, and are generally weaker at night.

- ***The canopy-layer heat island (CLHI)*** is observed in the layer of air closest to the surface in cities, extending upwards to approximately the mean building height. It is typically observed at night in stable atmospheric conditions with little cloud or wind, and is weaker or non-existent during the daytime.
- ***The boundary layer heat island (BLHI)*** forms a dome of warmer air that extends downwind of the city. It may be one kilometre or more in thickness by day, shrinking to hundreds of meters or less at night. Wind often changes the dome to a plume shape (Erell, Pearlmutter et al. 2011)

According to Oke's classification of UHI scales *urban boundary level refers to meso scale, urban surface layers appears in Local scale and canopy layer to micro scale.*

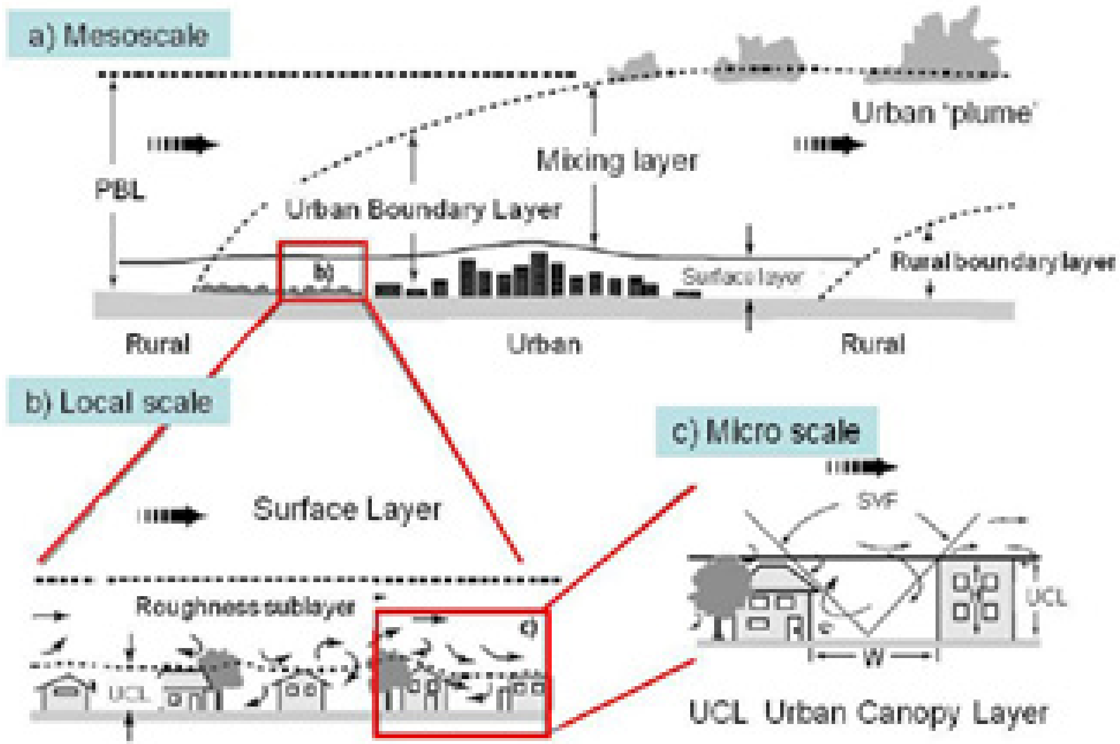


Figure 2.1 Urban heat island layers *Source: Alterra 2011*

Although urban heat islands have been reported during the daytime (especially SHI), the phenomenon on the other scales is more typically observed at night. As temperatures begin to decline in the late afternoon and early evening, the cooling rate in the city is often lower than in the rural area. As a result, a temperature difference is formed, typically reaching a maximum several hours after the sunset. This trend is reversed shortly after the sunrise, when urban warming occurs at a slower rate than in the rural surroundings. Thus the general urban heat island phenomenon is often referred to as the ***'nocturnal heat island'.***

Formation

The formation of UHI reflects the sum effect of the multitude of man-made alterations to the natural environment that continually take place in the city.

There are various factors that refer to the UHI formation:

1. ***Urban form and building density*** – city fabric of buildings and open spaces. Here we also can refer geometry of the street canyon the linear space – street with adjacent buildings form the both sides. Dense matrix of buildings and artificial urban canyons create UHI through the variety of processes.

    • First, trapping of solar energy due to multiple reflection and absorption within the canyons.
    • Second, the low sky view factor in deep and narrow street canyons which limits the net emission of long wave radiation to the sky, and turn the rate of cooling which occurs on the sunset.
    • Finally, the dense urban structure reduces wind speeds near the ground and limits the rate air flow through the canopy spaces, significantly impairing ventilation cooling.

2. ***Impervious surfaces*** - pavement consisting of materials such as concrete, asphalt or interlocking masonry bricks contribute to increase of air temperature due to absence of the slow evaporative cooling effect that is common to the pervious surfaces like soil or vegetated areas in the country side.

3. ***Heat released by human activity*** – which is possible to separate in anthropogenic heat – produced by vehicles and heat losses form the heated buildings in winter or waste heat form air conditioners in summer and emission of carbon dioxide (CO_2) that is contributing to the urban scale greenhouse effect and thus the increasing of the air temperatures.

4. ***Vegetation coverage*** – it can intercept solar radiation, block incoming long wave radiation (from the sky) and outgoing radiation emitted by ground, reduces the air speed

when the wind is blowing and provides moisture through the evapotranspiration.

5. ***Water surface*** – water elements around or in the city provide cooling effect due to evaporation in the summer time or daytime but at the same time have the ability to store heat and release it during night time or colder periods of the year.

6. ***Geographic location*** – determines the intensity of UHI and its effects.

7. ***Weather*** - winds and clouds can affect the intensity of UHI. Heat island magnitudes are largest under the calm and clear weather conditions (Klok, Zwart et al. 2012) (Erell, Pearlmutter et al. 2011).

Urban heat in the streets

Street as an urban space can be seen as the interference of architectural and urban scales as it consists or shared surfaces between the building and the open urban canopy. Hence, the street affects both outdoor and indoor microclimates, and as a result influences thermal sensation of people and energy consumption in urban buildings. (Ali-Tourdert and Mayer 2006). “Street” or “street canyon” is the most commonly used model for description of the urban fabric in the urban climate formation; it can express density or other physical properties that influence the micro –scale level climate and thus cause the impact in larger scales (Erell, Pearlmutter et al. 2011).

Heat produced in the street level or Urban Canopy layer influence people in a direct way. No one in the ordinary everyday life circumstances experience urban heat island effect in the Mesoscale or Urban Boundary layer, and very few actually experience it or have any concern about it in the Locale Scale or Surface layer. Urban Canopy layer heat is mostly produced and experienced during the daytime and affects the environments that people use every day. The more attractive and pleasant those environments are the more people use them. If outdoor environments are too hot it not only result UHI effect above the city contributing to the global warming problems but also affects the everyday humans’ life causing lack of movement, health issues and in the end – increased mortality. Therefore, providing the pleasant environmental conditions on the street level is extremely important for people well-being.

Description of thermal conditions and heat problems at street level derive from the general heat problems described above.

First of all, form all UHI layers street refers to ***Microscale and Urban Canopy layer***. Thermal conditions of a single street contribute to situation of Local scale and Surface layer, and in the end to the general Mesoscale and Urban Boundary layer.

From the factors that influence formation of urban heat, street will be studied as an ***Urban Canyon form.*** Thus thermal conditions will be mostly influenced by canyon geometry - height-width ratio, the canyon axis orientation and sky view factor. Analysis of typical urban configurations with typical dimensions can describe their influence on climatic conditions and temperature patterns (Herrmann and Matzarakis 2012).

Anthropogenic heat, released by vehicles and buildings also has its impact and need to be taken into account. Intensity of the impact may vary from the street and building size, exploitation intensity and functions that can change in seasons or even the daytime. Unfortunately it is hard to control the amount of released anthropogenic heat with landscape elements, but landscape elements can create desirable warmer or cooler environments and this way lower the amount of energy used by vehicles or buildings to heat or cool down the indoor space, which in its turn will lower heat emissions outdoors and can make a space cooler (Futcher 2008).

Surface permeability, vegetation coverage, water bodies have the certain impact on thermal conditions as well, they may vary in every street and need to be studied and analysed as an existent situation in every particular case.

Geographic location and weather conditions mainly influence the UHI intensity in city in general. As an exception might be location of urban canyons next to certain landscape elements – like water bodies, parks or forests that drastically influence local thermal conditions. But it also has to be studies in the particular design sites.

2.2 Human thermal comfort

Despite the significant temperature differences between urban and rural areas and the global tendencies for city growth urban heat island doesn't have a huge contribution to the global warming. Things that matters are unpleasant thermal conditions for humans, therefore, one of the main reasons for considering microclimate is landscape design is to create thermally comfortable habitats for people.

A person in a landscape can be considered to be thermally comfortable when the energy received from the environment nearly equals the energy loses from the body.

> ***The main sources of energy available to heat a person*** are metabolic energy (generated from the body) and radiation (from the sun and all objects on the earth around).
>
> ***The main ways in which energy can be lost from a person's body*** are through evaporation (due to perspiration), convection (due to the wind) and radiation of the body itself.

All "steams" of energy form ***energy budget of the body*** (measured in W/m^2) or ***physiological equivalent temperature*** (PET) measured in ^{o}C. There are special formulas to calculate the exact values for both parameters but the simple way to understand the principle looks like:

Energy budget/PET= (metabolic energy + solar radiation gained + terrestrial radia-

tion gained)-(evaporative heat loss + convective heat loss + terrestrial radiation emitted) (Brown and Gillespie 1995).

Table 2.1 present assumption of PET values thermal sensitivity and grade of physiological stress calculated for human perception with average metabolic rates for the central European cities (Matzarakis and Mayer 1996).

Studies by Nikolopoulou and Lykoudis (2005) which were based on the environmental monitoring and field surveys revealed that the actual neutral temperature according to human perception differs from the regions and seasons (Table 2.2) (Nikolopoulou and Lykodis 2006). At the same time, studies by Katzschner in Kassel (north of Germany) based on the PET measurements and subjective responses shows that the different human activities require the different types of thermal conditions, thus different PET values (Table 2.3) (Katzschner 2004).

Considering all thermal comfort data about places and different activities it is needs to be understand that even the most thoughtful use of landscape elements can't provide the exact required PET value. But the design goal is to use the landscape elements is a way, so they can contribute to the situation improvement as much as possible.

The purpose of site microclimatic design is the thermal comfort of the majority of people the majority of time and once the big picture is resolved it is possible to deal with the specific cases (Brown and Gillespie 1995).

It is also important to establish out *the season* when the thermal comfort should be provided. Winter and summer temperatures in the mid-latitude cities are very different, and mainly determine human activities. So it is necessary to figure out what time of the year the designed area will be used.

PET	Thermal sensitivity	Grade of Physiological Stress
	very cold	extreme cold stress
4 °C		
	cold	strong cold stress
8 °C		
	cool	moderate cold stress
13 °C		
	slightly cool	slight cold stress
18 °C		
	neutral (comfortable)	*no thermal stress*
23 °C		
	slightly warm	slight heat stress
29 °C		
	warm	moderate heat stress
35 °C		
	hot	strong heat stress
41 °C		
	very hot	extreme heat stress

Table 2.1: Psychological Equivalent Temperature indexes. *Source: Mayer, Matzarakis 1993*

Neutral air temperature			cities
year	summer	winter	
22.8	28	21	Athens
25.3	29	15	Thessaloniki
12.9	16	11	Fribourg (Switzerland)
18.3	24	21	Mailand
17.8	17	11	Cambridge
15.3	16	11	Sheffield
18.5	22	15	Kassel

Table 2.2 Neurtal PET values for European cities. *Source: Nikolopoulou and Lykodis 2006*

activities	needed thermal conditions for use of open space	PET
sitting	warm	30
calm activities	warm moderate	26-32
children play	warm moderate	24-26
recreation	neutral	16-24
light movement	neutral	16-24
shopping	warm moderate	26-32
movement	lightly cool	14-24
strong movement	cool to cold	12-24
garden activities	lightly cool	12-24
work outside	neutral to cold	16-22

Table 2.3 Overview of thermal conditions for different activities. *Source: Katzschner 2004*

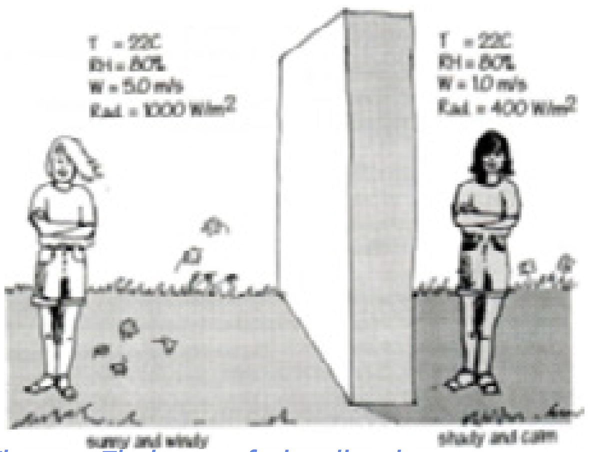


Figure 2.2 The impact of microclimatic components on human temperature perception.
Source: Brown and Gillespie, 1995

2.3 Heat mitigation strategies in urban areas

Why urban heat needs to be mitigated?

The urban heat island is not necessarily detrimental. In cold climates temperature difference may actually contribute to the thermal comfort of people, who otherwise would experience much colder outdoor conditions. However in the hot period of the year or in the cities with warm climate, there is certain amount of benefits from the reduction of temperatures(Erell, Pearlmutter et al. 2011).

- Decreased demand for cooling energy in the buildings
- Decrease in some photochemical reaction rates and thus lower ozone levels
- Decrease in temperature-dependent biogenic hydrocarbon emissions from vegetation
- Decrease in evaporative losses.

All these factors contribute to an improvement in the overall quality of the outdoor areas and may lead to more intensive use of urban space, which may contribute to people health conditions. The improvement of microclimatic conditions of urban spaces provides more attractive environment and contribute to the sense of well-being (Katzschner 2004).

What are the strategies for urban heat mitigation?

Microclimate is usually described by four elements – *humidity, air temperature, wind and radiation*, out of them only ***wind and radiation can be influenced by landscape elements enough to affect change in thermal conditions.*** Atmosphere fluxes mix humidity and air temperature so efficiently that it is almost impossible to detect any significant changes in the boundaries of the same landscape (Brown and Gillespie). Although sometimes, modifications of wind and radiation that are provided by landscape elements can slightly cause some changes in the air temperatures or humidity level in a small sites.

Any strategy to mitigate heat islands should be evaluated in the context of complex interrelated effects of the varied controls of urban microclimate and final objectives should be established. Sometimes, microclimatic landscape solutions for one problem in certain place and time can contribute to the directly opposite effect on microclimate with the change of season or hour.

1. The first step in planned modification of the urban microclimate is usually ***control of solar gain or radiation*** (wind modification comes

later). This refers to both – shading the urban surfaces to prevent direct sun beams reach them and use the high reflective albedo surfaces.

- ***Shading surfaces*** is described in several studies. It can be the i*ncrease of urban density* – that will provide more shade and thus prevent surfaces form heating (Herrmann and Matzarakis 2012) (Ali-Toudert and Mayer 2007) (Futcher 2008) or it can be done by ***increase of vegetation (***trees and shrubs) (Shahidan and Jones 2008).
- ***Replacing surfaces with high-albedo materials*** reduces the temperature of surfaces exposed to the direct sun light, by reducing absorption of solar radiation. Various case studies and climate simulations approved the efficiency of this method (Latini, Cocci Grifoni et al. 2012) (Brown and Gillespie 1995) (Santamouris 2012).

Both of these principles will influence thermal conditions during the daytime period, but during the night time both of these solutions may provide directly opposite effect on the UHI. First of all, the denser building fabrics due to higher H:W ratios will and lower SVF will cause heat capture inside of the canyons. Secondly, trees that prevent surfaces from overheating by direct sun light during the daytime, during the night emit the absorbed long wave radiation themselves, thus may also restrict nocturnal cooling (Brown and Gillespie) (Erell, Pearlmutter et al.). Finally, increased use of high-albedo surfaces can have a number of unpleasant indirect effects, such as visual glare and increased radiation reflection on pedestrians and building facade, including the glazed parts (Erell, Pearlmutter et al.)

2. The next step in UHI mitigation is usually ***use of airflows and winds.***

- Wind promotes the exchange of energy between the airflow and the surface and thus contributes to cooling effect. Wind speeds in the urban areas are usually 40 to 60 % lower than in open rural surroundings, except for the cases when wind is exaggerated by building geometry (Jacobs 1995).

At the same time, winds, that are so welcome during the hot period of the year are very unwelcome when it is cold, in addition to that, strong winds are not desired by humans, therefore usually winds tried to be avoided and sheltered.

As we can see there is a lot of controversy information in the general heat mitigation methods. Therefore it is suggested to take a closer look in the microclimate modification principles, establish the main objectives for the desired result and choose the methods that are suitable for the particular cases. ***This study research will focus on the impact of radiation and it's modification principles.*** Winds are hardly to predict, especially in urban areas and in addition wind flows are partly or completely blocked in the urban fabric.

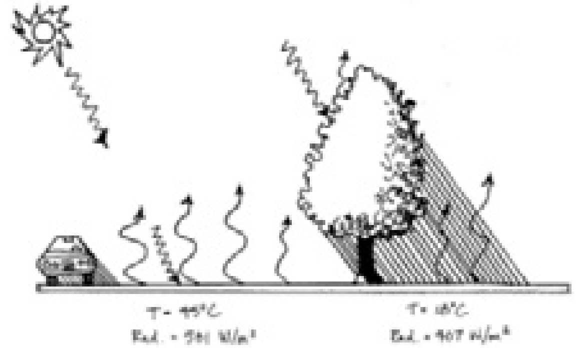
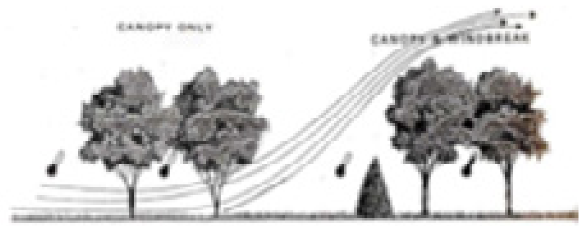


Figure 2.3 The difference between shaded and unshaded area. *Source: Brown and Gillespie, 1995*



Fugure 2.4The impact of air layers movement influenced by tree and shrubs design and as the temperature difference as the result. *Source: Robinette, 1968*

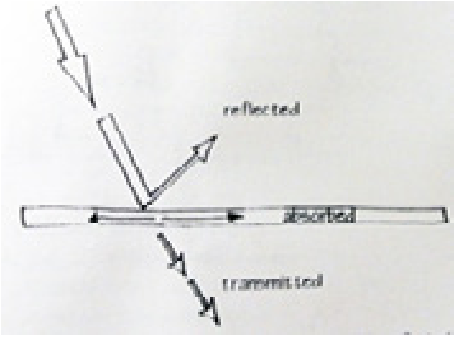


Figure 2.5 The actions of radiation meeting surface
Source: Brown and Gillespie, 1995

2.4 Radiation and it's modification principles

Radiation for the sun "drives" the weather in earth and is the fuel for virtually every microclimate. It is an element of every microclimate that can be significantly modified by the landscapes. It can strongly affect human thermal comfort, energy use of the buildings, and many other elements in a landscape. Despite its importance, radiation often is an elusive element of the landscape. It is important to have a mental image of where radiation comes from, what happen to it when it reaches surfaces, and where it goes.

Radiation behavior

When radiation arrives at any surface, some of it may be reflected, some may be absorbed, and some may be transmited thorough the object. Nothing else can happen to it (Figure 2.5).

- Some of the radiation the reaches a surface is normally reflected, this is a function of the surface's reflectivity. When we discuss the visible light, this is called the albedo of material. The reflected radiation is then available to strike another surface and be similarly reflected, absorbed or transmitted.
- Some portion of radiation reaching the surface is absorbed into material. The energy from the radiation is transferred to the molecules of the material. That excites the molecules and increases the temperature of the material. In opaque materials everything that is not reflected must be absorbed (Brown and Gillespie).
- For transparent and translucent materials there is one more way for radiation – transmittal through the material. This radiation is then available to be received by another surface in the landscape. Natural elements that transmit radiation through them include leaves and water. Artificial elements such as windows, glazing façades of the buildings are also important in the context of this work.

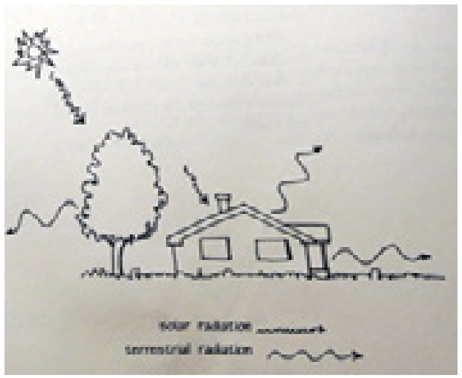


Figure 2.6 Solar and terrestrial radiation
Source: Brown and Gillespie, 1995

Radiation types and geometry

Radiation is normally discussed in terms of two types: ***solar radiation*** (that emitted by the sun) and t***errestrial*** (that emitted by objects on earth). They both are emitted in the same manner, they tend to move through a landscape in the same way, and all radiation has energy that it carries with it.

- ***Solar radiation*** can be received as direct beam (directly from the sun, in parallel beams), and as reflected radiation (after bouncing of another surface), or as diffuse radiation (reflected from the sky).
  - *Direct beam* travels in a straight line.
  - ***Diffuse radiation*** comes approximately equally from all parts of the sky.

- ***Reflected radiation*** can be either directional or diffuse.

- Almost all ***terrestrial radiation*** is received as *direct beam* (directly from other objects, but received from all quarters of the landscape, not in parallel beams).

Because radiation beams travels as straight, parallel lines, the geometry of radiation is fairly easily calculated and very reliable. Thus knowledge of sun angles and some simple trigonometry can provide excellent estimates of shadows cast by objects at various times of the year. Moreover, the amount of terrestrial radiation emitted is a direct function of an object's temperature, so amounts of radiation are also readily determined.

The location of the sun in the sky at any place and at any time can be estimated either from the equations or from tables and charts. Both options work well in most of the cases. Equations for the sun position calculation are programmed in most of three-dimensional graphical software e.g. Sketch Up, Autodesk packages and others. Shadow calculations help to create shadow diagrams that can be useful in estimating whether areas will be in the sun or in the shade at key times of the day and of the year. Shadow diagrams can be expressed in top views, sections and perspectives. In most of the cases it is quite revealing.

Figure 2.7 Impact of radiation. Direct solar light in combination with terrestrial radiation emitted by stone surfaces allows people to lie on the beach in early spring while there is still ice in the water. *Source: http://www.break.com*

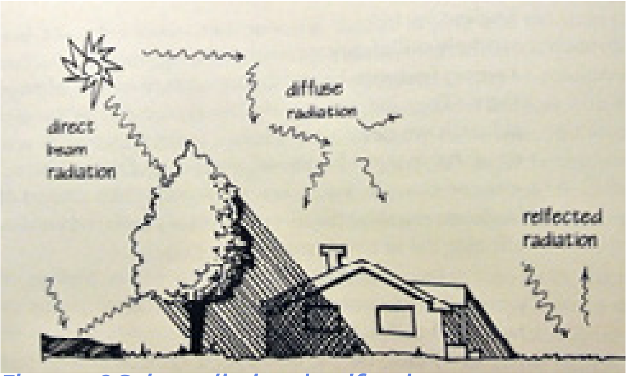


Figure 2.8 Solar radiation classification
Source: Brown and Gillespie, 1995

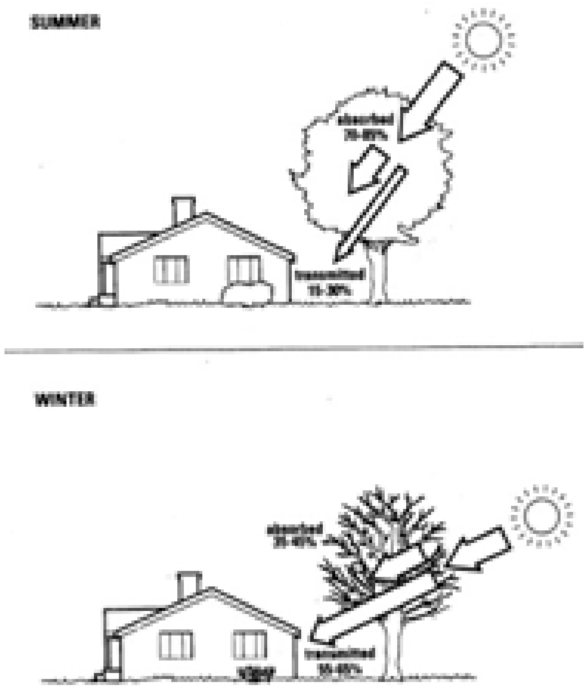


Figure 2.9 Impact of trees in summer and winter
Source: Brown and Gillespie, 1995

Landscape elements and radiation

There are two important issues relative to the impact of landscape elements on solar radiation: ***characteristics*** (size, transmissivity, capacity to store heat, etc.) of landscape elements, and their ***location and orientation.***

With landscape elements it is possible:

1. *Intercept* the radiation before it reaches a surface by placing them in its path.
2. *Cause more or less solar radiation to be reflected or absorbed* by altering the colour and material of an object
3. *Cause more or less heat to be absorbed and emitted* during the different times of the day.

1. Solar radiation can be intercepted by any object between the surface in which you are interested in and the sun. The landscape elements that have the greatest influence on solar radiation in a landscape are generally woody plants and solid structures.

Buildings and solid structures create shade. Radiation in the shade consists of diffuse and reflected radiation, but has very little solar radiation in it. The amount of solar radiation in a shadow is typically about 10% of that in the open on a sunny day, otherwise it would appear completely black to the human eye.

Deciduous trees intercept more radiation when leaves are on the trees and less radiation when they are leafless. All trees allow some solar radiation to pass through their canopies. Different species of trees intercept radiation at different rates at different times of the year. These characteristics cannot be modified, but can be used as valuable knowledge in design. For example, the transmissivity of trees varies by species. It is not possible to change the transmissivity of any tree, but knowing transmissivity values allows you the opportunity to use a tree with a heavy or a light shade in given situations.

Landscape plants have characteristics that affect solar radiation:

- Individual leaves that allow some radiation to be transmitted through them (normally about 20%), absorb some radiation (normally about 50%), and reflect some radiation (normally about 30%)
- The dates when individual species leaf in spring and the dates when they drop their leaves in fall,
- The maximum height of a plant, and
- The transmissivity of the canopy in different seasons (a combination of the characteristics of the leaves, twigs, branches, dates, and size).

Solar radiation is the key consideration in summer. Design should reduce solar radiation receive by a building during overheated periods. It should be just simply shaded form a building to keep the indoor area as cool as possible. In winter, spring and fall all heat sources are welcome, so solar access to exterior walls, roofs, and windows allow radiation to penetrate into the interior of the building and heat the living spaces directly. Deciduous trees that fall their leaves during the winter are the best solutions for this situation.

2. ***Various surface materials and their colours can significantly affect microclimate of the area by reflecting or absorbing solar radiation.*** For example light concrete pavement and dark asphalt influence on the human thermal conditions in a different ways. Dark asphalt absorbs all solar radiation it receives, which in the first half of the day create a cooler thermal conditions for people, because they are not affected by reflected light, in the second half of the day temperature starts to grow because of the emitted terrestrial radiation if the asphalt, after the sunset, asphalt will continue to emit heat, producing warmer environment than the surroundings. Light concrete will mostly reflect solar radiation, which will cause the warmer thermal conditions for people during the first half of the day, later on the thermal conditions will be similar to the conditions in the asphalt pavement and after that become actually cooler, because the reflected solar radiation will cause less heat than the hear emitted by asphalt. At night, concrete surfaces emit much less heat than the asphalt surfaces, what will result cooler environment.

3. Like the surfaces with different albedos, other landscape elements can affect microclimate by ability to absorb solar light and emit terrestrial radiation later. Long wave radiation cannot be seen with the human eye but can be a significant component of a microclimate. This is especially true on clear nights in spring and fall. The earth emits large amounts of long wave radiation, while the clear sky emits very much less. The negative balance can result in considerable cooling of surfaces, and possibly frost. However, if there is the canopy of a tree between the ground and the clear sky, the tree emits considerably more radiation toward the ground than would the sky, so frost can often be eliminated (Brown and Gillespie 1995).

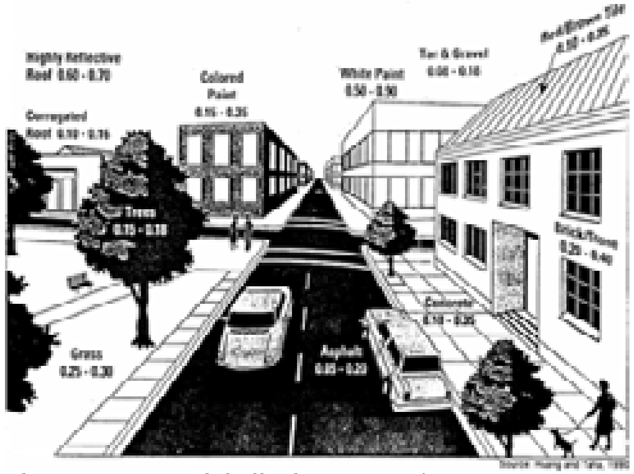


Figure 2.10 Material albedos *Source: http://www.concretepromotion.com/education_11.html*

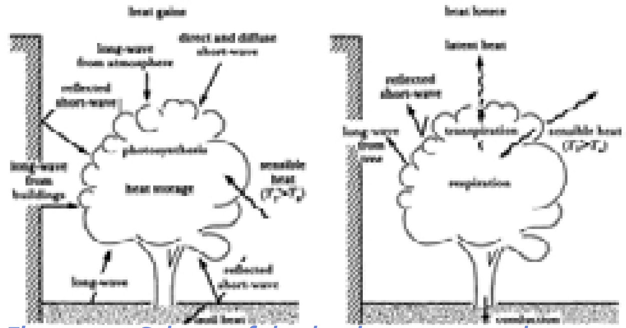


Figure 2.11 Scheme of the daytime energy exchanges between an isolated tree and its street canyon environment. (T1, Ta. temperatures of leaf and air.)
Source: Oke, 1989

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3. Street level research

3.1 What makes a good street?

3.2 Thermal comfort requirements for streets

3.3 Specifics of radiation modification in the street level

3.4 Street canyon geometry

- Height to Width ratio
- Street solar orientation

3.5 Green elements in the streets

- Aesthetical benefits
- Climatic benefits
- The other benefits of green elements

3.6 Complex aspects of street design, climatic control potentials and limitations

- Terrestrial radiation trapping
- Wind tunnel effects
- Summer and winter shadow patterns

3.7 Following research steps

3. Street level research

Streets are the most typical urban spaces that city inhabitants use on everyday basis. They exist in the densest and busy areas of city centres, residential areas of the city peripheries, former or present industrial areas and in the green parts of the cities like parks, urban forests, revitalized or newly developed areas. Some streets are crowded almost all day long, some are used only during certain hours a day and some are empty and deserted almost all the time. Streets can be used only by pedestrians, successfully combine both – human and car traffic and some seems to be made only for the cars. The primary functions of each street as a part of an urban environment are transportation and access, although the streets that are considered as successful urban spaces embrace much more other functions(Carmona, Tiesdell et al. 2010).

Heat mitigation in urban streets canyons and creating comfortable thermal environments for city's inhabitants is the main objective of this research. According to studies about climatic conditions in urban areas it is decided to mitigate heat by modifying radiation which means increasing amount of shadows in the streets and/or, use of high reflective (cooler) surfaces or materials with different abilities to store or emit terrestrial radiation.

Thermal comfort on street level will be achieved by analysis of street functions and strategic use of landscape elements for proving the necessary microclimatic conditions for the certain street parts.

To develop the design concept and principles it is important to understand what makes streets overheated and thermally uncomfortable and what kind of improvements those streets may need?

This will require answers to the certain questions.

First of all - ***what actually makes street comfortable and pleasant***, and what are the qualities of Good Street.

Secondly, ***how can we create heat mitigation strategy*** based on the obtained information? What elements should be used for heat mitigation and thermal comfort and not to sacrifice street qualities at the same time?

Streets are very complex elements of an urban environment; all the strategies to improve the certain qualities of the streets may have side effects on the other aspects of street life. The insight into ***the side effects of chosen urban heat mitigation strategy*** will take place in the final part of this chapter.

3.1 What makes a good street

Streets have to be designed as places. The terms street, boulevards, avenues, etc.,imply design elements lacking in the term 'road': rather than separation, they suggest accommodating and reconciling the demands of movements and social space within substantially the same physical space. Streets should be considered as both social space and connecting – rather than dividing. Moreover streets should be designed with consideration of all users in mind – not only cars, but also cyclists, public transportation vehicles and riders, and pedestrians of all ages and abilities (Carmona, Tiesdell et al. 2010).

Jacobs (1995) in his book "Great Streets" describes the requirements that are necessary for the street to become 'great'. There are certain physical qualities that have to be present, all of them, not one or two: accessibility, bringing people together, publicness, liveability, safety, comfort, participation and responsibility.

The other requirements, described by street characteristic are:

- Places for People to Walk with Some Lei sure
- Physical Comfort
- Qualities That Engage Eyes
- Transparency
- Complementarity
- Maintenance
- Quality of Construction and Design

All these qualities need to be considered during on the stage of street design or during street reconstructions steps. ***Physical comfort*** is the term that most closely refers to the main purpose of the research that is why deserves deeper insight.

The best streets are comfortable, at least as comfortable as they can be in their settings. They offer warmth or sunlight when it is cool and shade and coolness when it is hot. People understand and respond to comfort and the best street designers have understood that. For some streets trees bring shady relief on hot summer days, making a delightful place to be, and they provide some protection from the rain, as do shop awnings (Jacobs 1995).

The need to provide comfortable conditions within the public spaces is an essential part of urban design. Levels of sunlight, shade, temperature, humidity, rain, snow, wind and noise have an impact upon our experience and use of urban environments. A number of design actions can help to make the conditions more acceptable, including the configuration of space and the use of buildings, walls, trees, canopies and arcades for shade and shelter. Desirable conditions will vary by season and by the activities that take place (Carmona, Tiesdell et al. 2010).

As long as the current research focuses on radiation modification which includes and is driven by ***solar light,*** thus it is highly important to find out what is its impact on the streets.

Figure 3.1 Via dei Giubbonari. *Source: Jacobs 1995*

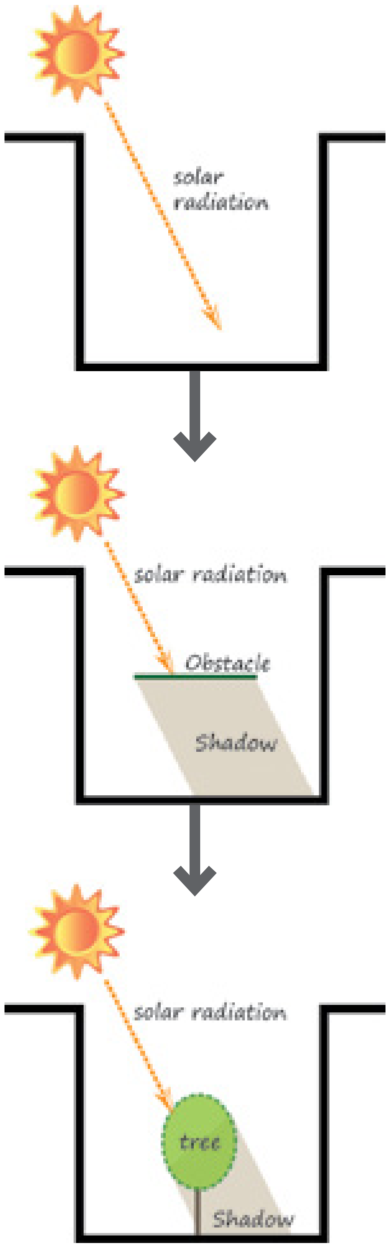

Figure 3.2 Solar radiation modification strategy in street canyon

Sufficient sunlight penetration makes the street pleasant. It also encourages outdoor activities; reduces mould growth; improves health by providing vitamin E; encourages plant growth; and provide a cheap, readily available source of energy for passive and active connection.

The value of sunlight penetration varies over the cycle of the seasons and, while places in the sun are desirable at some times of the year, at other time shade is preferred. Natural lighting provided by sun makes an important contribution to the characters and utility of the public space (Erell, Pearlmutter et al. 2011).

The play of light in urban spaces also has aesthetic dimensions (Carmona, Tiesdell et al. 2010). The contrast of direct sun light and sun light that is penetrating through the tree crowns or other canopies creates sometimes dramatic, sometimes calm and pleasant effect that instantly brings the mood and specific, sometimes unique atmosphere to the place (Jacobs 1995).

This brings the importance of landscape elements that can partly intercept the solar light and create shadows. First and the most common elements that provide this function for the streets are ***trees or the other elements of street vegetation that can provide shadows.*** Trees are considered as elements that brings a significant contribution to general quality of the street. It is also the most efficient, easiest and even cheaper way how to improve street environment (Jacobs 1995).

Due to shadowing abilities trees have contribution into heat mitigation processes as well, enhanced by their evapotranspiration processes (McPherson and Muchnick 2005). At the same time trees on the streets provide the number of ecosystem services such as storm water management, noise barriers, enhance of biodiversity and many others (Bolund and Hunhammar 1999).

Taking into account all benefits that of trees may bring to street qualities it is decided to choose trees and their shadows as a main tool for heat mitigation strategy. The other design elements that can provide shadows will be considered as possible complementing elements as well.

Concluding everything that is said previously, there are certain requirements for making a street a successful urban place and physiological or thermal comfort is one of them. Important climatic parameter that influence street environment is solar light (or solar radiation) which penetration influence street thermal conditions. ***Street trees and their ability to intercept solar radiation are considered as one of the best factors that contribute not only to the heat mitigation but also to the general streets' quality therefore they will be used as a heat mitigation tool for the further research.***

3.2 Thermal comfort requirements for streets

The purpose of design with microclimate is to make the suitable thermal conditions for the place for the majority of people for the majority of time (Brown and Gillespie 1995). Therefore it is important to understand what kind of people are on the streets, what are they doing there and which part of the day, and do they actually experience problems with urban heat.

Streets are mostly used during the daytime by different kind of people. There are the plenty of activities that may take part in the streets but the most general activity is different kinds of movement (e.g. walking – fast and slow, running or biking). The case study of the research is the city of Rotterdam, which refers to mid-latitude cities with moderate climate. Heat stresses in mid-latitude occurs during the warm period of the year and mostly in the summer time.

Assuming the given information, thermal comfort should be provided mostly for:

- ***people on the move***, that requires cool to neutral thermal stress
- ***light time of the day*** – morning, noon and evening, when the PET value and even air temperature are usually higher than required,
- ***warm season of the year*** when the heat stresses are most common.

Main microclimatic landscape design strategy will be ***to cool down the streets during the day by providing shadows for the hot period of the year.***

activities	needed thermal conditions for use of open space	PET
sitting	warm	30
calm activities	warm moderate	26-32
children play	warm moderate	24-26
recreation	neutral	16-24
light movement	neutral	16-24
shopping	warm moderate	26-32
movement	lightly cool	14-24
strong movement	cool to cold	12-24
garden activities	lightly cool	12-24
work outside	neutral to cold	16-22

PET	Thermal sensitivity	Grade of Physiological Stress
	very cold	extreme cold stress
4 °C		
	cold	strong cold stress
8 °C		
	cool	moderate cold stress
13 °C		
	slightly cool	slight cold stress
18 °C		
	neutral (comfortable)	*no thermal stress*
23 °C		
	slightly warm	slight heat stress
29 °C		
	warm	moderate heat stress
35 °C		
	hot	strong heat stress
41 °C		
	very hot	extreme heat stress

Table 3.1 and 3.2 Thermal conditions for typical street activities (marked with fed frame). *Adopted from: Mayer, Matzarakis 1993 and Katzschner 2004*

3.3 Specifics of radiation modification in the street level

The basic solution to cool down the street during the daytime is ***to reduce amount of solar radiation by providing shadows for the street.*** To achieve this street scale landscape design elements like trees and constructions for climbing plants will be used.

Nevertheless there are several specific cases to deal with:

- due to the fact that Rotterdam and the Netherlands in general don't enjoy too much sun during the year, some solar access at least for the indoors should be provided,
- even for the hot summer time the solar radiation shouldn't be removed from the streets completely,
- Parts of the streets that stay shaded for the most of the day by street buildings itself, should remain exposed to the sun when it is possible.

To implement this strategy it is important to:

- First, analyse the shadow patterns of street canyons itself to figure out which parts of the street face heat problems and for how long, which refers to studies about street canyon geometry.
- Second, take a closer look on the shading abilities of different types of green elements e.g. trees or constructions for climbing plants.

The successful combination of canyons and vegetation shadow patterns will reduce solar radiation where it is necessary and will make the environment more comfortable.

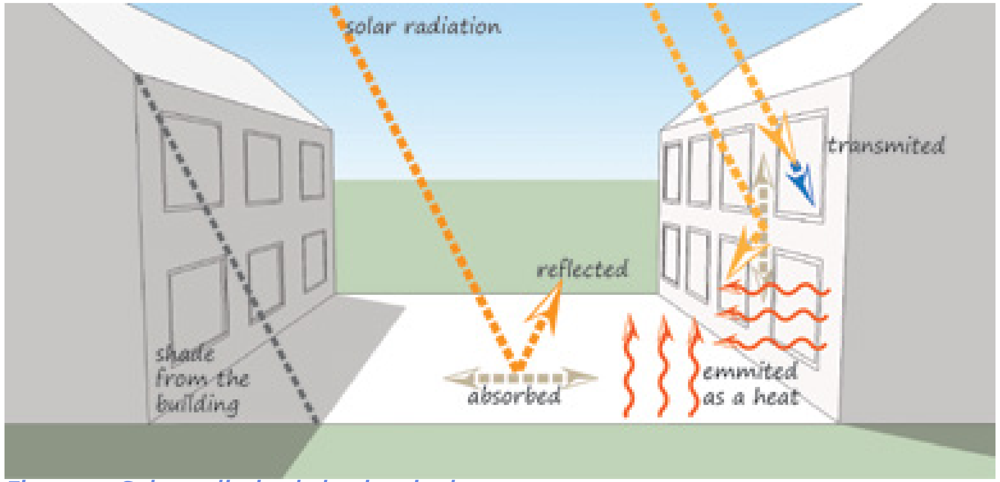

Figure 3.4 Solar radiation behaviour in the street canyon.

3.4 Street canyon geometry

Street is a linear three-dimension spaces, enclosed on opposite sides by buildings (Carmona, Tiesdell et al. 2010). Good streets always have clear spatial definition. Streets are defined in two ways: vertically which has to do with the height of walls or trees along a street; and horizontally, which has to do with the length of and spacing between whatever is doing the defining. The wider the street gets the more mass or height it takes to define it. Many fine streets are lined with trees, and these may be as important as the buildings in creating street definition (Jacobs 1995). The definitions of the streets with buildings and other solid structures are at the same time the factors that convert space into the street canyon and the group of canyons creates the specific building density and building form of urban area (Erell, Pearlmutter et al. 2011).

Built density and built form are composite variables combining parameters such as the area of exposed external surface, the thermal capacities and surface reflectance of built elements, and the view of sun and sky by surfaces. Individually or in combination, these parameters have multiple effects on the urban microclimate. They influence the magnitude of incident solar radiation, the air movement inside and outside buildings, and the mean and peak temperatures of outdoor air and surfaces (Yannas 2001). The deeper insight in the solar radiation gain in the urban areas shows two contrary things. The external area of buildings and streets is much larger compare with flat open rural surroundings and receive a larger total amount of solar radiation. However view of the sun is often obstructed due to overshadowing by neighbouring buildings. It can be stated in the conclusion, that surface's view of the sun at any given time is largely determined by the built form and by street widths and orientations (Yannas 2001).

Studies of Ali-Tourdert and Mayer (2006), Futcher (2008), Herrmann and Matzarakis (2012) are focusing on the temperature patterns within the urban canyons and the way they are influenced by street geometry. Those studies conclude that ***the more exposed to the sun the canyon is the higher mean surface and air temperatures are.*** The results are influenced by streets height to width ratios and orientation towards sun. It is needs to be mentioned that studies were made independently in different cities, with different sun falling angles, and yet, all of them came to the similar conclusions.

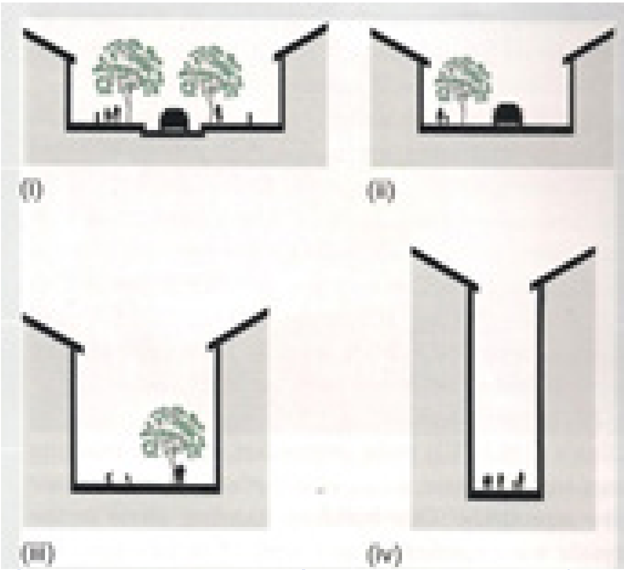

Figure 3.5 ***Canyon H:W ratios.*** *Source: Carmona and Tiesdell et al. 2010*

Height to Width ratio

The height to with ratio, also known as the aspect ratio, describes the sectional proportions of the urban canyon. It is defined as the ratio between the average height of adjacent vertical elements and the average width of the space (wall to wall distance across the street).

The aspect ratio of the street is a basic urban design descriptor that even has historical ramifications. The street dimension is defined as the ratio between the width of the street floor and the height of the vertical elements, usually comprising by buildings and vegetation, or both. This ratio indicates the spatial characteristics of the street, architecturally differentiated between the narrow alleys of the medieval and the broad boulevards of the Baroque. Each architectural trend has developed its own definition of optimal street dimensions, and numerous theories dive description of the three-dimensional significance of the streetscape, or its 'architectural dynamics'(Erell, Pearlmutter et al. 2011).

Street has only two walls to determine the space. The continuity of street wall and the height-to-width ratio determine the sense of spatial enclosure within the street, while its width determines how the surrounding architecture is seen. Streets with 1:4 ratios have three times as much sky as wall within the cone of vision, giving a weak sense-of-enclosure. Ratios between 1:2 and 1:2.5 provide a good sense of enclosure in a street. Ratios of 1:1 are often considered the minimum for comfortable urban streets. If surrounding building height exceeds the width of the space then the tops of the buildings won't be visible without looking up. Such ratios, like 2:1 or more reduce light penetration into the space and may be claustrophobic (Carmona, Tiesdell et al. 2010).

Besides the psychological impact and the architectural tendencies height to width ratio of the street canyon ***determines the amount of the surface area that is exposed to the sun and that stays in the shadow.*** The amount of heat transferred from the canyon facets to air depends upon the surface temperature, which in turn directly affected by the exposure of the sun. The surface temperature is lower for shaded areas, typically favoured by high aspect ratios (Ali-Tourdert and Mayer 2006). It shows the importance to analyse the solar exposure if the canyons with different H/W ratios to understand what parts of the streets get too much of the sunlight and cause urban heat, and what parts of the streets stays in the shadow, and, therefore don't have much influence on heat production.

Street solar orientation

The canyon axis orientation represents the direction of the elongated pace, measured (in degrees) as the angle between a line running north-south and the main axis running the length of the street or other linear space, measured in clockwise direction. Often the canyon axis orientation is simply described by the closest cardinal direction (N-S or E-W) or diagonal (NW-SE, NE-SW) (Erell, Pearlmutter et al. 2011).

If the amount of area that is exposed to the sun (both for vertical and horizontal surfaces) depends mostly on the height to width ratio of the street canyon, ***the exact locations of the areas with peak temperatures depends of the street orientation towards sun*** (Herrmann and Matzarakis 2012).

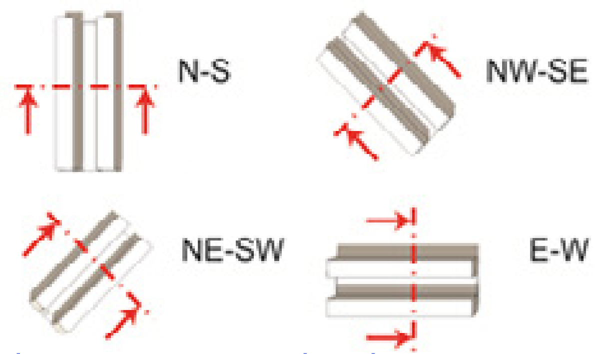

Figure 3.6 Street canyon orientations.

3.5 Green elements in the streets

In the last thirty years there is an increasing scientific knowledge and a more general awareness about the beneficial effects of green area and vegetal biomass (Correa, Ruiz et al. 2012). Trees and nature are an important element of outdoor environments and there is a positive relationship between natural environments and psychological or social benefits (Wolf 2008). Moreover, urban trees have different functions which can be classified as architectural, functional, engineering, climatic and aesthetic.

Aesthetical benefits

From the aesthetical perception Jacobs (1995) writes that trees refer to the qualities that contribute to the good street. Streets might not have trees, but be very successful in the general perception. However, from all the possible improvements of the street aesthetical qualities – trees are the easiest, most effective and cheapest way. Green is a psychologically restful, agreeable colour; trees move and modulate light that is a major contribution not only to physical conditions, but also to psychological comfort and sense of wellbeing.

The assumption of positive effect of trees and vegetation can look like this:

- Physical comfort (microclimate)
- Definition, boundaries to the streets
- Safety
- Qualities that engage eyes
    - o Shadow pattern
    - o Leaf movements
    - o Seasonal changes
    - o Smaller details, textures
- Sighs of habitation
- Transparency
- Psychological comfort and sense of well-being (Jacobs 1995).

Figure 3.7 Trees on the street.
Source: http://lebomag.com

Climatic benefits

The climatic impact of plants around the building is quite certain and performs in a different ways.

- Trees with high canopy and pergolas near walls and windows provide shade and reduce the solar heat gain with relatively small blockage of the wind (shading effect).
- Vines climbing over walls and high shrubs next to the walls, while providing shade, also reduce appreciably the wind speed next to the walls (shading and insulation effects).
- Plants near the building can lower the air temperature next to the skin of the building, thus reducing the conductive and infiltration heat gains. In winter, they reduce desired solar gain and may increase wall wetness after the rain.
- Ground cover by plants around a building reduces the reflected solar radiation and the long wave radiation emitted toward the walls from the surrounding area, thus lowering the

solar and long wave heat gain in summer.

- If the ambient temperature around the air conditioning condenser of a building can be lowered by plants, the COP of the system can be improved.
- By reducing the wind speed around the building in winter, plants can reduce the infiltration rates and the heating energy use of buildings (insulation effect).
- Plants on the southern side of a building can reduce its potential to use solar energy for heating. Plants on the western and eastern sides can provide effective protection from solar gain in summer.

Seen from a human bio-meteorological point of view, the micro-scale climate below canopy is pleasant to people because of a reduced thermal stress in summer. Tree canopies provide the shelter between people bellow and direct sun this way significantly reducing the direct solar radiation gain. The reduction of thermal stress by tree canopies can be up to three levels of thermal perception according to the classification by Matzarakis an Mayer (1996) presented in the table 1 (Mayer and Martzarakis 2006).

The other benefits of green elements

Urban green areas can have a marked effect on many aspects of the quality of the urban environment not only because its aesthetical values and climate control functions. Urban vegetation affects air pollution, works as a noise barrier, and even shapes the urban development and provides number of general ecological functions.

Besides urban climate improvement vegetated areas also ***improve urban natural ventilation***, in certain conditions ***reduce air pollution*** from transportation, industry, heating installations and natural dust. Green elements also work as a different scale ***noise barriers***: from the large traffic areas till noises that are coming from the children plays and neighbours next door.

From the urban development point of view, green areas ***determine future urban expansion***; reserve the land for the future development, ***increase safety of motor traffic*** by open space margins alongside the roads, ***separate the areas*** between neighbourhoods or areas with different land uses.

Finally, the general ecological factors of green elements in urban environment are ***flood control***, ***retention and absorption of rain wate***r, ***protection of natural flora and fauna*** and enhancing biodiversity in urban areas.

Urban parks provide also a ***variety of social and psychological needs of the residents***, for example children's play, social meeting, recreation, privacy, etc. Under a favourable circumstances and appropriate physical design details, the parks may help in creating a feeling of a "community" in the neighbourhood (Givoni 1991).

So, as it is possible to see: vegetation in urban areas is highly desirable by various reasons, which makes it probably the most welcome tool for heat mitigation in street urban canyons.

Figure 3.8 Water retention by green infrastructure.
Source: http://water.epa.gov

3.6 Complex aspects of street design, climatic control potentials and limitations

This study focuses on urban geometry, green elements and shadow patterns they cause to reduce urban heat gains. At the same time streets are very complex elements of the urban areas and there are plenty of factors that influence different environmental qualities. Streets have certain functions that determine its layout, and using intensity. Streets have specific architecture of the buildings and buildings themselves can significantly influence space qualities.

Those factors may influence microclimatic conditions as well. For example – sky view factor determines nocturnal cooling potentials. Wind contributes to street cooling, influences thermal comfort and air quality. Both of those factors in a combination with green elements may minimize urban heat, and even cause directly opposite effect.

Seasonal changes result lack of sun in the cold period of the year, when it is highly desirable. Trees that meant to provide shadows during summer time can make this situation even worse in winter.

That is why not only shading but other impacts of vegetation on a microclimate need to be mentioned as well. They are not necessarily negative or imitating, but nevertheless it is important to be aware, and take them into account during the design principle development and actual street design part.

Figure 3.9 Street completely shaded by trees. *Source: http://www.deeproot.com/*

Terrestrial radiation trapping

One of the important parameters in the Urban Heat island formation is the heat trapping within the street canyons and ***low potential for nocturnal cooling due to low sky view factor*** (Brown and Gillespie 1995; Erell, Pearlmutter et al. 2011; Andreou 2013).

Although trees' canopies perform best for urban heat mitigation and creating more comfortable thermal environments during the hot summer days they may have a significant impact on the restriction of the nocturnal cooling (Correa, Ruiz et al. 2012). Terrestrial radiation that is emitted from the ground surfaces get trapped in trees' canopies. At the same time trees are able to emit terrestrial radiation themselves that is why the air below the trees on the street level during the summer nights may be much warmer than in the open surroundings (Brown and Gillespie 1995).

According to this information it is important to keep in mind that open areas with low Sky view factor that are exposed to the sun during the daytime and cause significant heat gains, have certain potentials for street cooling during the night time.

It can be quite beneficial to leave the open, treeless spaces in the certain areas of street canyons to provide nocturnal cooling and enhance heat mitigation. High albedo surfaces should be used in these situations because they absorb less solar energy due its reflectiveness and therefore emit less heat into the air.

Sky-view factor regulation within street canyon can be achieved by varying tree species according to height to width ratio of street canyon itself. Small streets will have a larger SVF with short trees, larger street canyons will benefit from the taller trees (Correa, Ruiz et al. 2012).

It is need to be mentioned, that in the middle latitude European cities thermal conditions during the night are not very hot. Nevertheless the continuous heat gains and low heat losses finally may become critical and create quite unpleasant and even problematic situations; therefore it is quite important to focus not only on shadowing surfaces during the day but also on the heat loses during the night.

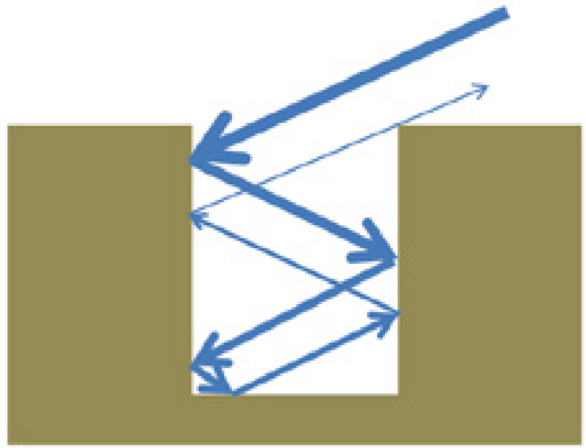

Figure 3.10 Heat absorbtion in the street canyon. *Source: Harst 2011*

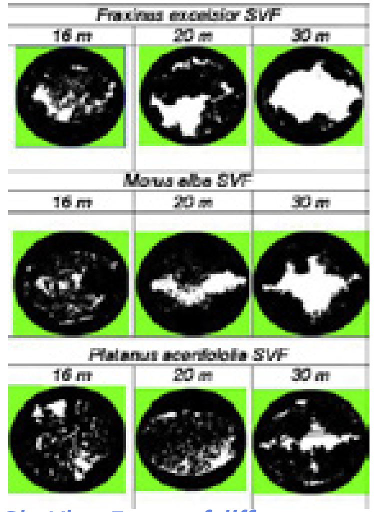

Figure 3.11 Sky View Factor of different tree species for the different street widths. *Source: Correa, Ruiz et al. 2012*

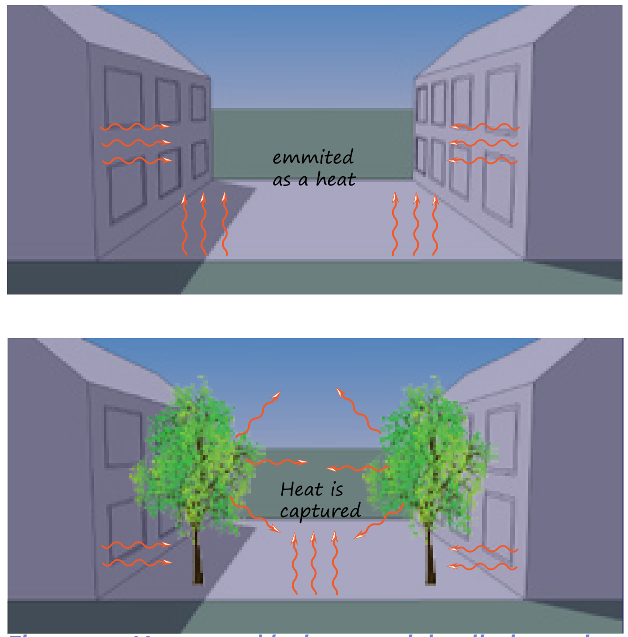

Figure 3.12 Vegetaton block terrestrial radiation emission and therefore prevents nocturnal cooling.

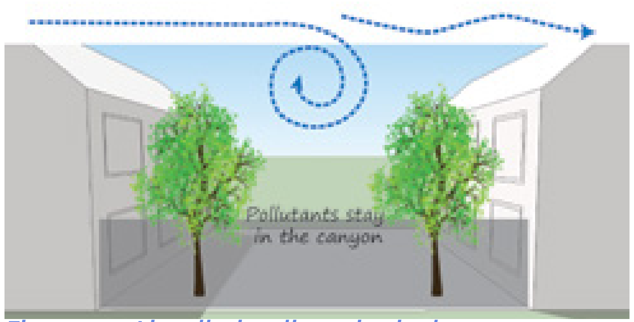

Figure 3.13 ***Air pollution dispersion in the street canyons with and without trees.*** *Adopted from: Beplanting en Luchtkwaliteit. 2012*

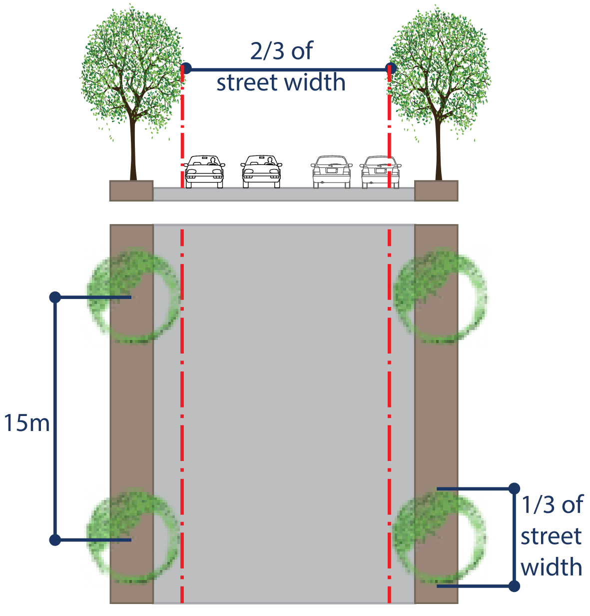

Figure 3.14 ***Recommendations for trees plantations along the streets to avoid poluttant particle concentrations.*** *Adopted from: Beplanting en Luchtkwaliteit. 2012*

Wind tunnel effect

Wind conditions inside the street canyon un urban areas are reduced till 40-60% of the possible wind speeds in the open rural areas unless it is not enhanced within the street configurations (Erell, Pearlmutter et al. 2011) (Jacobs 1995). Trees within the stress canyons reduce the wind speeds even more, minimising the dispersion potentials and therefore ***reducing the amount of particles coming out of the street canyon*** (Salim, Cheah et al. 2011). At the same time the turbulence effects caused by trees on the both sides of the road contribute to the ***vertical mixture of layers which affects air quality even more*** (Salim, Cheah et al. 2011; 2012).

This problem is occurs in almost every street canyon but the most relevant cases are the street canyons with heavy vehicle load.

It is need to remember that permeable windbreaks reduce the turbulence effect. So it is important to use the trees with tall trunks, loose foliage and absence of shrubbery to form permeable and penetrable wind barriers.

One of the studies on air quality along the roads proposed the guidelines to keep trees in with 15m distance between trees in the line and tree crown to spread for no longer than 1/3 of the street width (Figure 3.14). These recommendations may improve the air quality in the street level but at the same time significantly reduce street shading that is desirable in the context of this thesis.

That is why it is important to understand which kind of problems streets may face and which improvements are more relevant. Does the heat mitigation is more important than the air quality? Will those interventions actually improve or worsen the situation? Trees on the street may significantly influence thermal perception, but would it be more pleasant to stay in the street with high air pollution level? From the other side, would wind vortexes solve the problem in this case? Winds can provide the cooling effect as well but would people feel better staying in the windy street even if they would know that the air quality there is better?

All aspects and factors should be carefully analysed for its relevance and importance and there is never the one and only right solution.

Summer and winter shadow pattern within street canyons

In the European cities and in the case of Rotterdam shadow patterns in summer are the shortest. Urban heat problems arise during the summer time as well, that is why summer time solar patterns will be considered further in the shadow pattern research.

However the thermal comfort in winter shouldn't be sacrificed. In winter people actually need sun both: outdoors and indoors. Shadows in winter are the longest due to the low sun angles and largest. That is why trees may cause lack of solar access.

From the other side, shadows caused by deciduous trees are transparent, so they do not provide that much shade in winter in comparison with coniferous trees.

However, long and dense rows of trees even leafless may noticeable block solar light along the windows or places where people have slow or calm activities (like sitting or children playing).

It is unusual to see the coniferous trees in the street plantations; however, even the single plant in the private garden in some conditions may cause the large and unpleasant shadow for all over the street in the time of year where people actually need sun.

Trees in the rows next to the buildings should be planted with some visible distance between trees' crowns. Places that are used for some rest, or children playgrounds, or small squares in front of the cafeterias need to have parts with year round solar access. Coniferous trees should try to be avoided, unless the space for the plants isn't thoughtfully analysed in terms of shadowing pattern all year round.

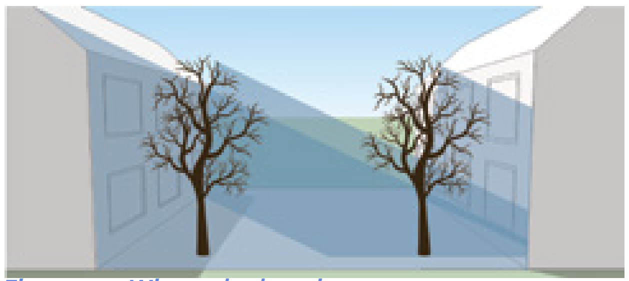

Figure 3.15 Winter shadows in street canyon

3.7 Following research steps

After theoretical aspects of urban climate in streets canyons were studied and possible heat mitigation strategies and tools were described it is necessary to develop the actual model for thermal condition analysis in street canyons and create the specific design principles for heat mitigation.

The role of street canyon geometry and urban green elements needs to be investigated more carefully. This will be achieved by using the graphical design software for shadow simulation and result processing in the following chapter - Shadow pattern research.

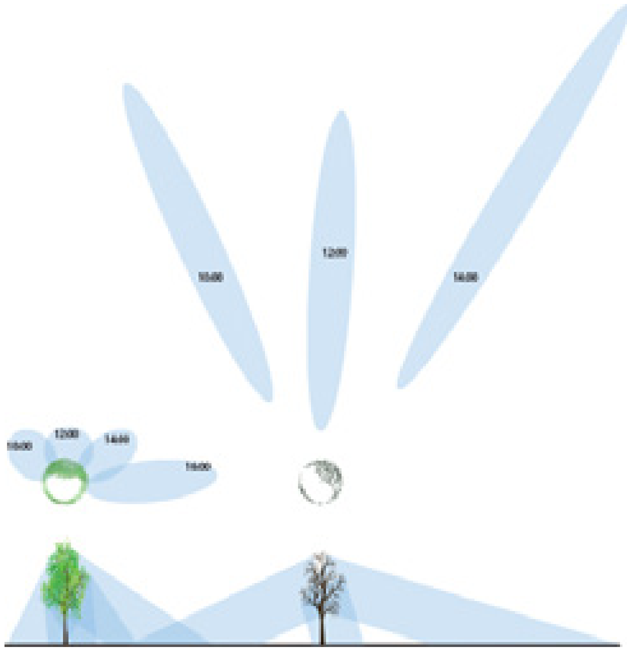

Figure 3.16 Summer and winter shadow pattern of a single tree.

Figure 3.17 Seasonal change of deciduous and coniferous trees. *Sources: www.shutterstock.com and http://www.123rf.com.*

Figure 3.18 Under the leafless trees. Yanidel street photography. *Source: http://www.yanidel.net*

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4. Development of shading design in street canyons

4.1. Research objectives and methods

- Shadow simulations
- Shadow pattern overview
- Street and trees shadow pattern combination

4.2. Shadows in the street canyon

- Parameters of street canyon geometry that influence shading
- Solar exposure/shading analysis

4.3. Shadows by green elements

- Parameters of green elements that influence shading
- Shading impacts of green facades
- Shadow efficient application of green elements

4.4. Combination of street geometry and green elements

- Street shading guidelines
- Street canyon and trees specifications and process
- Recommended street shading combinations and design principles

4.5. How to design thermally comfortable streets? Recommendations for practitioners

4. Development of shading design in street canyons

Thermal condition in the street canyons especially during the day strongly depends on the amount of the area that is exposed to the sun (Herrmann and Matzarakis 2012). Shadows influence thermal environment is two ways:

- first, surfaces that stay in the shadow get less solar radiation, and, therefore stays cooler and emit less terrestrial radiation to the air afterwards (Brown and Gillespie 1995; Klok, Zwart et al. 2012);

- secondly, people who stay in the shadow feel cooler due to the lack of solar radiation (Brown and Gillespie 1995; Katzschner 2004; Mayer, Kuppe et al. 2009).

According to this ***the more surface is shaded, the cooler thermal environment is***, which is very important in the summer time. At the same time too much shadow on the streets may cause the negative effect in winter time, when shadows are not desirable and landscape elements that are used for shading may influence the other aspects of street environment in a negative way.

Practical search for the most efficient solution for street shading is the main topic of this chapter.

4.1. Research objectives and methods

The objective of the research is ***to find the efficient way for street shading.*** This requires:

- Study of ***shadow patterns of street canyon itself*** to figure out what parts of the streets need additional shading and
- ***Studies of the shading abilities of*** such landscape elements like ***trees and green facades.***

Shadow simulations

Visual representation of shadow pattern can be achieved by digital simulation of the shadow from any object for the given location and time period. In this research shadow simulations will be created by computer programme SketchUp – one of the basic 3 dimensional design software developed by Google. Main parameters for shadows simulation are:

- ***Location*** - case study of this research: Rotterdam, ***Bergpolder-Zuid.***
- ***Time of the year – Summer and Winter solstices***
- ***Periods of the day:***
    - ***10:00*** (morning sun) when the air temperature starts to grow.
    - ***12:00*** (noon sun) the highest so-

lar activity, the shortest solar falling angle.

- ***14:00*** (afternoon sun) still high solar activity and air temperature close to maximum during the day
- ***16:00*** (evening sun) low solar activity but the maximal registered air temperatures during the day.

Shadow pattern combination – shadow patterns at 10:00, 12:00, 14:00 and 16:00 will be combined together to get and overview of diurnal patterns for summer and winter solstices.

Shadow pattern overview

Combinations of shadows forms diurnal shadow patterns and are created with the help of graphical design software. AutoCAD from Autodesk and Illustrator from Adobe Suit are used in this thesis and represent in 2 dimensions – side view, for the streets it is a canyon section and top view.

Example of shadow combination process for street canyons is represented on a Figure 4.1 and for the trees on the Figure 4.2.

Street and trees shadow pattern combination

After diurnal shadow pattern combinations are created ,they will be used to find the optimal solutions for street shading. ***Shadow patterns in the street canyons will represent areas that are exposed to the sun for the certain amount of hours*** and determine the different requirements for certain street parts. ***Shadow patterns on the trees will help to find the optimal distances, arrangements and locations of trees between themselves and in a context of street canyon.***

After both of the aspects will be combined together for the search of the best combinations of trees in street canyons. Those combinations will be considered as design principles for the heat mitigation strategy in streets and will be applied for the case study design.

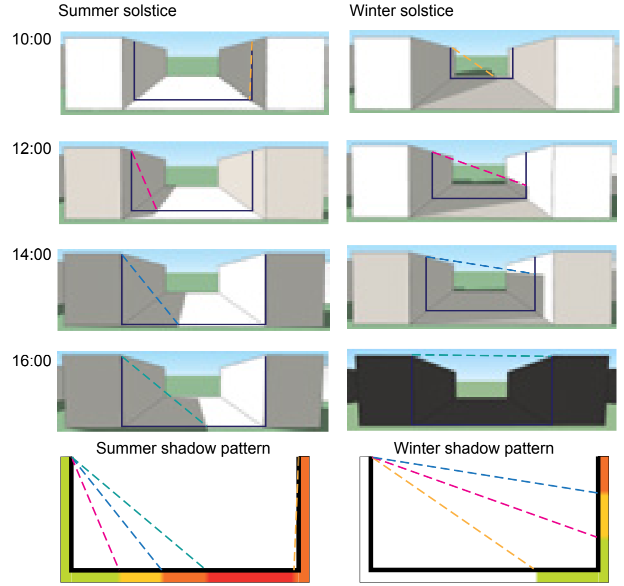


Figure 4.1 Example of shadow pattern simulation and diurnal solar exposure calculation in street canyon.

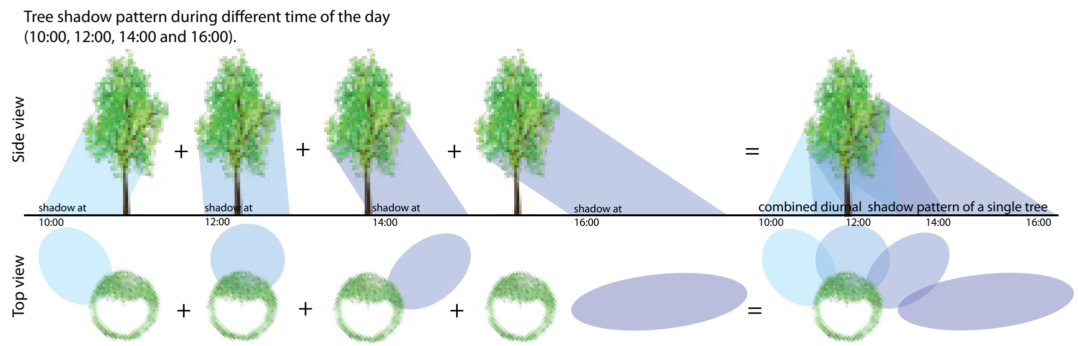


Figure 4.2 Example diurnal shadow pattern calculation.

4.2. Shadows in the street canyon

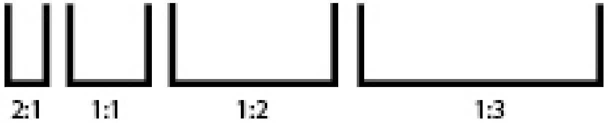


Figure 4.3 4 analyzed street H:W ratios

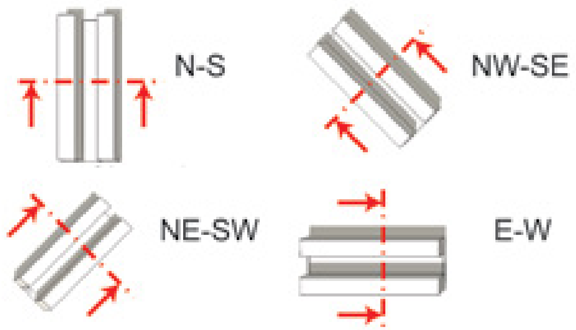


Figure 4.4. 4 analyzed street orientations towards the sun

Figure 4.5 Base for street canyon diurnal solar exposure analysis

Parameters of street canyon geometry that influence shading

Heigh to Width ratio

Height to width ratio of the street canyon determines the amount of the surface area that is exposed to the sun and that stays in the shadow. The aspect ratios represent proportion of the urban canyon, not the actual dimensions. Visible solar radiation travels like a straight line and therefore the results should be equal for the small countryside street with actual dimensions of 10 m width and houses of 10 m tall and for the major city street with 30 m width and the buildings with the same height.

Based on Carmona's description of the impact of H/W ratios of street enclosure (2011) and studies of Ali-Tourdert and Mayer (2005) on the effect of aspect ration the thermal comfort it is decided to simulate shadows for 4 groups of street canyons with aspect ratios 2:1, 1:1, 1:2 and 1:3.

Orientation towards sun

Orientation towards the sun determine the exact locations of the areas with peak temperatures (Herrmann and Matzarakis 2012). Shadows of street canyons will be simulated for both cardinal and both diagonal directions – N-S, E-W, NE-SW ad NW-SE. It will provide more or less precise overview for almost all possible street orientations.

Solar exposure/shading analysis

To make an analysis of street canyon solar exposure based on the canyon geometry it is decided to combine the aspect ratios and orientation towards sun and make the shadow simulations for all obtained street canyons. The amount of shaded and exposed to the sun areas will be calculated in three dimensional models, but presented in two dimensional sections to simplify the general overview (figure 4.1).

Analysis is presented on the Figure 4.6, where it is possible to see how much area is exposed to the sun and for how many hours. Based on this analysis, literature studies about thermal conditions on the streets and average diurnal temperatures patterns in the city of Rotterdam it is concluded that:

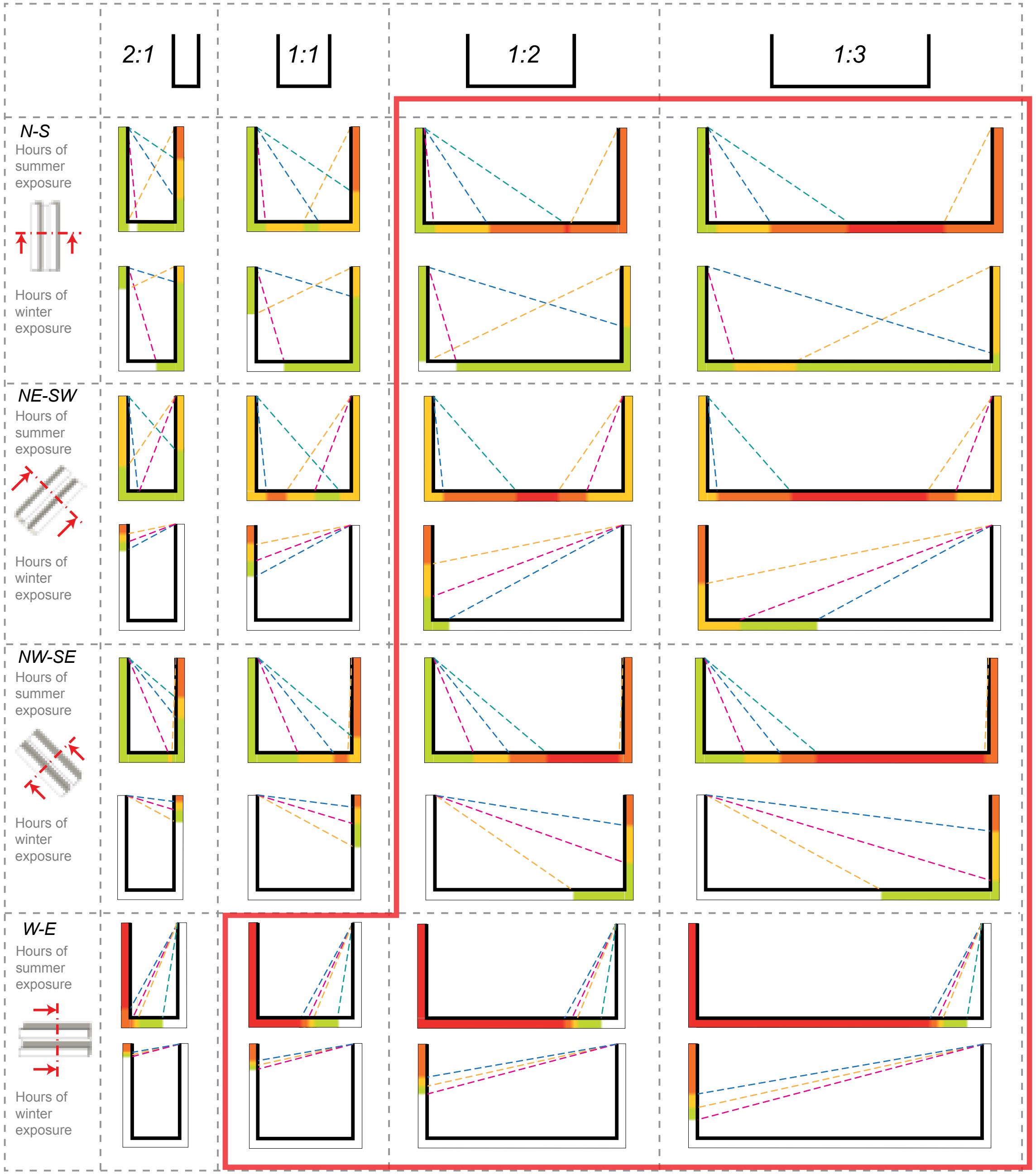
- ***streets that mainly face urban heat problems are the streets in which half the horizontal surface is exposed to the sun longer than 6 hours a day between 10:00 and 18:00 in the hot period of the year.***

That means that all four possible street canyon orientations (N-S, NE-SW, NW-SE, E-W) with H/W ratios 1:2 and 1:3 and E-W orientated street canyon with H/W ratio 1:1 are problematic due to uban heat vulnerability.

• If street is exposed to the sun for longer than 6 hours – it means that it will definitely be exposed to the sun during the noon time (12:00 and 14:00) – when the solar activity is the strongest and the surface is heated the most ad afternoon time (14:00 and 16:00) when the air temperature is the highest plus some hours more.

This analysis can be relevant not only for the city of Rotterdam. Shadow simulations can be done for every point of the world as well and for every situation in the world it can be decided which amount of solar light can be acceptable for which street.

For example, for the streets in the warm climates even 4 hours of street solar exposure can create too hot thermal conditions. At the same time for the cold northern climates areas that are exposed to the sun for all day long are used the most and considered as pleasant.



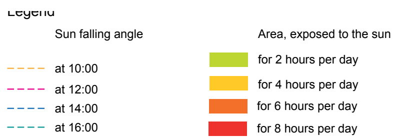


Figure 4.6 Diurnal solar exposure analysis of street canyons.

4.3. Shadows by green elements

Figure 4.7 Tree shadow.
Source: http://www.glynnislessing.com 2009

The areas of street canyons that are not shaded by the canyons themselves and remain exposed to the sun for 6 or 8 hours a day is possible to shade by green elements such as trees and/or constructions for climbing plants. This chapter will focus on the shadow patterns that are provided by these green elements.

This part of the research will discuss parameters of green elements that influence their shading abilities. Shadow patterns of the trees will determine optimal locations, arrangements and distances between trees themselves and even canyon facets.

Parameters of green elements that influence shading

Forms, shape and sizes of a single tree

Shadow simulations originally were made for 5 tree shapes: coniferous (pine tree and spruce tree) and deciduous (column, oval and round shape). Each tree form were presented in 3 sized – small (less than 10m high), medium (between 10m and 15m) and large (taller than 17m).

After the literature review of the most common street tree plantations in the Netherlands it was decided to exclude the coniferous trees from the research because they are almost never used for the street vegetation and in addition to that cast too much undesirable shadows in winter and continue to work with ***deciduous trees***.

Shadow simulations showed, that the largest shadows were performed by ***round tree shaped of each size***. Therefore it was decided to use the round tree shapes of each of 3 sizes for the further research.

The greater are trees sizes the larger shadow they cast.

- ***Taller trees cast longer shadows than shorter trees.***
- ***Wider crown diameters create wider shadows than trees with narrow crowns.***

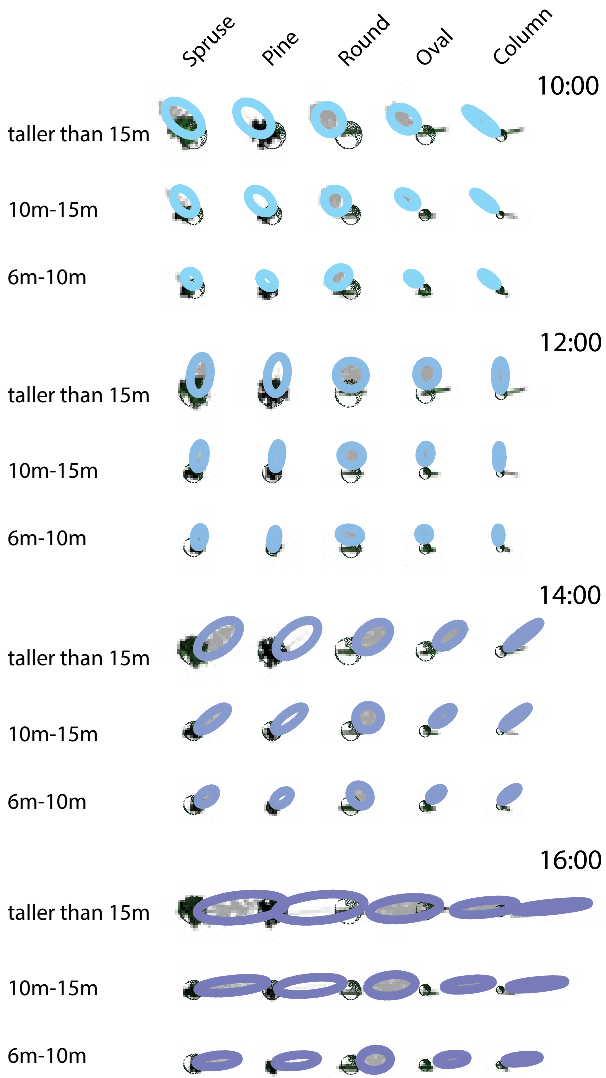


Figure 4.8 Shadow simulations for different types of trees

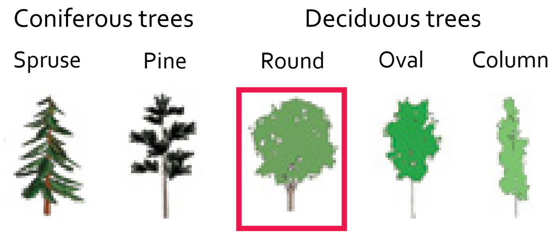


Figure 4.9 Analyzed types of trees

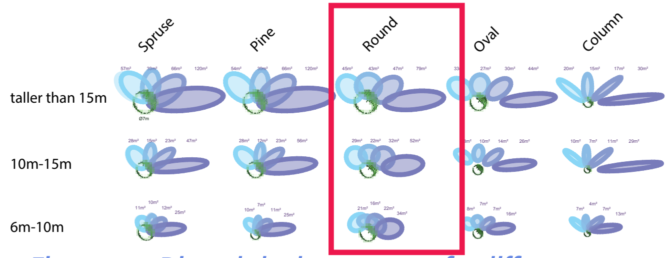


Figure 4.10 Diurnal shadow patterns for different types of trees

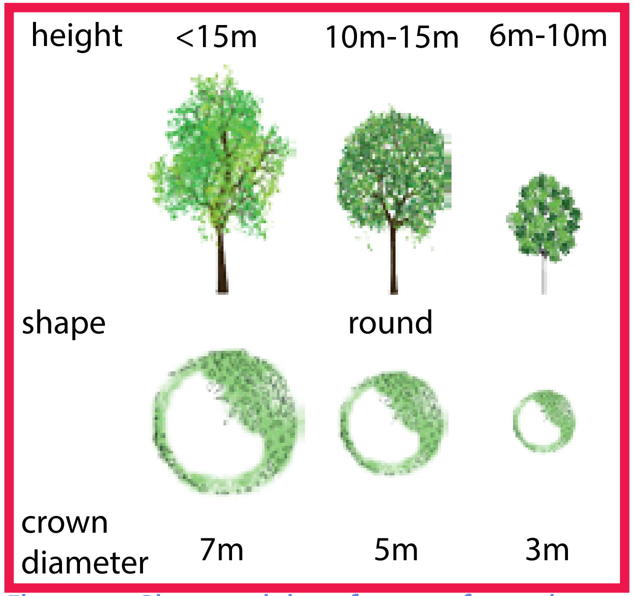


Figure 4.11 Shapes and sizes of 3 types of trees that were chosen for further consideration

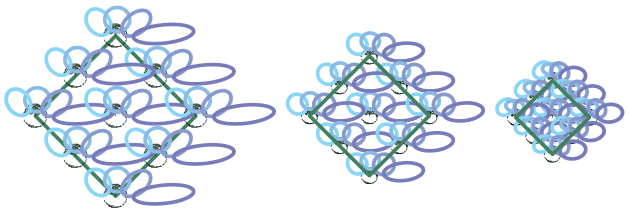


Figure 4.12 Diurnal shadow patterns for groups of trees with different size and different distances in between.

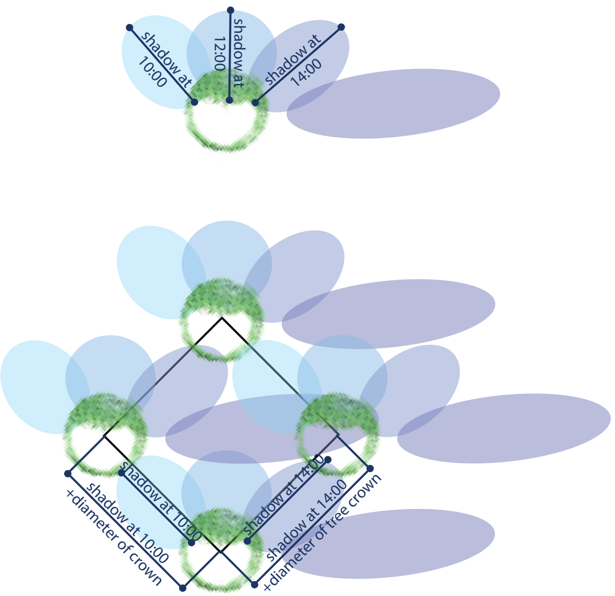


Figure 4.13 The optimal distances between trees.

Distances between separate trees

Trees can be planted close or far away from each other. Depending on the planting distance shadows they create can be denser or looser. In cases when tees are planted too far from each other they can even have parts of the surface that is exposed to the sun.

Due to the fact that streets have a certain functions that do not allow planting trees too close to each other and the purpose of the research is to find the most efficient way of planting trees for heat mitigation, it is decided to find the way to plant trees in a group that can shade all possible surface below at least for a certain period of the day.

In this case, ***the distance between trees in a group should be short enough to shade all horizontal surface below tree canopies at least for some hours and at the same time long enough to exclude the overlap of the shadows.***

Shadow pattern projections vertically and horizontally can visually represent the distances between trees in a groups and rows (Figure 4.14). According to this figure the optimal distances between trees are the cases, where shadows complement not overlaps each other. In this case the distance between tree crowns equals tree shadow lengths at 10:00 or 14:00. (Figure 4.13)

Of course this if in the exact design case denser, or looser shadows are required trees can be planted with relatively closer of longer distances.

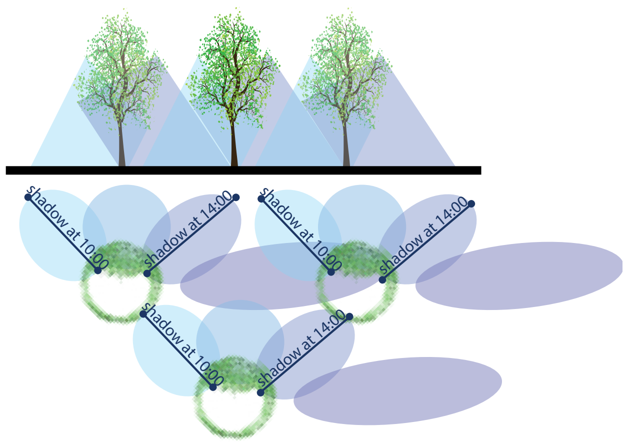


Figure 4.14 The optimal distances between trees.

To shade the largest area with the minimal use of trees ***distance between crowns of the trees should be equal the shadow length at 10:00 in the morning and at 14:00 in the afternoon.***

Arrangement of the trees in a different canyons

One of the important parameters in the tree placement on the street is the ***arrangement between trees in rows.*** It can be coherent or opposite. The aim is to distinguish which arrangement cause larger shadowed area.

To test this statement trees were arranged into 2 grids, representing the opposite and coherent arrangements according to the N-S orientation. Shadow pattern simulation results were adjusted to the both (Figure 4.15).

The results showed that in case of opposite arrangement representation shadows tend to overlap with each other, leaving large areas exposed to the sun, while the shadows in coherent arrangement don't overlap and shade larger areas.

Due to the fact that street canyons have the different orientations grids with coherent arrangement were placed in the canyons with all 4 possible orientations (N-S, E-W, NW-SE, NE-SW). It showed that ***coherent arrangement is relevant only for the canyons with N-S and E-W orientations.*** For the canyons with ***NE-SW and NW-SE orientations the trees arrangement because of the 45° rotation becomes coherent.***

For N-S and E-W orientated street canyons the optimal arrangement of the trees will be coherent, in the NE-SW and NW-SE orientated street canons the opposite.

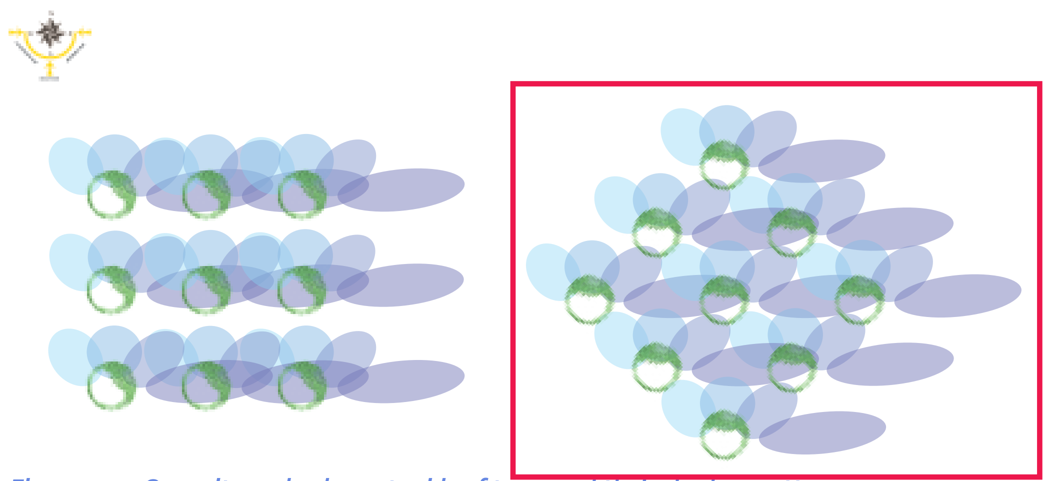


Figure 4.15 Opposite and coherent grids of trees and their shadow patterns.

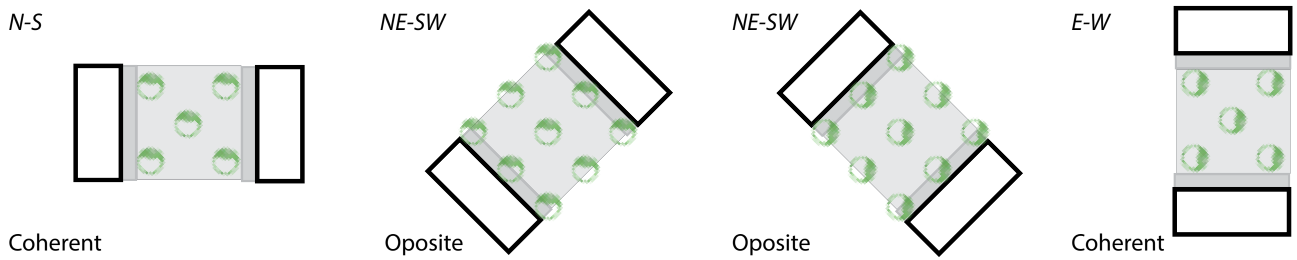


Figure4.16 Arrangement of trees inside street canyons with different orientations.

Distance between trees and the streets facades

Tree shadows can prevent large, paved street surfaces like traffic or parking areas from overheating, but at the same time can prevent solar access to the vertical surfaces of the street canyons – like facades and windows.

In a country like the Netherlands the solar access to the windows at least for several hour of the day is highly desirable. Therefore, it is important to locate trees in a distance so they could provide the solar access to the building facades at least for several hours in a day.

The second reason why it is important to keep the distance between trees and building facades – is that in all canyon configurations building cast the shadows itself, therefore there is no need to plant the trees too close to the buildings because shadows will overlap with each other and therefore won't play a big role in the street heat mitigation.

The optimal distance between trees and canyon walls can be determined based on the shadow length of the trees or canyon walls. To figure out this distance it is decided to represent street canyon sections with trees inside for all possible street orientations and take a closer look at the shadow patterns during the day for 10:00, 12:00 and 14:00 o'clock. Shadows at 16:00 are too long to take them into account for the distance calculation; moreover, solar activity is not that strong at 16:00 in the evening, that is why it is not that important to take a solar access into account at this time of the day. Figure 4.17 shows shadow patterns at 10:00, 12:00 and 14:00 and the selected results (marked with red frame) provide as much as shadow for horizontal surface, and leaves façade exposed to the sun for the longest period of the day.

Recommended distances between street canyon walls and trees according to shadow patterns for each street orientation:

NS orientated canyon: tree or wall shadow at 10:00 and tree or wall shadow at 14:00
NE-SW orientated canyon: wall shadow at 10:00 and tree shadow at 10:00
NW-SE orientated canyon: wall shadow at 14:00 and tree shadow at 14:00
E-W orientated canyon: shadows from both – walls or trees do not differ much according to the time, so it can be 10:00, 12:00 or 14:00

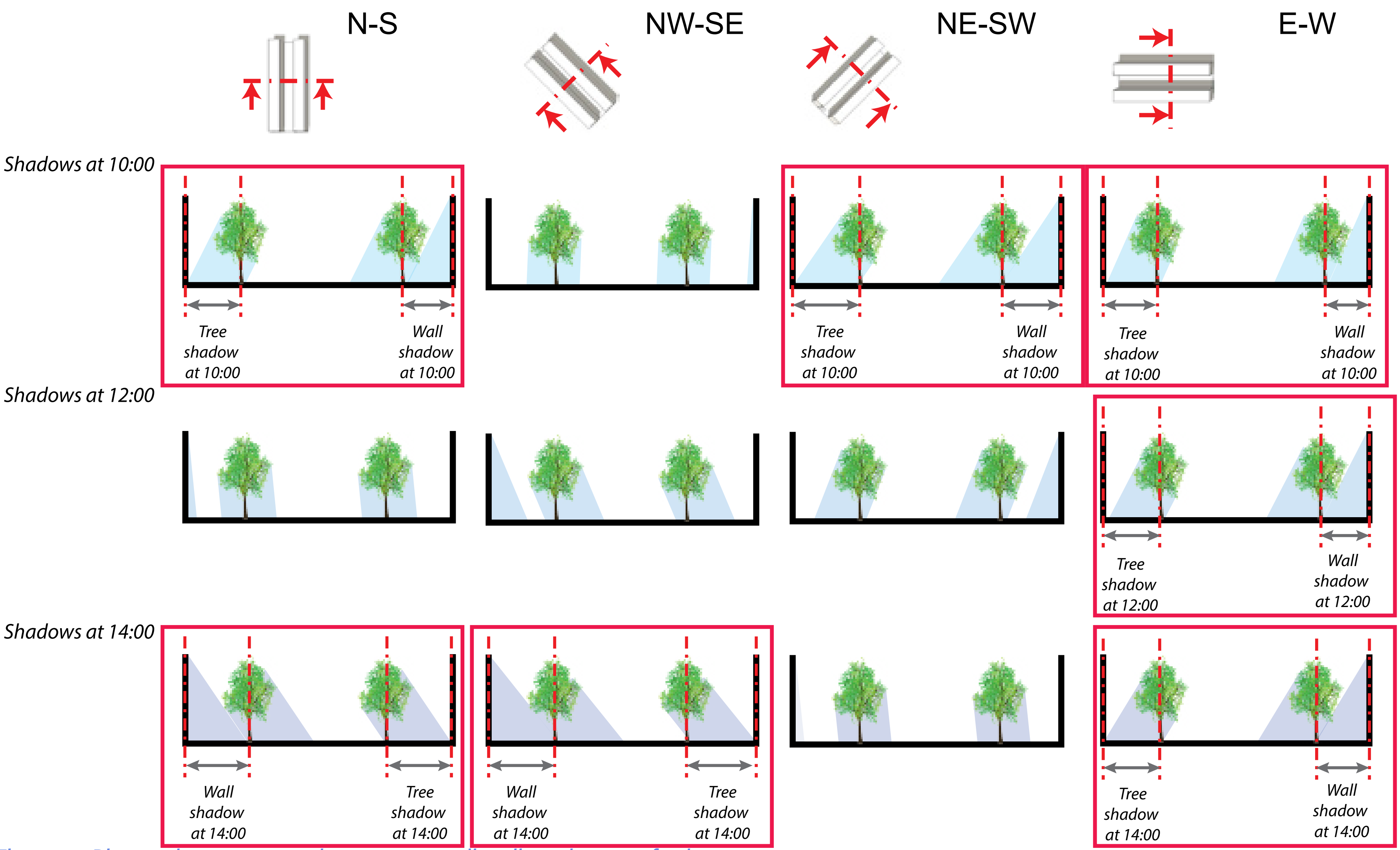


Figure 4.17 Distances between trees and street canyon wall to allow solar access for the façade for 2 or 4 hours a day.

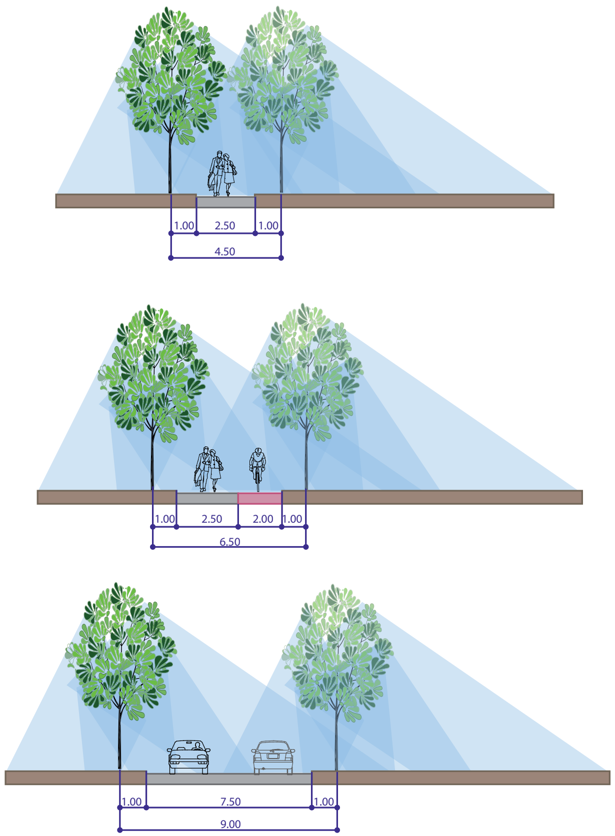


Figure 4.18 Shadows in alleys with different width (N-S orientation)

Shading patterns between rows of trees with different distance.

The trees in the streets are usually represented by long alleys of the trees. In fact, rows of tees in both sides of the street often define its borders in the same way that canyon walls do. But streets are not walls; tree trunks and canopies do not provide the same shadow patterns as building walls therefore it is important to define what people can experience (sun, shade or partly-shade) in the tree alleys with different distance between the tree rows. The simulations of the rows with different tree sizes help to understand when the are between trees is exposed to the sun and when does it stay in the shadow.

According to the context of this research it is decided to take into consideration three possible of distances between tree rows that equals to the measurements of certain street functions

– 4.5m distance that equals the width of the pedestrian path (2.5m) and plantation zone in between (1m from each side),

– 6,5m equals pedestrian (2.5m) and bicycle path (2m) including the plantation zone (1m from each side), and

– 9m width that equals to the vehicle road (7m) plantation zone (1m from each side)

Like street canyons such alleys are also analysed for 4 orientations towards the sun and for 6 combinations of the trees in the alleys: large and large, medium and medium, small and small, large and medium, large and small, medium and small. The last three combinations were analysed twice, taking in account the mirror reflection of alley's sectional view.

The results are represented in the Figure 4.20 a, b and c. Alleys of trees can cause

- shade for at least 6 hours a day (dark grey),
- partly-shade – shadows from 2 to 4 hours a day (medium grey),
- solar exposure – small or no shadows during all day long (light grey).

For some cases only one row of trees provides shading function which is also marked on the figures.

Studies of this parameters proved that ***wider distances between tree rows require taller trees and wider canopies for sufficient shading, at the same time narrow distances requite relatively smaller trees.***

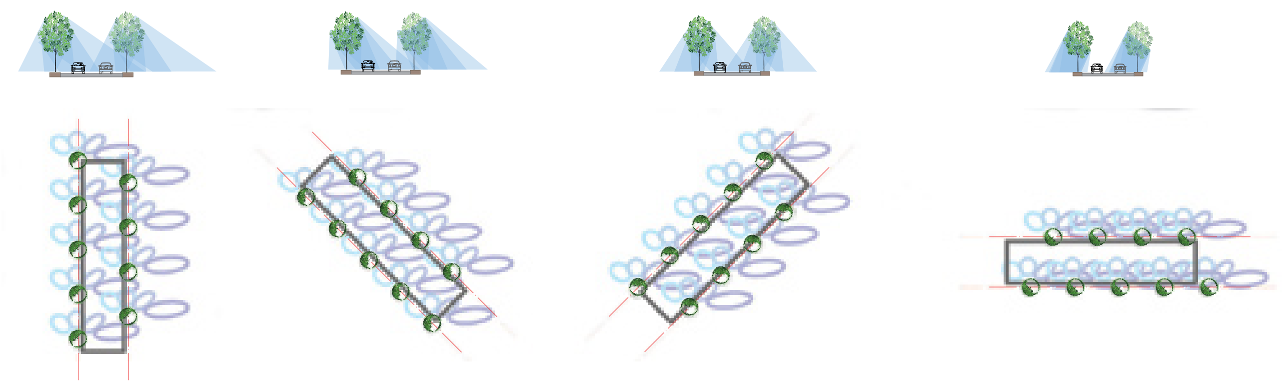


Figure 4.19 Examples of solar exposure/shadow calculations for alleys with 9m width.

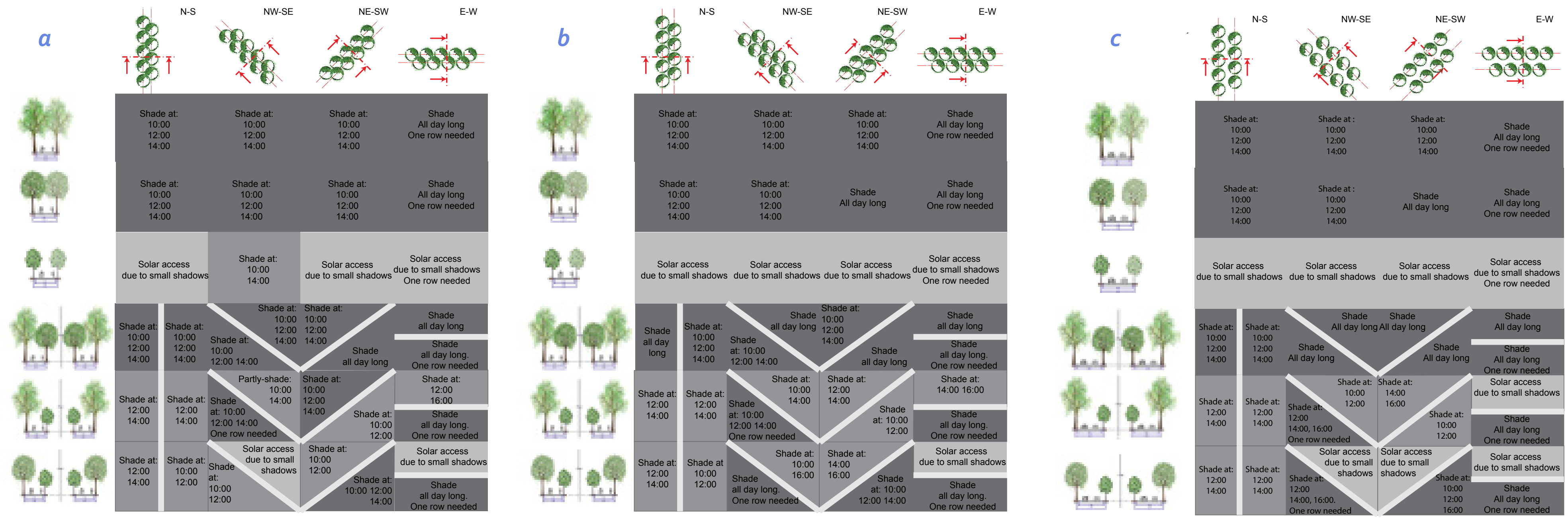


Figure 4.20 Results of solar exposure/shadow calculations between alleys: a-alley with 4.5 m width, b-alley with 5.5m width, c-alley with 9m width. 2 options in some squares represent impact of mirror combinations.

Shade all day long (6 to 8 hours a day)

Partly-Shade (2 to 4 hours a day)

Solar access

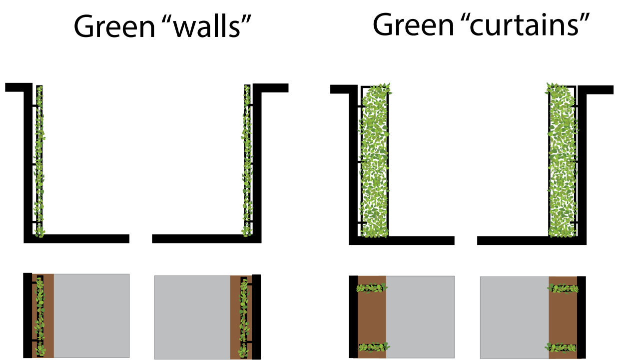


Figure 4.21 Façade shading elements

	N-S	NW-SE	NE-SW	E-W
Walls	Shade	Shade	Shade	Shade Facade is always in the shade
Curtains	Partly-shade	Partly-shade	Partly-shade	Sun Facade is always in the shade

Figure 3.22 Impact of "green facades" according to canyon orientations towards sun.

Shading impacts of green facades

Trees are not the best solutions for shading street canyon walls due to blocking the solar light for the windows. As long as the solar access inside the houses is still very welcome and desirable, there is a need to search for another solution to shade the walls.

Vegetation like climbing plants in combination with the artificial plant constructions had long been used for the facade shading. In this case installations can be a part of the facade construction and with the right management can cause even much efficient shading potentials as trees.

Facade shading elements in this research are represented by :

- ***"green facades"*** structures that are located along the walls and have an openings for windows creating the green walls,
- structures that are located perpendicular to building facades creating so called ***"green curtain"*** for the building

Simulations of every type of façade shading elements are made according to 4 street canyon orientations. Results showed that for 3 street canyon orientations (N-S, NE-SE, NW-SE) green walls provide shade and green curtains – partly-shade. While for E-W orientated canyon – green walls provide shade but green curtains due to its perpendicular location provide solar access.Also for E-W orientated canyons but these results are relevant only for that side of street canyon that faces the sun.

The results are shown on the Figure 3.22.

Shadow efficient application of green elements

The analysis of parameters that influence shadow geometry of the trees could be use independently for parks, squares, gardens or other large open areas that requires shading by trees. At the same time shadow parameters can be used in a context with street geometry analysis and create the complex model for the heat mitigation on street level during the daytime.

Like the studies of the shadows in a street canyon, ***shadows of the trees can be recalculated for every location on the world for any time of the day. Therefore, can be applied everywhere with the according modifications.***

Figure 4.23 Green façade. *Source: http://casavogue.globo.com/*

4.4. Combination of street geometry and green elements

The parameters of street geometry and green elements on the street are described it is time to combine the both aspects together. It is important to test the shadow patterns of trees inside the street canyons, analyse the results and find the most suitable design recommendations. The developed matrix will be evaluated according to the shading abilities of combined street and trees profiles and become a design toolbox for the future projects.

Street shading guidelines

Before streets and trees are combined and evaluated it is necessary to figure out what would be the optimal solution for the street canyon shading. Solar exposure/shadow analysis shows what parts of the streets are exposed to the sun and create hot thermal conditions, shadow patterns of trees inform us about the best parameters for street trees plantations, but what would be the best way to combine both of these aspects to create thermally comfortable streets?

When it comes to applying thermal comfort information to the landscape design, there are certain steps that should be taken. The main purpose of design is the thermal comfort for the majority of people in the majority of time, considering the season. After the general problem is solved the detailed adjustments for specific situations could be made (Brown and Gillespie 1995).

As long as it was decided to base heat mitigation strategy on control of solar radiation by shadows, the way to do it is to put an obstruction between the sun and the surface that needs to be protected.

According to the canyon solar exposure table, vertical facets of street canyons already create this obstruction that partly or permanently block the solar radiation gain. Canyons with ratios 1:2 and 1:3 still have the large areas that are exposed to the sun almost all day long (6 or even 8 hours) therefore create hot outdoor environment and contribute to urban heat island. These areas are marked with orange and red colour in the solar exposure analysis table. In this case of street canyons with such ratios, shading should be achieved by placing trees or overhanging constructions above areas that are expose to the sun for the longest periods of the day.

As long as the solution for the main problem is found, the adjustments for the specific parts come. Parts of the streets that are exposed to the sun for less than 2 or less than 4 hour a day still can generate urban heat, but it is important to keep them open to the sun for those hours; otherwise the place will become unpleasant due to all day long shadows.

Another issue that is relevant for urban street canyons is the gain of the solar radiation by canyon façades. Walls that are exposed to the sun generate heat as well as the street surface, but sunlight that is coming indoors though the windows is vitally important for people. Too much sun light can be always regulated by window awnings, curtains or window hoods or tents but sun that is blocked from the window by trees can't be gained back. Shading the facades by artificial constructions for the climbing plants allows the solar access for the windows and can be a good solution for this case.

This way the recommendations for the urban heat mitigation and creation of the thermal comfort in the urban street canyons are following:

- Provide shadows for the most solar exposed areas of the street canyons (areas that are exposed for the sun for 6 or 8 hours during the day).

- Provide as much solar access as possible for the horizontal areas that are exposed for the sun for 2 or 4 hours a day.

- Shade the exposed to the sun façade walls by constructions for the climbing plants or green facades and try not to shade the walls with trees.

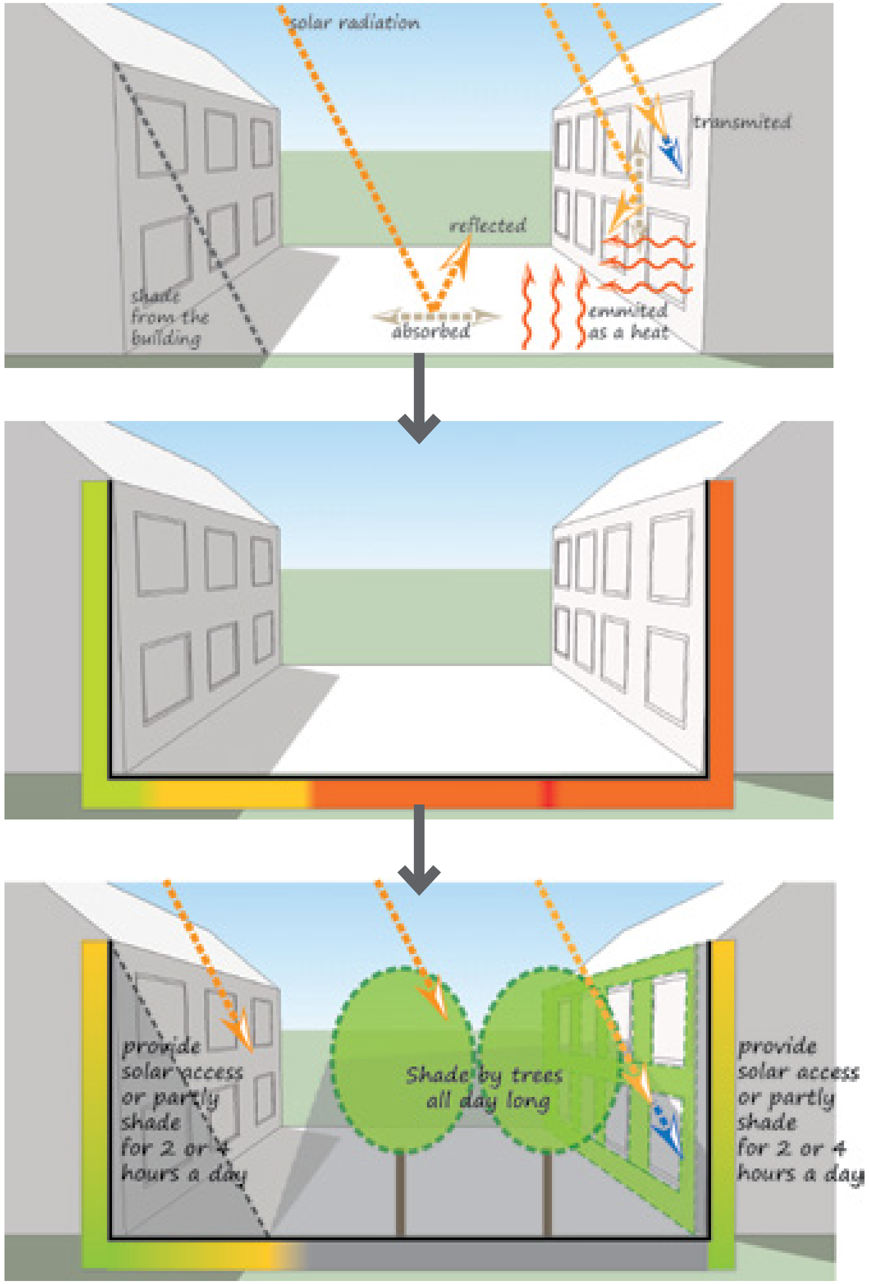


Figure 4.24 Shading requirements for trees in the canyon

Figure4.25 Examples of the chosen street canyon type.

Street canyon and trees specification and process

Due to the large variety (almost infinity) of all possible street canyon dimensions and relatively small variety of the analyzed trees (only 3 sizes – large, medium and small) in is decided to choose the street canyon with the certain dimensions, place trees in it and simulate the shadows for all 4 mentioned orientations. This will represent the exact impact of trees in the real street conditions, and create the comparison of different green parameters on the same situation.

Street canyon choice

The important aspect for this step of the research is to choose the right street for testing. The research is taking place in the Netherlands, and it is logical to choose the street that would be typical for this country. But even here exists the huge variety of streets with different functions, measurements, orientations and ratios. Some streets have limitations for the trees plantations due to pollution of heavy traffic, at the same time the wide streets without heavy traffic could have countless variety of trees combinations.

Regarding these factors it was decided to test the green parameters on the relatively small street canyon that is formed by one of the most popular Dutch housing typologies. According to SenterNovem research the 2 floor row-houses with the single family apartments take almost 50% of the last years housing production in the Netherlands. ¾ parts of it, or 36,5% in total is located in the towns, therefore faces the Urban Heat problems and refers to the purpose of this research (2006). In addition to this the majority of the described housing streets is quite stony, or has a lack of vegetation may be due to the relatively short exploitation period, but at the same time streets have a potential for planting trees and creating the small front garden. It is also can be mentioned that this type of streets usually forms clusters (2004), therefore the solution for Urban Heat mitigation on the one street can be applicable for the whole cluster and significantly improve the thermal conditions of the urban environment in the larger scale levels.

The mentioned 2 floor row houses located on the both sides of the streets form the street canons with the average of 6 m height (excluding the pitched roof) and form 10 to 15 m (depend on the situation) width. Thus the ratios of the canyons like this are between 0.4 and 0.6. According to the solar exposure analysis table, street canyons with such ratios contain the areas that are exposed to the sun longer than 6 hours per day and therefore are affected by Urban Heat.

This choice of the street is giving the certain benefits to the research. First of all, the street canyon is located mostly in residential areas, where the main target groups are people who actually stay in the houses almost permanently, actively use the outdoor environment and directly face the problems that UH may cause.

Secondly, this type of streets almost never has heavy traffic loads therefore there is no limit on the tree crown's size or planting distance. The low traffic and large quantity of parking places allow tree planting almost everywhere. Finally the narrow width of the street canyon with variety of street functions will allow testing the combination of only one or maximum two trees rows. This will be enough to test all the tree sizes combination behavior described previously in the parameters and analyze the impact on the street canyon vertical and horizontal parts, to use it in the future designs.

Green combinations

The chosen street canyon allows locating of one or maximum 2 rows of trees in it without sacrificing its function. According to this it is decided to use various combinations of the given street canyon and Large, Medium and Small trees with round shape crown.

It is decided to test 4 types of trees locations within street canyon.

- 2 rows of trees with the same sizes: Large, Medium and Small. (3 combinations) (Figure 4.28 a)
- 2 rows of trees with the different trees sizes: Large and Medium, Large and Small, Medium and Small in this case trees combinations are asymmetrical and therefore will be studied twice with a mirror reflection option. (6 combinations) (Figure 4.28 c)
- 1 row of the trees from the each side of the street. 3 sizes of trees and 2 sides of the street. (6 combinations) (Figure 4.28 d)
- 1 row of trees in the middle of street canyon for each size of trees. (3 combinations) (Figure 4.28 b)

In total 18 combinations of street canyon and trees will be tested for 4 possible street orientations.

- Trees will be arranges coherently for the N-S and E-W orientated street canyons and oppositely for NE-SW and NW-SE canyons.
- The distance between rows of trees is 6,5 m (in case of 2 rows). The distance between trees 8m.

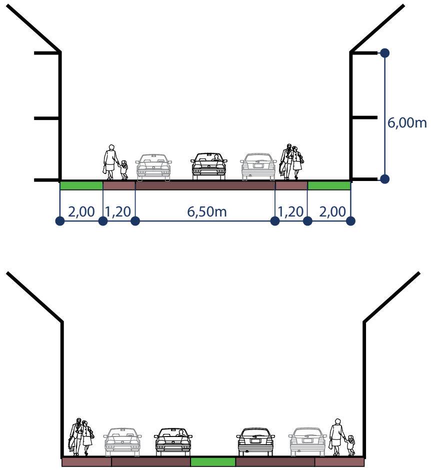


Figure 3.26 The actual measurments an possible layout of street canyon

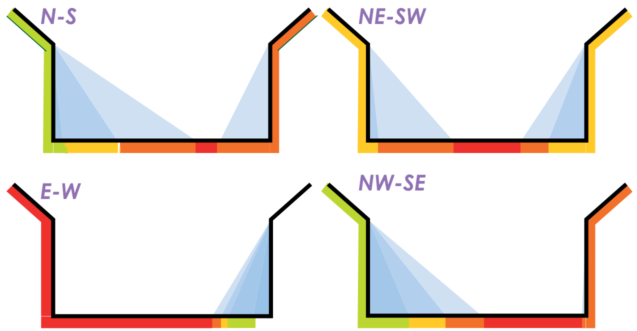


Figure 4.27 Canyon solar exposure analysis.

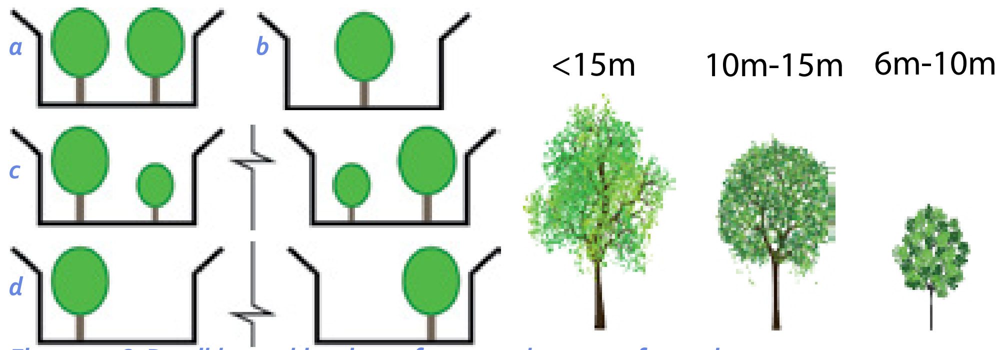


Figure 4.28 Possible combinations of trees and 3 types of tree sizes

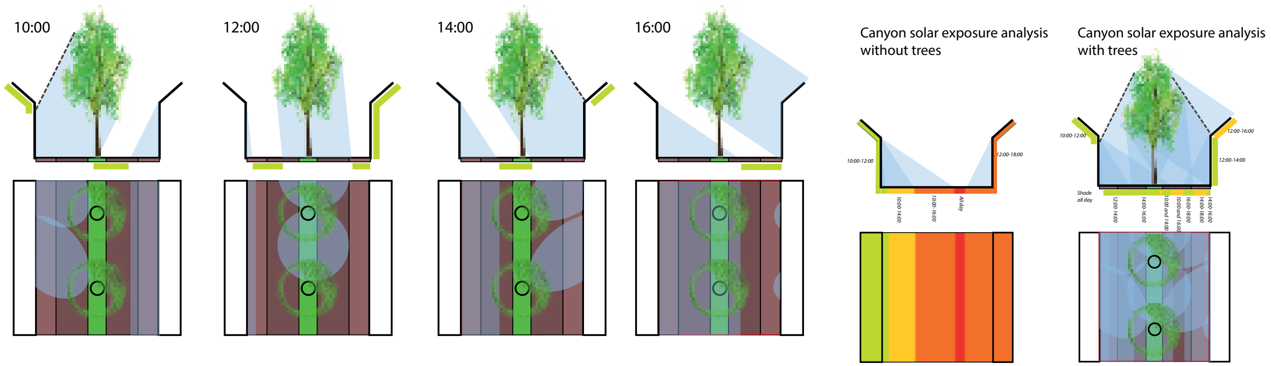


Figure 4.29 Example of solar exposure analysis calculation for street canyon with trees.

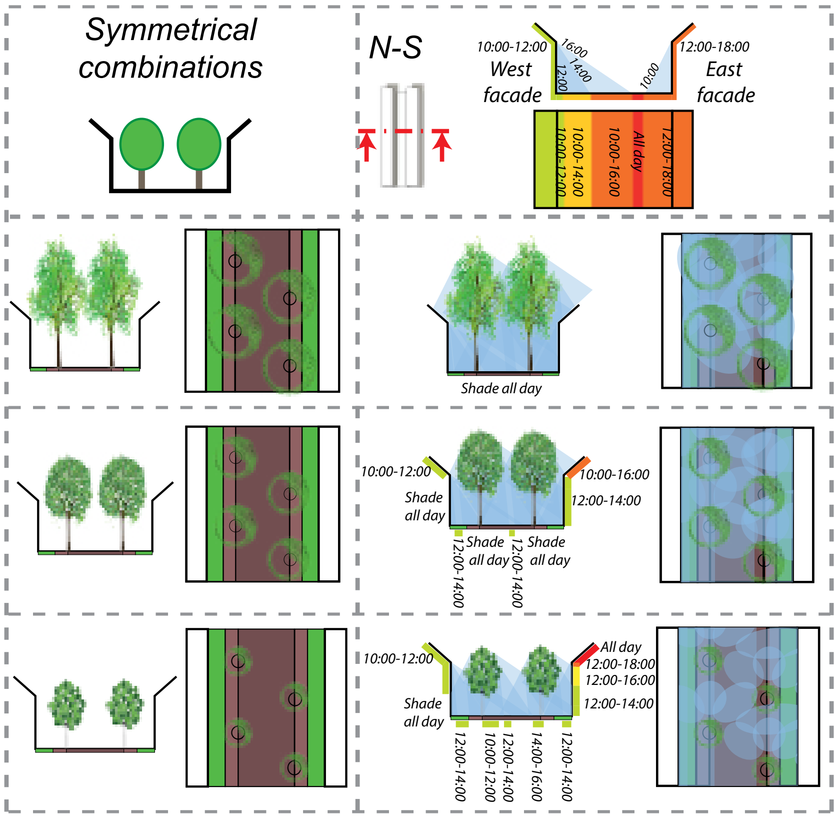


Figure 4.30 Combination of canyon with trees (part of a Matrix), example for NS orientated street canyon with symetrical combination of the trees

Shadow pattern calculation process and example

1. Urban street canyon is analyzed for the solar exposure analysis for all 4 possible orientations of the street (N-S, E-W, NE-SW, NW-SE)
2. Rows of trees with 3 described sizes (Large, Medium and Small) are placed in the street canyon in 4 ways creating 18 different combinations.
3. New analysis of solar exposure analysis for street canyon with trees (Figure 4.31).

All options are arranged in the matrix and analyzed for the shadow patterns and solar exposure hours. Afterwards all the combinations will be evaluated according to the street shading requirements that were mentioned before: to shadow the horizontal areas of the streets that are exposed to the sun for longer than 6 hours in a day with trees, but allow possible solar access to the windows and parts of the streets that are exposed to the sun for 2 or 4 hours in a day.

Facades that are exposed to the sun for a long time period can be shaded additionaly by green façade structures and climbing plants. The suitable options are chosen according to the street shading guidelines and marked in a Matrix (Figure 4.31).

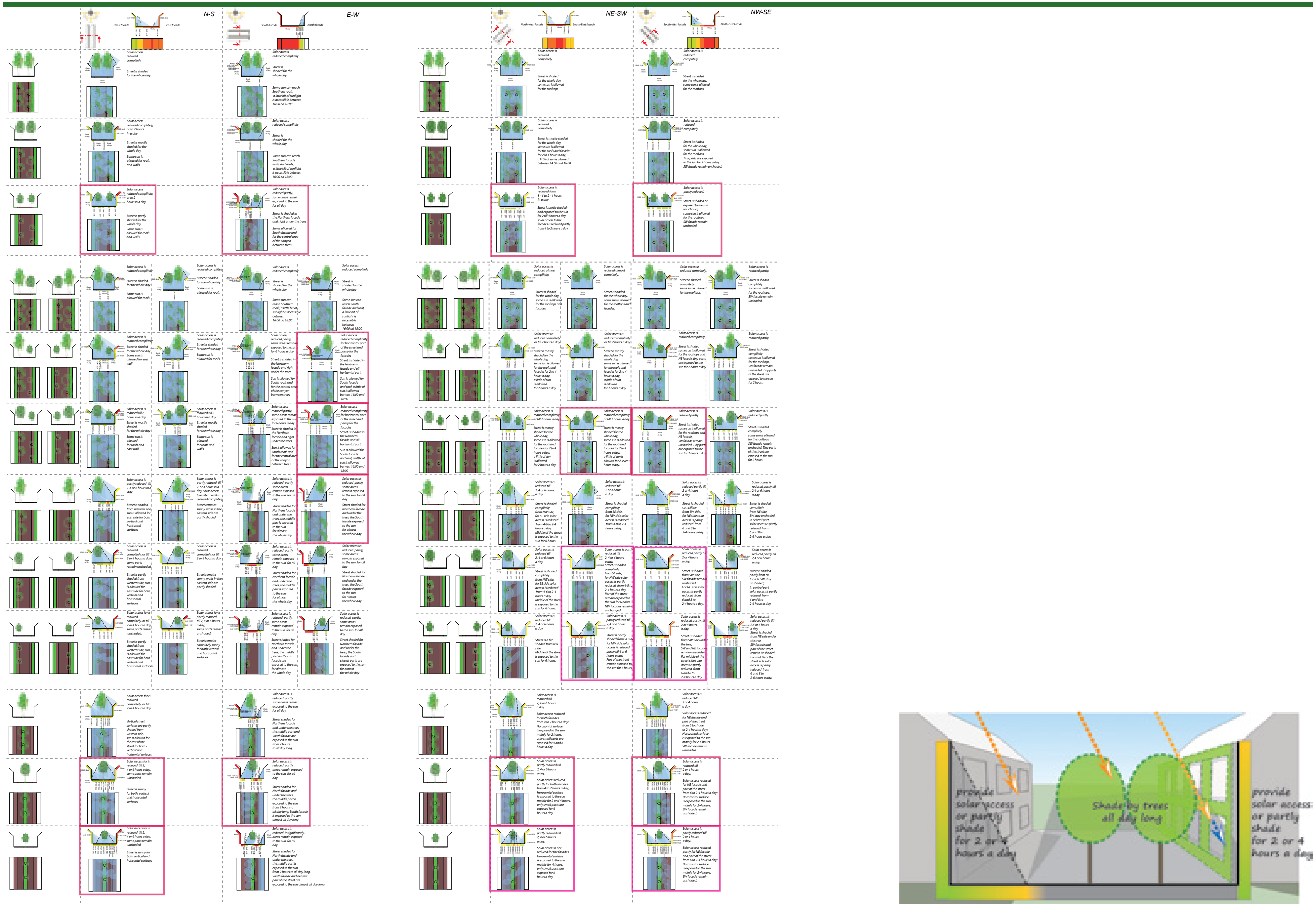


Figure 4.31 Matrix of street canyon and trees combinations and shading requirements for trees in the canyon. Larger version available in the apendix

Recommended street shading combinations and design principles.

The combination of street canyon with actual measurements and trees combinations revealed a number of quite interesting moments.

First of all, there are 2 general controversy statements that need to be pointed out.

Positive

- Trees combinations indeed result an increased amount of shadows in the streets, which make the streets cooler and thermally more pleasant in the hot summer days.

Negative

- In most of the cases trees cast too much shadow. As the result they shade canyon walls and prevent the solar access to the windows. At the same time too many shadows may result unpleasant environment in the cooler period of the year. Overhanging tree canopies may restrict nocturnal cooling and wind access. Therefore amount of trees and their shadows have to be minimized.

To simplify the information amount it is decided to sort out all the marked options from the Matrix and present them separately. The selection of the most suitable solutions for street shading while keeping the solar access for the walls is presented in the Figure 4.32.

The main conclusion form this overview stated:

- In order to meet the requirements for street shading ***size of the trees in the canyon should be proportional to canyon height.***

The small street canyon is chosen for the combinations and small trees provide the most suitable shading conditions. In case of the bigger street canyon it would be wiser to use accordingly bigger trees.

The most suitable shading result table reveals very interesting things as well.

- First of all, ***the symmetrical tree row combinations work well in every canyon orientation*** in case that trees are proportional to the canyon size and the distance between trees and canyon wall is big enough not to drop tree shadow on the walls. The single row of trees in the middle of the canyon works very well for every canyon orientation especially with taller tree species.

- ***For the asymmetrical street canyons*** (with one row on the each side of the street or with taller and shorter trees together) ***there is a strong pattern that determines which solution will work best in which situation.*** It is possible to see from the table which side of the street canyon is more preferable for row of trees or in which side of the street rows should be talle (red frame in the figure 4.32).

• According to the conclusions asymmetrical patterns results is also possible to mention that ***E-W orientated street canyons require combinations with taller trees than canyons with other orientations*** (blue frame in the figure 4.32).

All mentioned conclusions in combination with the table of the most suitable shading result create the number of design principles that might be used for the future design steps. Design principles can simplify the choice of trees combinations for the streets and help to predetermine the exact shading effect of street canyon and trees and inform us about shadow or solar exposure locations or hours.

Another thing that the Matrix reveals – ***there are never conditions for the shadow patterns to meet the shading requirements perfectly.*** Streets layouts are usually predefined by the vehicle roads and accesses for the buildings. There is seldom any room left for trees or trees can be planted only in the specific places.

It is important to deal with the present conditions and choose the solution that works best into the existing circumstances although it might not meet all shadowing requirements 100%.

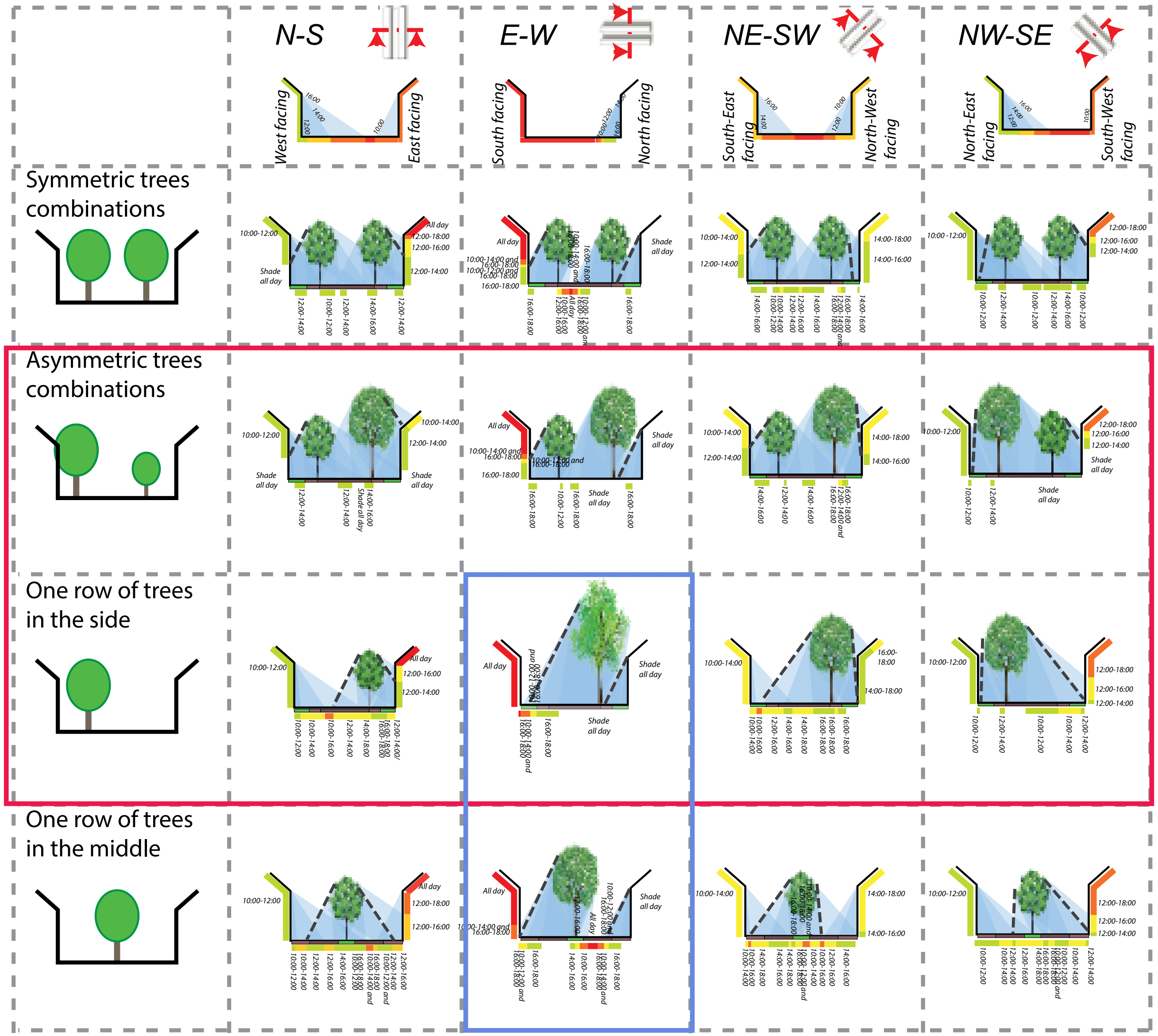


Figure 4.32 Selection of the most suitable solutions for street shading and keeping the solar access for the walls

4.5. How to design thermally comfortable streets? Recommendations for practitioners.

This chapter discussed street canyon geometry and vegetation shading potentials for urban heat mitigation on the street level. The results proved the importance of every aspect consideration separately as well as in a combination.

Street canyon geometry (its H:W ratio and orientation towards sun) is responsible for street thermal conditions and potentials of street heating and cooling. Street geometry itself can determine the thermal comfort conditions indoors and outdoors in the planning step. This chapter analyses the situation in the street canyon according to its geometry and presents solar and shade exposure analysis, where it is possible to see which areas of the street are exposed to the sun and for how long.

The thoughtful use of vegetation can enhance heat mitigation effects, but too much or too less of vegetation on the street can create unpleasant conditions. Street vegetation like trees and green facades is also analyzed on its shading potentials in order to contribute to proper street shading.

The combination of the street canyon together with trees make the visual presentation of the exact impact of the trees in the streets and enable shadow pattern analysis, search for the most successful shadowing solutions and design principle development for the future design steps.

Besides theoretical information of this chapter it is decided to conclude the results by developing practical steps for designing thermally comfortable streets based on the outcomes of this research.

1. The first step is to analyze solar exposure/shadow pattern of the street canyons according to its Height to Width ratio and orientation towards the sun.

This analysis will help to understand which streets face urban heat problems and which areas generate urban heat.

2. Secondly – streets have to be analyzed on the presence of shadows from green elements. Some of the streets may have large areas of solar exposure, but they might be shaded by trees or other green elements, that is why it is highly important to figure this aspect out.

3. When streets where urban geometry cause urban heat problems and amount of vegetation do not provide sufficient shading are defined it is a time to select the suitable desgn principles from the table with selected combinations of streets and trees. If we are working with a street that has NW-SE orientation we are choosing the desirable trees combinations from the solutions for NW-SE orientated streets.

4. After the possible combination is chosen, it is applied to the situation of the existing street. It is need to be mentioned that the dimensions of the particular street are never match perfectly to the dimensions of the combination from the design principle table. Moreover street might have a total different functions and situations. That is why it is important to use the chosen design principle as a concept tool and modify it accordingly to the existing situation.

All these steps will be described more deeply in the following chapter.

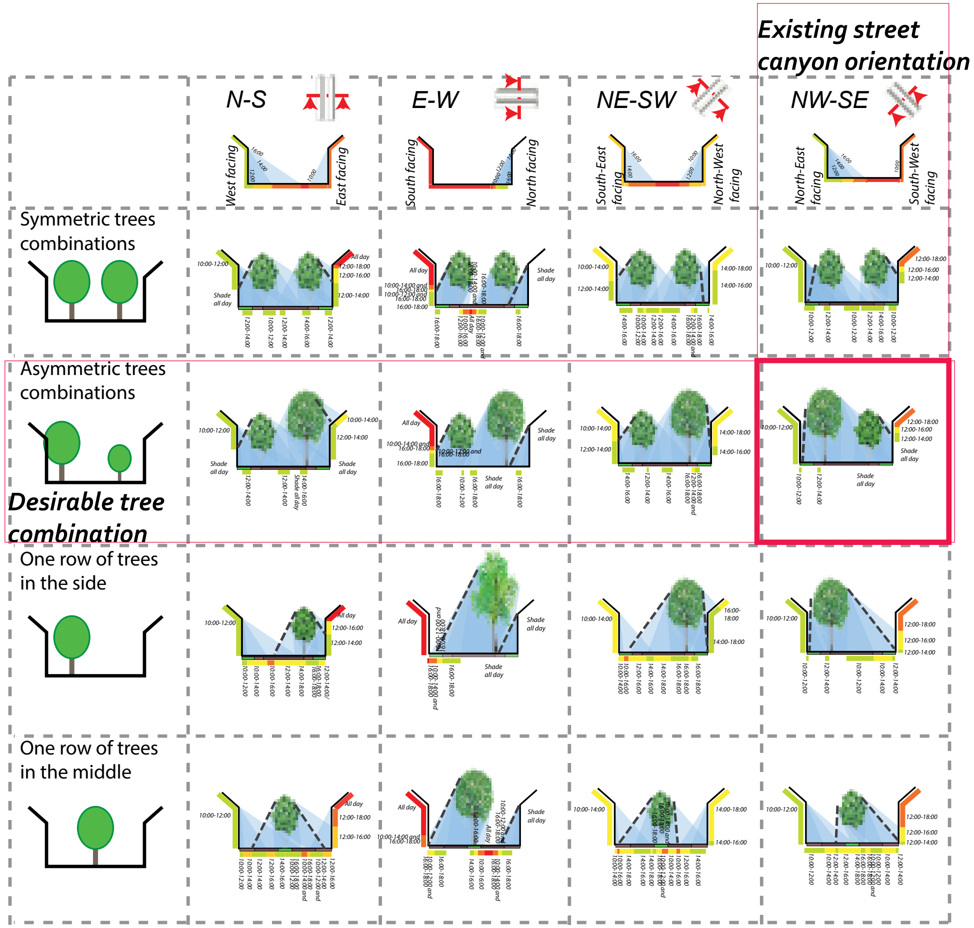


Figure 4.33 Desing principle selection.

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5. Case study: Bergpolder-Zuid, Rotterdam

5.1. Design assignment and approach for the case study area

5.2. Existing situation of Bergpolder-Zuid area in Rotterdam.

- Urban climate in Rotterdam
- Bergpolder-Zuid area

5.3. State of street geometry and green areas in Berpolder-Zuid

- Solar exposure/shadow analysis of the area
- Existing green elements on the streets
- Site analysis conclusions and design objectives

5.4. Design process

- Design principles application for Bergpolder-Zuid streets
- Design elaboration

5. Case study: Bergpolder-Zuid, Rotterdam

Strategies and practical recommendations for urban heat mitigation are clear, but they are very general. It is important to apply them for the actual design process in the existing site.

The case study area of this project is located in the Rotterdam, Bergpolder-Zuid. Municipality of Rotterdam currently participates in a number of projects related to climate adaptation and sustainability issues. The main goal is to make the whole Rotterdam city cleaner and greener, improve the life quality and enhance the climate adaptation.

Bergpolder-Zuid is one of the neighbourhoods that were chosen for the improvements in the frames of the on-going Climate Proof Cities project. The new development master plan of the area was made in 2010 with a purpose to improve living and working aspects of the area, diversify the activities in the district and make Bergpolder-Zuid a better place to stay. Some of the project parts are already implemented; some of them are frozen on the current moment due to complicated financial situation.

According to CPC programme the newly renovated district should respond to principles for climate adaptation which includes urban heat mitigation strategies as well.

Bergpolder-Zuid is interesting case study for this thesis in several ways.

First of all it is a district where people work, live, go shopping and do other activities, and as a result spend quite long part of the day. The quality of the outdoor environment is very important, because people spend quite some time outside as well.

Secondly, streets in this relatively small area

Figure 5.1 ***Bergpolder Zuid in Rotterdam*** *Google satelite image.*

Figure 5.2 Area Bergpolder-Zuid. *Google satelite image.*

Figure 5.3 Plan of the area

are very different, some streets are busy traffic roads, some are important connections in the district scale, some are calm and quiet residential streets and some have potential to be converted into the pocket parks according to the existing structure of the surrounding urban fabric. Needless to say streets have diverse canyon geometry, which make this district a very interesting case for research.

5.1. Design assignment and approach to the case study area

The main design assignment is to mitigate urban heat in Bergopder-Zuid streets and make the area more climate proof. According to the main focus of this research heat on the streets should be mitigated by modifying the solar radiation and more specifically creating more shadows on the streets.

The previous chapter described the practical steps of how to design street canyons according to heat mitigation with shadow patterns. Those steps needs to be applied to the actual design to check if they actually can work or not. Therefore the recommendations for practitioners will be used as the main approach to the design of Bergpolder-Zuid streets.

Before using the research outcomes, it is important to understand the existing situation of Bergolder-Zuid: its location, specifics and climatic parameters in the general context of the city or Rotterdam.

Figure 5.4 Bird eye view of Bergpolder-Zuid. *Google satelite image.*

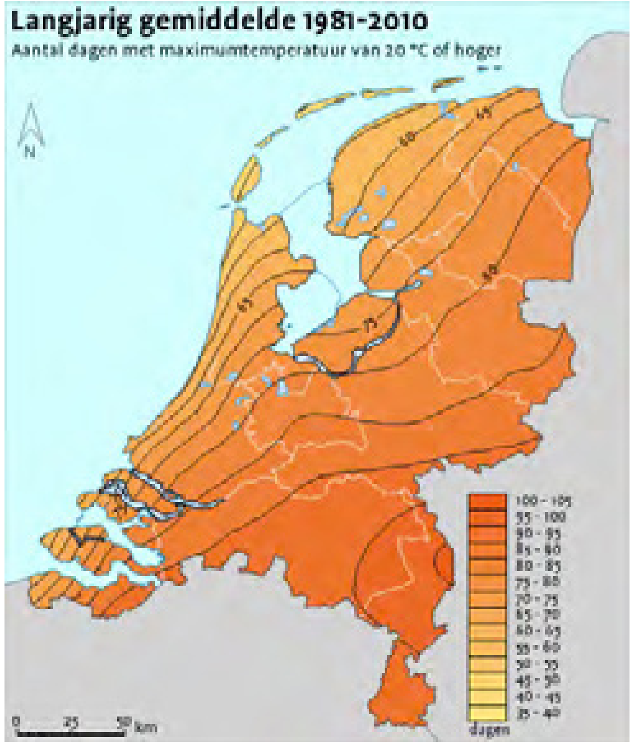


Figure 5.5 Average Number of hot days in the Netherlands from 1981 to 2010. Source: KNMI

5.2. Existing situation of Bergpolder-Zuid area in Rotterdam.

Urban climate in Rotterdam

Rotterdam is a major international commercial centre with a population of almost 600 000 inhabitants, massive activities and high building density. It is the second largest city in the Netherlands dominated by its port. The total land area covered 206 km2. Rotterdam is a part of a larger metropolitan with 1.6 million inhabitants. The city of Rotterdam itself consists of 22 districts, which are subdivided in 88 neighbourhoods. The city is characterizes by the river the Nieuwe Maas, the large harbour and large industrial areas (Klok, Zwart et al. 2012).

The preliminary wind direction all year around according to KNMI data is South-Western. Most of the time winds are quite strong and contribute a lot to the unpleasant (cool to cold) thermal conditions all over the year. South-Westren direction dominates also during the hot summer days, when the air temperature is above 25°C, but wind speed is not that strong in these cases. The second important direction during the hot days is North-East. It brings the warm air during the summer time but at the same time brings cold air flows during the coldest winter days (Harst 2011).

The warmest time of the year as it was already mentioned is summer, particularly July and August. The average number of days with maximum temperature of 20°C of above in Rotterdam is 85-90 in a whole year according to the data from 1981 to 2010 (KNMI 2011).

The characteristics of UHI effect have been studied extensively for many cities over the world for years, but studies in the cities in the Netherlands are quite recent.

According to the mobile platform measurements of Heusinkweld in 2010 the maximum UHI of Rotterdam is about 7°C (Heusinkveld,

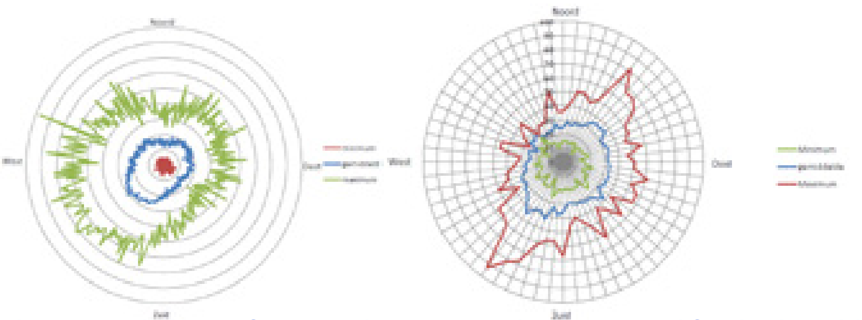


Figure 5.6 Wind roses for Rotterdam: average in the year and for the day with air temperatute above 20 °C. Source: Harst 2011

Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
4.0-4.5	4.0-4.5	6.0-6.5	9.0-9.5	12.5-13	15.5-16	17.5-18	17.5-18	15.0-15.5	11.0-11.5	7.0-7.5	4.0-4.5

Figure 5.7 Average temperature of Rotterdam form 1981 to 2010 (Adaption, based on data from KNMI) Source: Liu and Shan 2012

Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
5.5-6.0	6.5-7.0	10.0-10.5	13.5-14	17.5-18	20-20.5	22.5-23	22-22.5	19.0-19.5	14.5-15	9.5-10	6.0-6.5

Figure 5.8 Average maximum temperature of Rotterdam from 1981 to 2010(Adaption, based on data from KNMI) Source: Liu and Shan 2012

Van Hove et al. 2010). Klok in 2012 were measuring surface heat island intensity all over the city using satellite data from Landsat Thematic Mapper. Results of her studies are represented in 2 maps – *Average surface temperature distribution* (measured in Kelvins) and *Average SHI intensity of 22 Rotterdam districts*.

According to the maps SHI intensity in the area of Bergpolder Zuid is 5°K and the average surface temperature distribution is between 306° and 302° K. It is not the hottest areas of Rotterdam, but it is a living area, which means they are used by people all day long, not the certain hours like, for example industrial sites. Therefore it is highly important to create climatic comfort in this area.

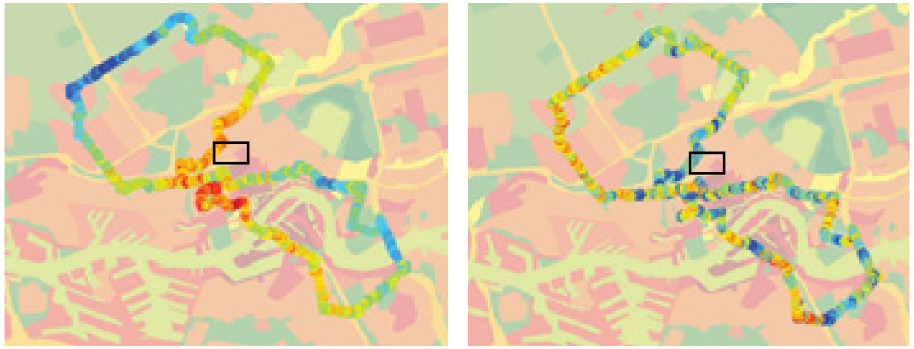


Figure: 5.10 Traverse measurements of Rotterdam, PET, left Panel 14:00-16:00 h. right panel 22:00-24:00 h (Central European Time).
Source: Heusinkveld, Van Hove et al. 2010

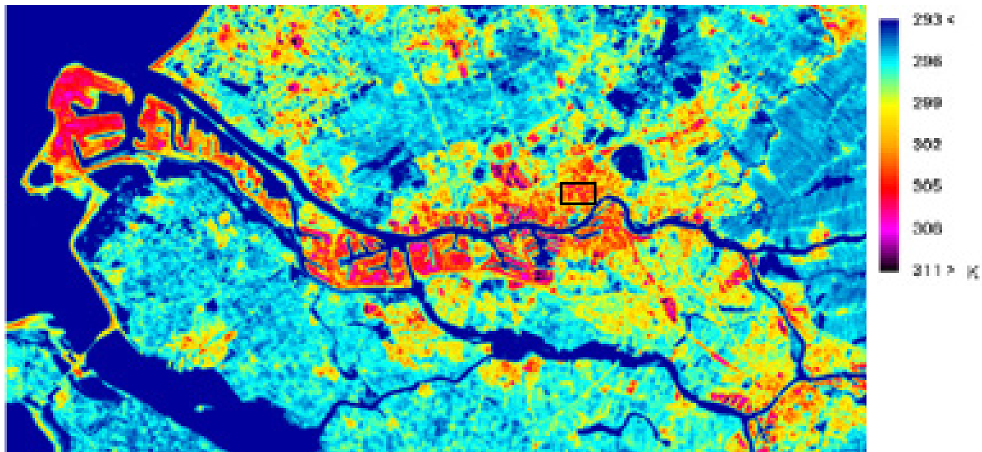


Figure 5.9 Average surface temperature distribution (K). *Source: Klok, Zwart et al. 2012*

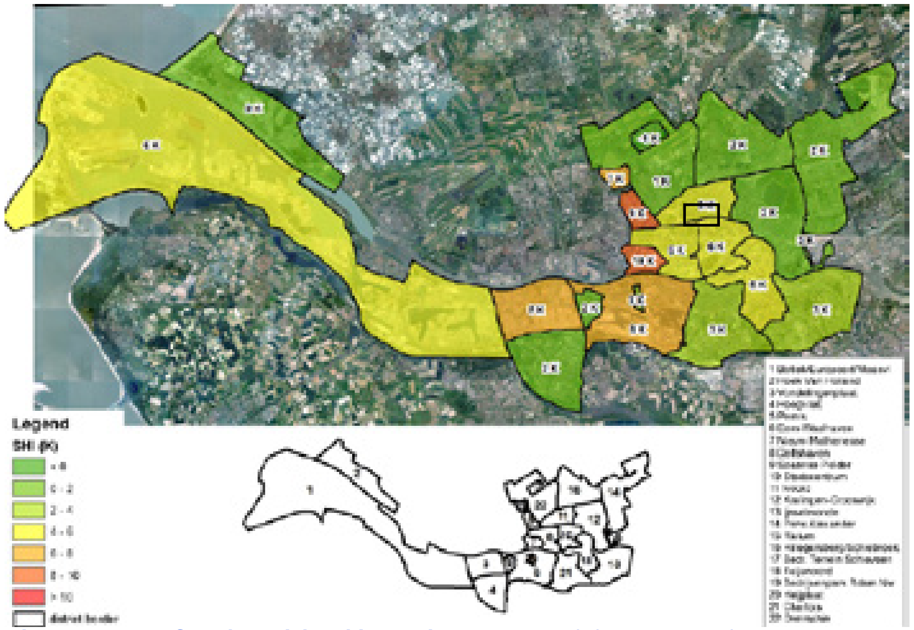


Figure 5.11 Surface heat island intensity. *Source: Klok, Zwart et al. 2012*

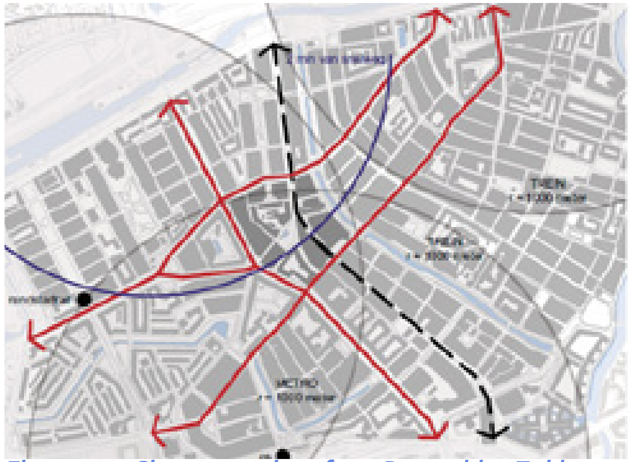


Figure 5.12 City connections from Bergpolder-Zuid.
Source: Ginter, Hornis et al. 2011

Bergpolder-Zuid area

Bergpolder Zuid is a part of the North district of Rotterdam. It located between two popular residential areas. It is well connected to the city centre. The central station is 10 minutes walking distance as well as the metro station. There are several bus stops along the edges of the district.

The identity of Berpolder Zuid is presented by its cultural heritage. There is a Catholic church in the Begsingel Street, built in 1927. It counts as a municipal monument and has a strong impact on the cityscape. There is a Catholic school and a kindergarten next to it. The complex plays an important role in the neighbourhood activities.

The railway viaducts de Hofbogen has the status of a national monument since 2002. It is 1.9 km long and used to be a connection between Rotterdam and den Haag. The arches under the viaduct were used as a workspace for artisans. Eight arches are still having the original façades. The viaduct like all the historical monuments should remain whole and indivisible.

Finally the housing blocks on the part of Bergselaan are protected by cityscape because they are important for the architectural style of Bergpolder.

Area of Bergpolder-Zuid is quite calm and peaceful, suitable for living or working. Public spaces of the neighbourhood are represented by three places. Eudokia Square – a neighbourhood plaza, that is a meeting place, offers games, culture, some greenery and place for the small events. Insulindeplein – an inside square for the neighbourhood, offers green space, trees and has children playgrounds. De Savornin Lohmanlaan Street just outside the area of Bergpolder Zuid is a neighbourhood park with a lot of greenery walkways, sitting areas, playgrounds and some sport activities. Inside the Bergpolder Zuid it turns into a small street with mostly parking functions. According to the development plan of the area the green

Figure 5.13 Catholic Church
Source: Ginter, Hornis et al. 2011

Figure 5.14 Railway viaduct
Source: Arthur Kamminga http://www.flickr.com

Figure 5.15 Railway viaduct and Housing block on Bergselaan Street

neighbourhood park should be continued for all street length and include Troelsrastraat – a small street, perpendicular to De Savornin Lohmanlaan.

In the North and East Bergpolder Zuide is surrounded by wide streets with large open green areas. Bergsingel is a beautifully restored green open space that is widely used by pedestrians and cyclists. Bergselaan is a green street with a lot of trees and large green middle part. At the same time streets inside Bergpolder-Zuid are stony, despite the fact that building blocks actually have inside green yards. Some street canyons do have some trees here and there. Church has some front yards and some green can be found in the private areas that are visible from the streets.

Streets inside the area are mostly narrow and available only for one way. Street parking is mostly allowed but still area lacks parking spaces according to the Rotterdam standards. This fact forced the development of several collective parking areas: the underground parking in the Insulindeplein and private garage next to Eudokia Plein.

In general, the area inside the neighbourhood has a sense of place and local identity, but lacks cosiness. Small but meaningful interventions can make a lot for the local atmosphere. The awareness of the climatic issues between inhabitants may enhance the social interaction and improve the community sense. The interventions with the aim of heat mitigation may contribute to all of those aspects, as well as provide the meaningful and sustainable development of Bergpolder-Zuid.

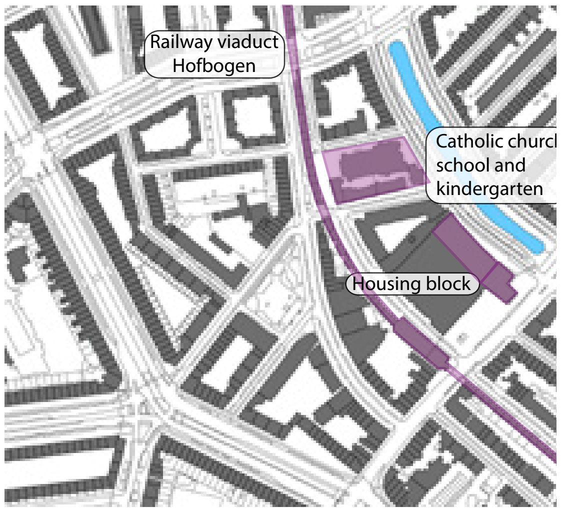


Figure 5.16 Cultural heritage object location

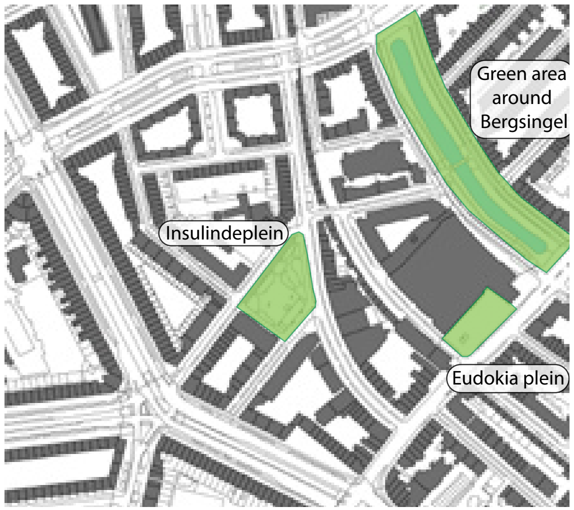


Figure 5.17 Green public areas

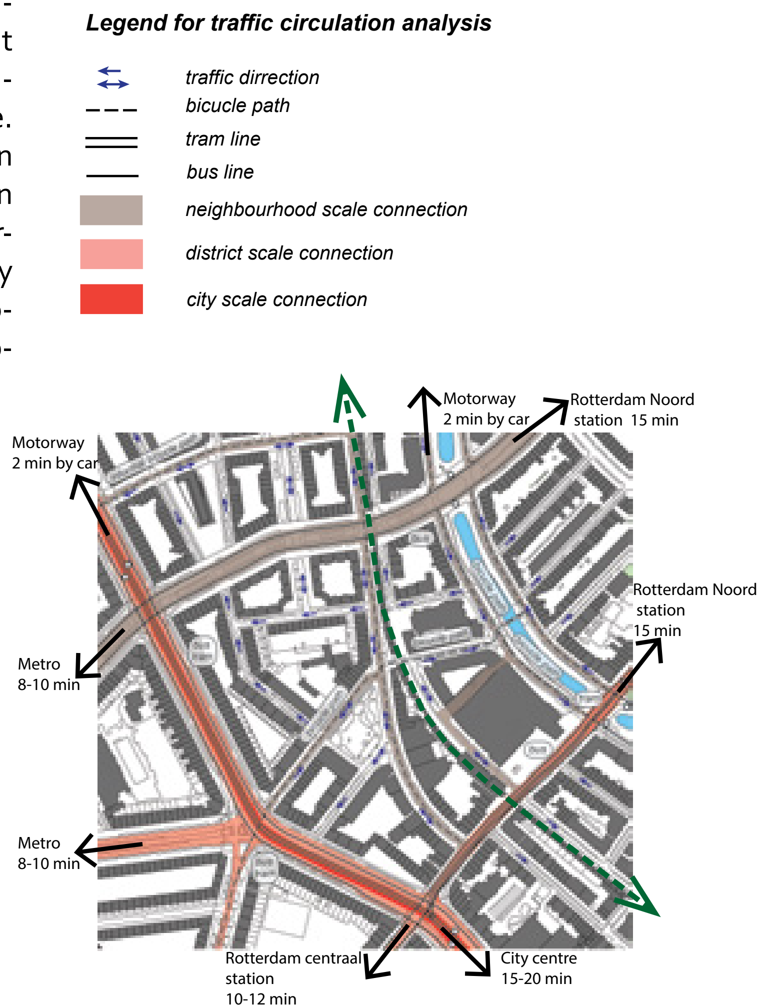


Figure 5.18 Traffic and accessibility analysis of the area

5.3. State of street geometry and green areas in Berpolder-Zuid

Name of the street	Orientation	Ratio
1. Bergpolderstraat	N-S	1
	NW-SE	0.8 - 1
2. Bergselaan	E-W	0.4
3. Bergsingen	NW-SE	0.3
4. Bergweg	NE-SW	0.6
5. De Savornin Lohmanlaan	N-S	0.5
6. Heulstraat	NE-SW	1
7. Insulindestraat	N-S	0.5
	NW-SE	0.5
8. Nootdorpstraat	E-W	1
9. Schieweg	NW-SE	0.4
10. Troelstrastaat	E-W	1
11. Veurstraat	E-W	1
12. Vlaggemanstraat	NE-SW	1
13. Voorburgstraat	N-S	0.65
	NW-SE	0.5 - 1

Table 5.1 Summary of streets orientations and H to W ratios.

streets that do not face urban heat problems according to canyon solar exposure/shadow analysis

streets that face urban heat problems according to canyon solar exposure/shadow analysis

Solar exposure/shadow analysis of the area

The first step of applying the design concepts in the real site situation requires ***street geometry analysis.*** Which means the orientation towards sun and aspect ratio of every street needs to be detected. Area of Bergpolder Zuid has 13 streets including wide surrounding streets like Bergweg, Schieweg, Bergsingel and Bergselaan.

The street geometry analysis includes each street Height to Width ration and orientation towards the sun (Presented in the table 5.1), moreover, graphical representation of the section of each street is made to get an overview of streets solar exposure/shadow analysis (Figure 5.19). Streets that may face urban heat problems due to the large areas (more than ½ of the street width) that exposed to the sun for more than 6 hours in a day are highlited with orange colour in the table 5.1.

There are 10 streets in Bergpolder-Zuid which might face urban heat problems. The rest of the streets do not have such areas and it means that heat mitigation interventions on these streets are not that urgent.

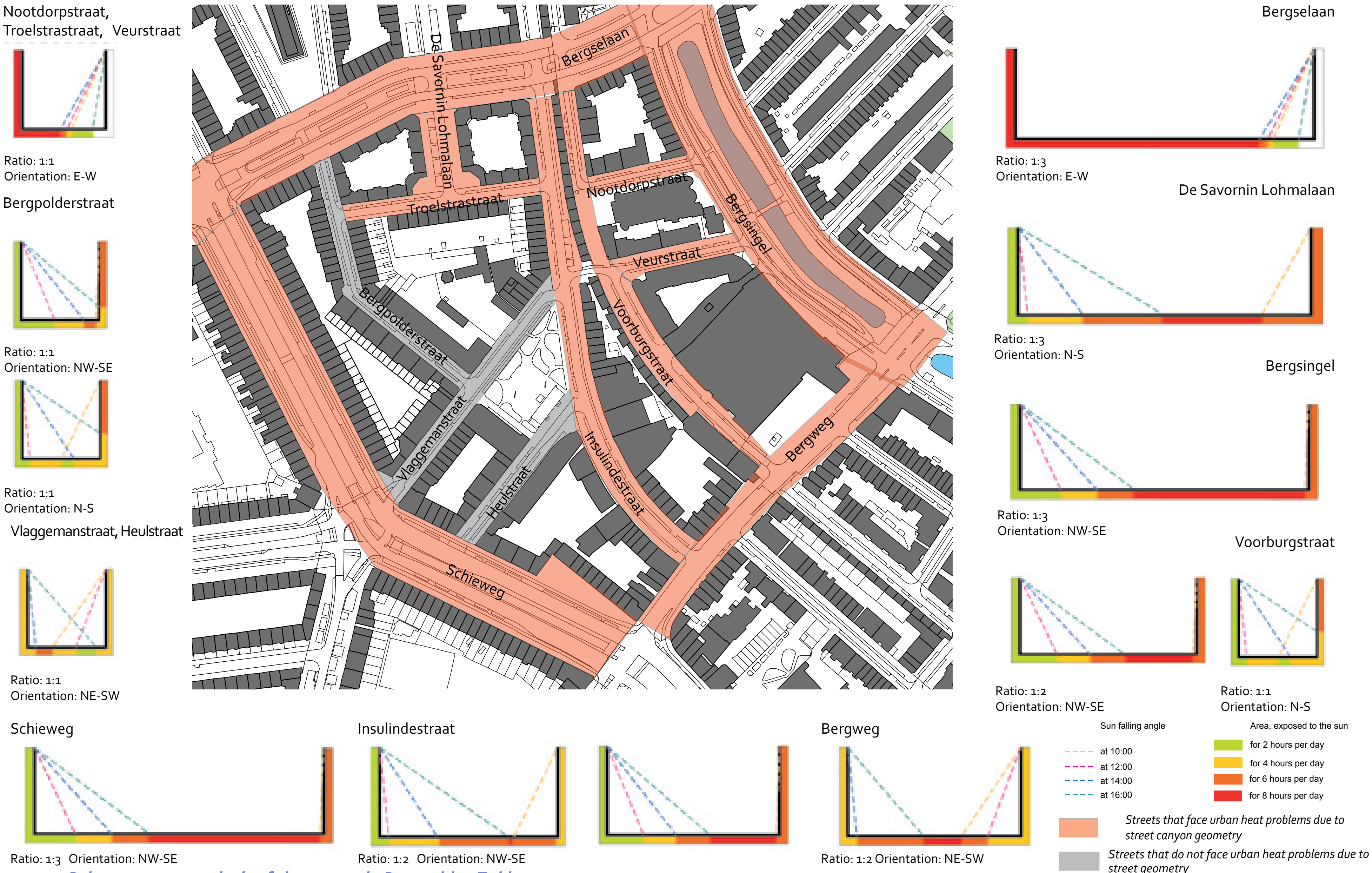


Figure 5.19: Solar exposure analysis of the streets in Bergpolder-Zuid

Existing green elements on the streets

Besides the street geometry analysis, it is important to understand which streets do and which streets do not have green, vegetated areas.

The certain amount of existing vegetation on the streets already plays heat mitigation functions; therefore the interventions in those streets may not be needed. The green elements on the street level are described and evaluated on the table 5.2.

The existing vegetation in Bergpolder-Zuid streets is analysed according to its ability shade the street surface, amount of green facades and open vegetated areas.

Streets where:

- half of horizontal surface is shaded by street trees, and/or
- have a large green open areas, and/or large green facades or
- vegetation next to the street canyon walls

will be considered as streets with sufficient amount of vegetation (these streets are highlited with green in the table 5.2).

Streets that are not shaded by street trees, even if they have some, have small green areas or green façade elements or don't have them at all will be considered as streets where amount of vegetation needs to be increased (highlited with red colour).

As we can see some streets like Bergsingel and Bergselaan already have large amount of vegetation; streets like Nootdorpstraa and Veurstraat do have green front yards and certain amount of vegetation that comes from the private gardens around so green interventions in these streets with the purpose of heat mitigation won't be very relevant.

Name of the street	Green elements.
1. Bergpolderstraat	One row of small trees, almost no shadows
2. Bergselaan	Trees on the South facing side of the street and large green area in the middle of the street.
3. Bergsingen	Large green open area with large trees and shrubs and canal
4. Bergweg	Almost absence of vegetation. Random front yards, vertical vegetation and some trees.
5. De Savornin Lohmanlaan	Small trees in the large, paved area, alost no shadows
6. Heulstraat	One row of small trees.
7. Insulindestraat	One row of small trees, with random distances.
8. Nootdorpstraat	Church front yards, greenery from private gardens, some vertical vegetation. Large green areas and shadows
9. Schieweg	Small trees with random distances. Lawn surface for tram line, small shadows, large areas exposed to the sun.
10. Troelstrastaat	One row of small trees on the south facing side, vegetation from the private gardens, small shadows
11. Veurstraat	One regular row of medium trees on the south facing side.
12. Vlaggemanstraat	No vegetation
13. Voorburgstraat	One row of small trees with regular distances very small shadows

Table: 5.2 Description of green elements in the streets

Streets that have green elements for urban heat mitigation

Streets that lack of green elements for urban heat mitigation

Legend for existing vegetation analysis

Streets with large green areas, or streets shaded by green elements for more than a half of the area

Streets with some green elements, but remain exposed to the sun

Streets without vegetation

Figure: 5.20 Analysis of amount of green elements in the street and their shading impact

Site analysis conclusions and design objectives

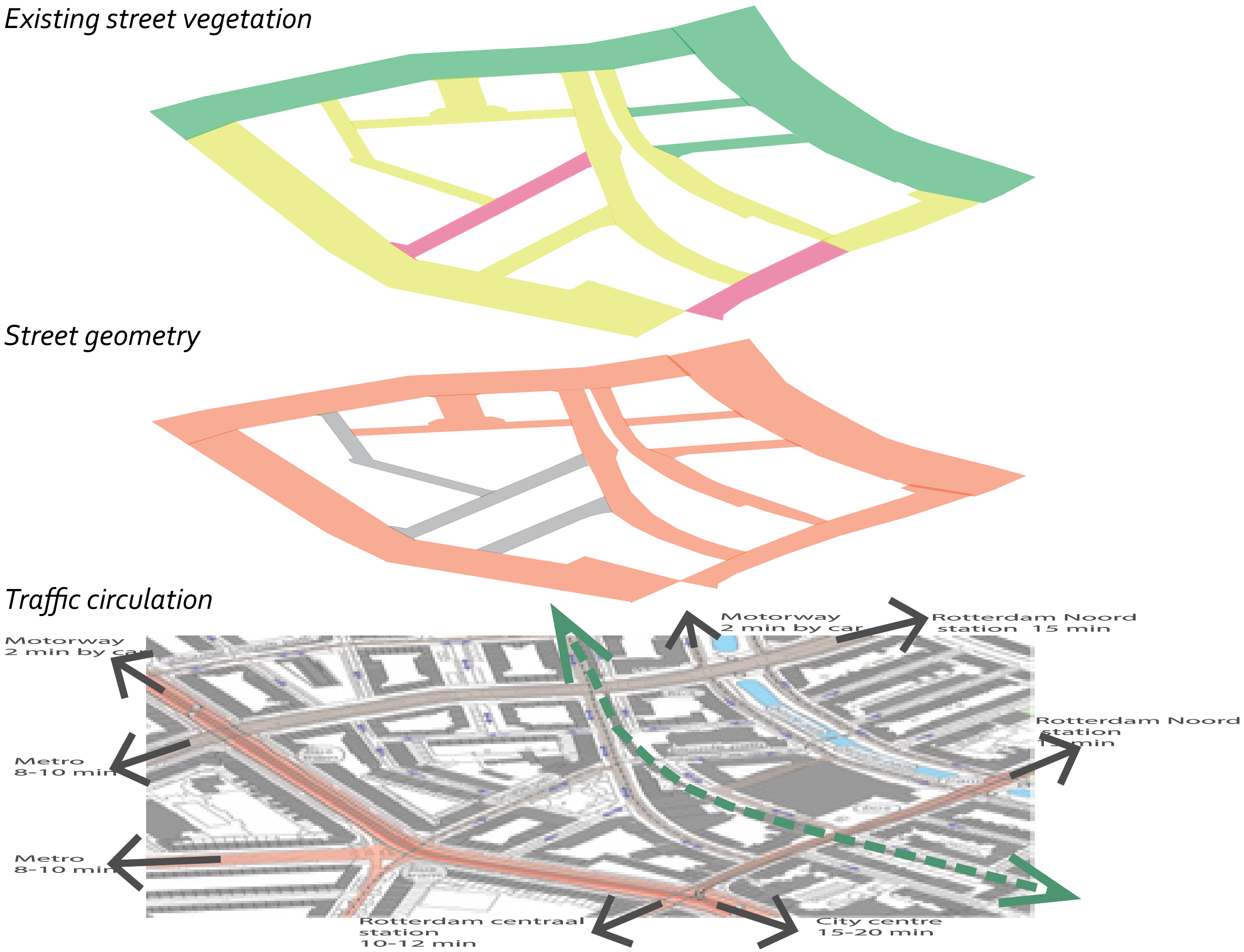


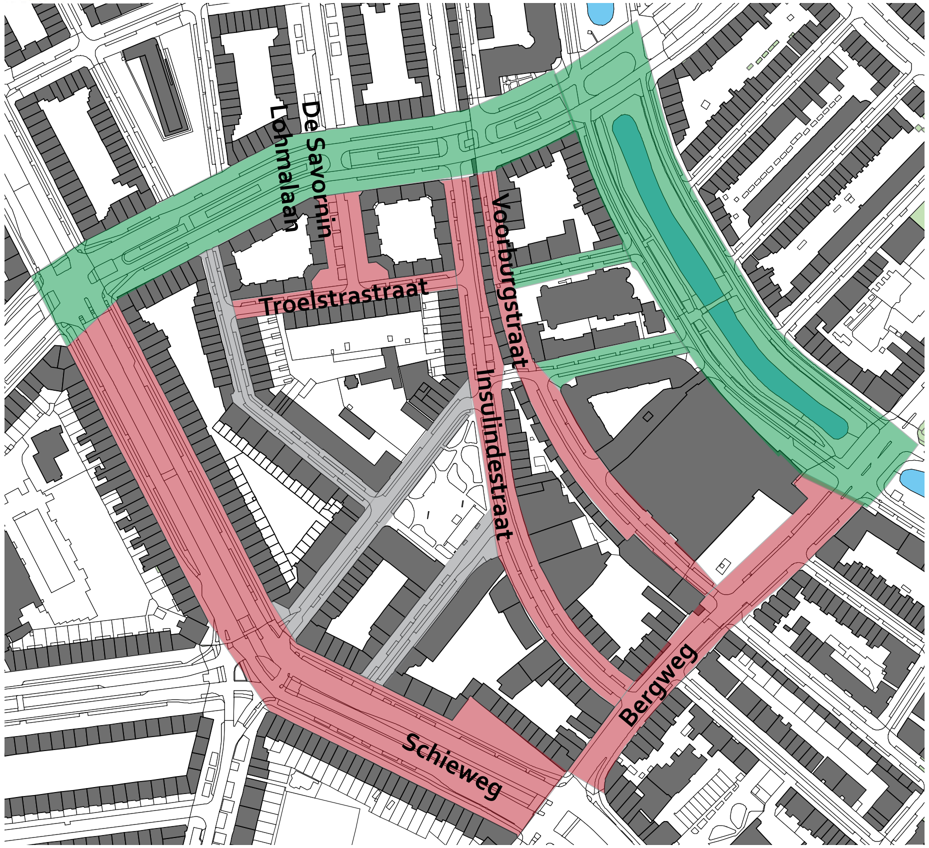
Table: 5.21 Layer analysis of Bergpolder-Zuid

To conclude the site design analysis it is decided to use the layer approach, combining both of the previous analysis of the existing street patterns. The combination of street geometry analysis and vegetation analysis of the area revealed that:

- Some streets do not face heat problems caused by solar exposure. Canyons of such streets have a high height to width ratio and that is why the surface of these canyons is not exposed to the sun more than 6 hours a day.
- Some streets might experience heat stress due to solar exposure caused by street geometry but the sufficient amount of existing street vegetation prevents it.

These streets do not need the detailed design solutions. Nevertheless, some streets may have improvements according to heat mitigation strategies. The coming design part will provide some recommendations and guidelines on which way to use more greenery or how to make a future development steps to make the streets more resilient to urban climate conditions.

The more careful attention will be paid to the streets, which face heat problems due to large areas of solar exposure that is concluded by street geometry analysis and lack of vegetation to mitigate generated urban heat. These streets are: Schieweg, Bergweg, Insulindestraat, Voorburgstraat, Troelstrastraat and De Savornin Lohmanlaan - 6 in total. ***All of them are chosen for the future design step*** due to the facing of heat problems.

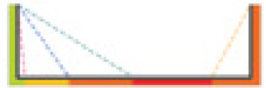


Streets that do not face urban heat problems due to street geometry

Streets that do not face urban heat problems due to green elements

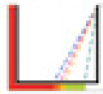
Streets that face urban heat problems because of street geometry and absence of vegetation

De Savornin Lohmalaan



Ratio: 1:3; Orientation: N-S

Troelstrastraat

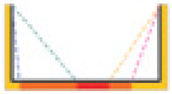


Ratio: 1:1; Orientation: E-W

Schieweg

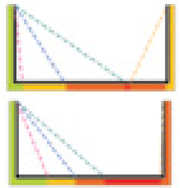
Ratio: 1:3; Orientation: NW-SE

Bergweg



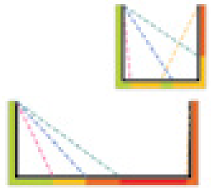
Ratio: 1:2; Orientation: NE-SW

Insulindestraat



Ratio: 1:2; Orientation: NW-SE, N-S

Voorburgstraat



Ratio: 1:2 1:1; Orientation: NW-SE, N-S

Table: 5.22 Conclusion of the analysis. Streets that are chosen for detailed design (marked with red) due to vulnerability to urban heat and lack of vegetated areas.

5.4. Design process

Design principles application for Bergpolder-Zuid streets.

Analysis part revealed streets that need design for thermal comfort. Streets face urban heat problems due to the large areas of solar exposure and lack of vegetation. Bergpolder-Zuid area Masterplan form 2011 (Ginter, Hornis et al. 2011), also stress out the absence of the vegetation and stony character of the streets in the area. Thus ***the design for thermal comfort will solve 2 problems at the same time: improve microclimate and create psychologically and ecologically pleasant green environment.***

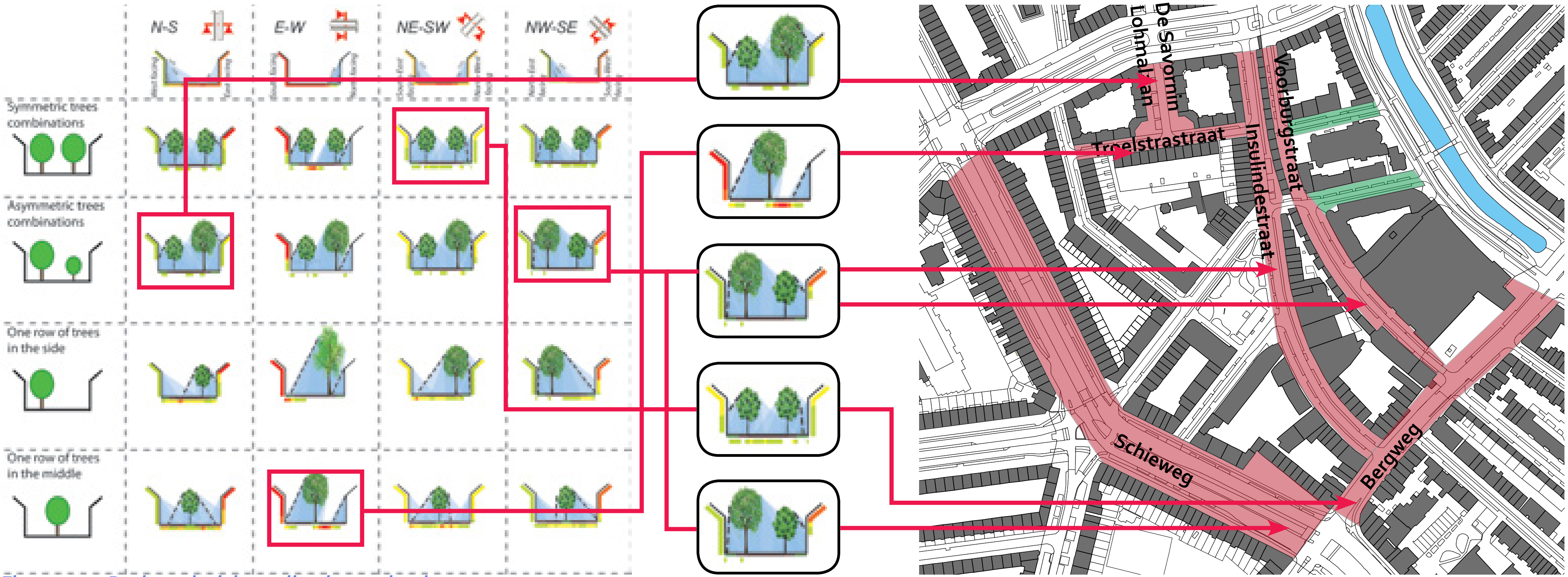


Figure: 5.23 Design principle application to the chosen streets

Application methodology

After the analysis of street geometry has been made it is time to apply the design principles for the streets that face urban heat problems.

The design principles are all the possible combinations of street canyons and trees that are chosen from the Matrix and concluded in the table of selections. These combinations are the most successful shading solutions due to the fact that they provide shadows for the horizontal surfaces in the streets and allow solar access for the street canyon walls at least for several hours a day.

Possible combinations are chosen for each street according to its urban geometry parameters.

The real life situation was taken into account as well. For example, due to the fact that Bergpolder-Zuid streets lack vegetation, combinations with 2 rows of trees in the streets will be more welcome.

To provide the identity to the area it is decided to give preference to asymmetrical combinations of the trees in the streets where it is possible (Figure 5.23).

Real situation adjustments.

Street functions, exploitation intensity and actual dimensions differ from street to street. Therefore the chosen design combinations for heat mitigation should be adjusted for each particular case.

One of the main modifications it is the ***adjustment of trees sizes.*** The design principles were created for the small street canyon, and all the solutions that fitted the best to shade the horizontal surface and leave the street facades exposed to the sun were provided by small trees. ***In case of bigger street canyons like the ones in Bergolder-Zuid taller and wider tree species should be selected.***

It is not always possible to plant a tree exactly according to its shadow pattern. Sometimes the place for the location can be in the middle of the road; in this case ***tree should be located as close to the required point of the street as possible.*** The shading pattern won't be the exactly the same as in the design principles, but nevertheless can noticeably improve the solar exposure situation.

In some cases (for example in case of Schieweg street) height to width ratio is much lover that 1:2 (the one in the design principles) ***therefore street may require more additional rows, or groups of trees that also can be placed according to the design principles.***

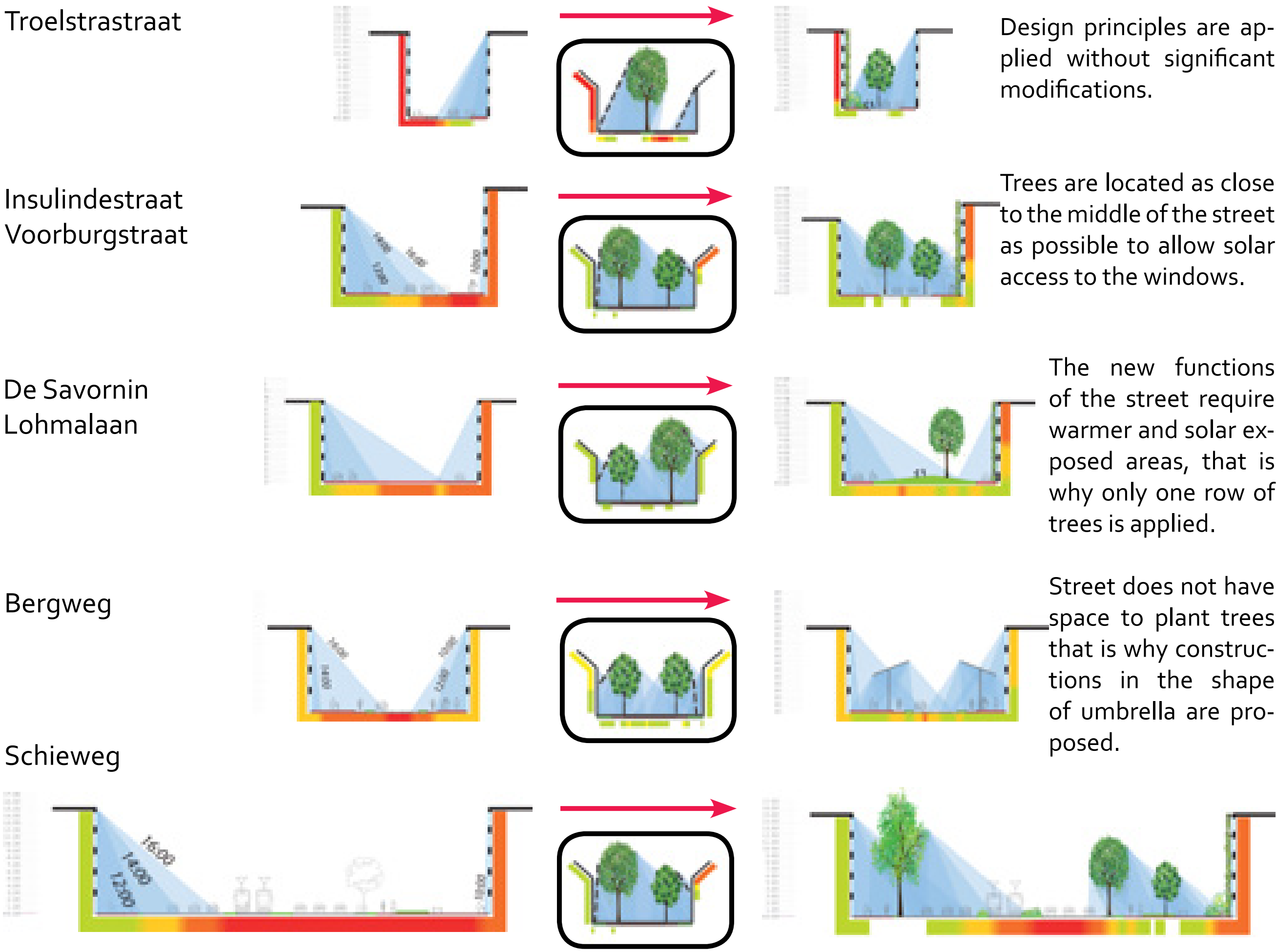
Evaluation of design principles

Figure 5.26 shows the application of the design principles to the each street of Bergpolder-Zuid area. As long as the exact combinations for heat mitigation are slightly modified it is important to calculate the exact street shading patterns in the streets after the green elements were applied.

The calculation of the shadow pattern of existing trees with green elements is similar to the shadow pattern calculation in the previous chapter and visually presents the amount of area that is exposed to the sun or shaded by trees or canyon walls.

As we can see from the Figure 5.26 it is not always possible to shade the street canyons completely. Due to street functions it is not possible to shade street with trees wherever it is necessary and some areas will remain exposed to the sun.

Nevertheless, ***the total amount of street areas that are exposed to the sun is significantly reduced*** which will improve the thermal conditions on the street in the hot summer days by making streets cooler.



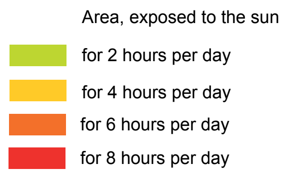


Figure 5.24 Modification and evaluation of design principles in according to the existiong situation.

Design elaboration

Figure 5.25: Masterplan of Bergpolder-Zuid area. Scale 1:2000, smaller scales of the Masterplan are available on the posters.

The design principles are applied to the existing streets and were accordingly modified. The impact of the trees in the street according to its solar exposure and shadow patterns was evaluated. Design concept proved itself and can be used further for the other areas that also require design for microclimatic improvement with shadows.

Nevertheless, pure design principle application to any specific area is not complete design. The place need to have an identity, landscape elements should be located in a context of the site. The whole urban heat mitigation strategy should work for, not against the situation.

This chapter will focus on each street leyout and desing specifically and will describe how exactly heat mitigation with shadows should work in the context of each street.

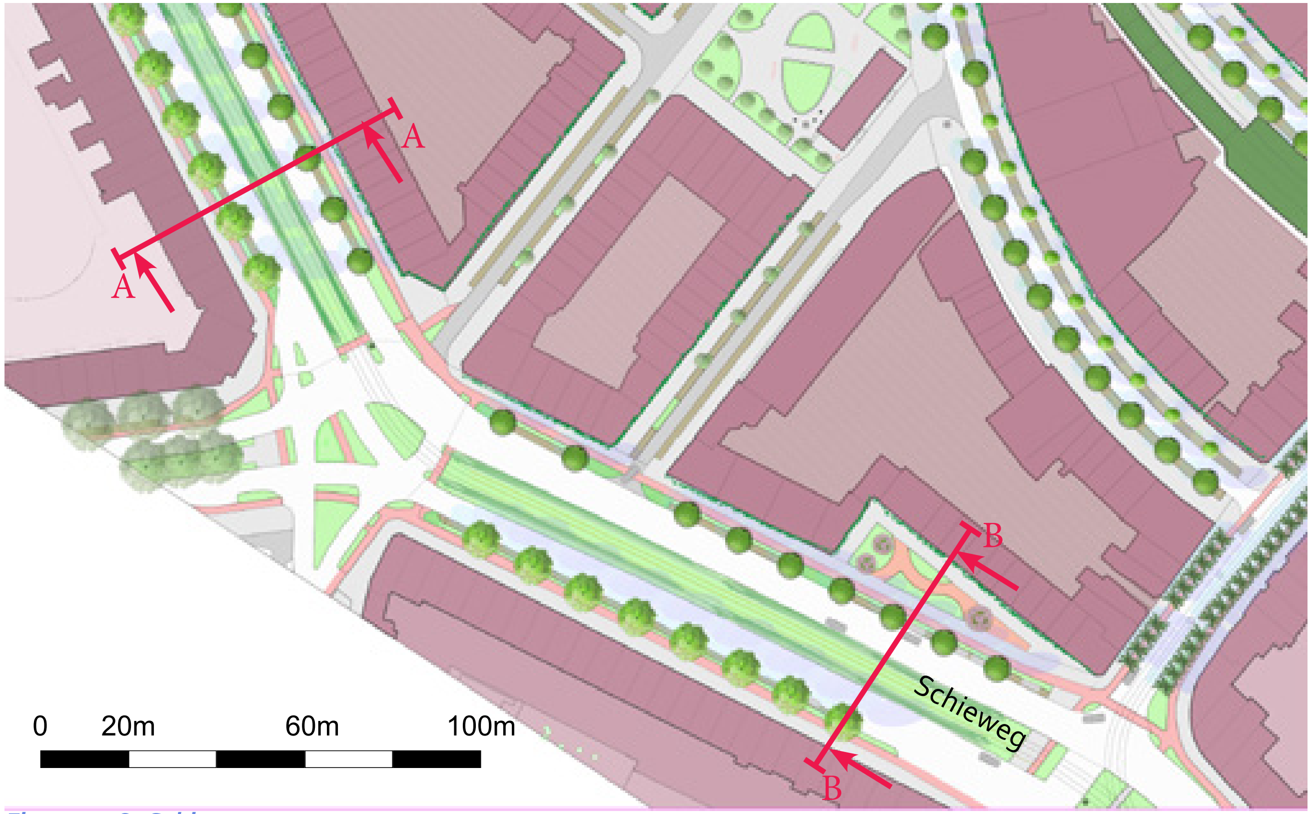


Figure 5.26: Schieweg

Figure 5.27: Schieweg, street section A-A. Shadows are shown for 14:00, summer time

Sunny/shady street walking

Schieweg. This street has NW-SE orientation and height to width ratios 1:2 and 1:3. The asymmetrical combination of trees is chosen for heat mitigation strategy.

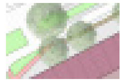
Rows of the trees are located as close to the road parts as possible, to provide shading for the middle part of the street and solar access for the walls. In fact, trees are located in the row with parking spots and provide sufficient shade for parked cars. Parking lots are separated from the pedestrian part and bicycle path by line of low plants combined with a permeable surface. Parking lots have a permeable surface as well to absorb access of rainwater, and evaporate it later, this way additionaly contribute to heat mitigation.

Pedestrian part is combined with a bicycle path; functions are defined by pavement pattern and colour. These parts of the street are shaded by trees for the most part of the day. Pedestrians and cyclists require cooler thermal environment that will be achieved with a help of shadows.

In the southern part of the street, near the crossroad with Bergweg, there is a small square that is located on a South-West facing part of the street. This square stays exposed to the sun for almost all day long and requires diverse thermal conditions due to the fact that people not only walking the, but also have a lunch on the benches, play with children, have a dates or just wait for each other. The diverse thermal conditions will be achieved by use of smaller trees with loose canopy and some open green areas that also affect thermal conditions. Besides thermal comfort, increased amount of green elements will make a square more attractive and pleasant place to be as well as play the representative role of the Bergpolder-Zuid area in general.

Facades of Schieweg, that face South-West are exposed to the sun for almost all day long, except, for may be some morning hours. That is why use of green facades, window blinds or awnings is recommended. These elements can be provided by individual households initiatives and through the general design implementations.

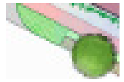

Buildings with inner yards


Exiting trees

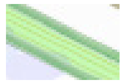

New trees


Green facades


Grass/lawn


Permeable surface with meadow plants


Permeable surface for parking lots


Taller vegetation along tram lines

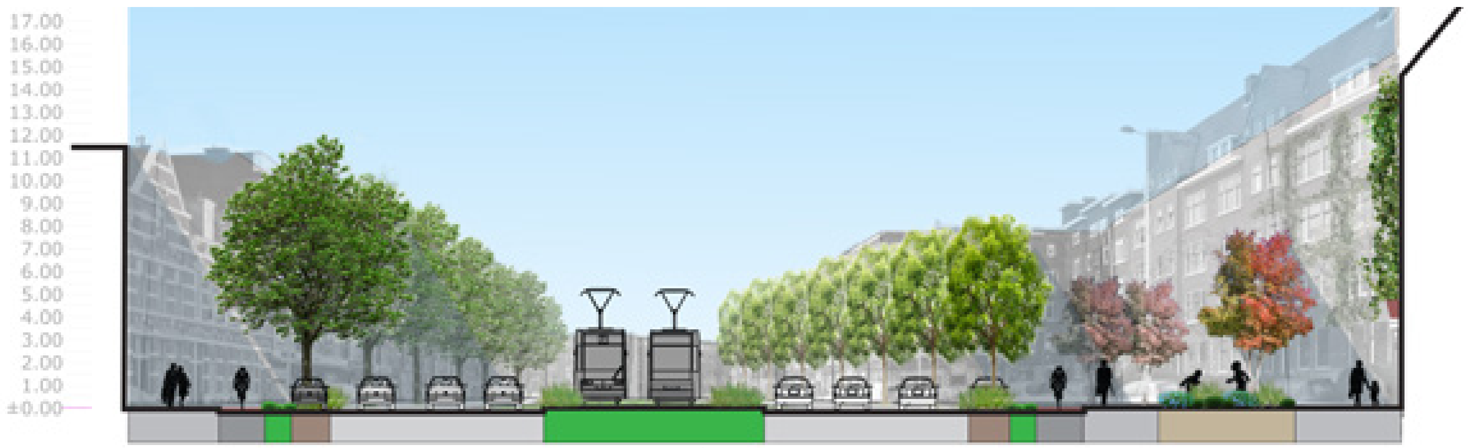


Figure 5.28: Schieweg. street section B-B. Shadows are shown for 14:00, summer time

Bergweg. This street has NE-SW orientation and height to width ratio 1:2. Street is very busy, architecture of the buildings is quite diverse. Qualities that engage eyes are very welcome in the streets, that is why Bergweg creates quite a good impression.

At the same time there are almost no large green elements like trees or green facades. Some small scale vegetation takes place but there is no coherency or unity in it.

The walls of NE-SW orientated street canyon are exposed to the sun for 4 hours a day, that is why there is no much need in application of the green facades, but nevertheless, middle part of the street canyons requires shadows.

Street has a very heavy traffic load and street zoning does not allow planting trees in it. That is why it is decided to use constructions for climbing plants that remind rectangular shape solar umbrellas. The place for a climbing plant is located on top of the structure, in the middle of the umbrella construction. Plant is placed in a double pot; the inner part is permanently fixed and filled with soil and fertilisers. Plant will grow in it. The outer part can be taken down with help of the wire construction, filled with water and placed back on the top of the construction, to provide enough of water to the plant.

Climbing plants will spread around the umbrella construction and provide loose shade for street surface. Umbrella construction won't claim any additional street space for roots or soil substrate, which is why the construction is highly recommended for such a busy streets as Bergweg.

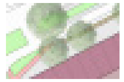
At the same time, coherent location of such solar umbrellas not only brig the special atmosphere and identity to the place, but also even out the diversity of the street facades.

Figure 5.29: Bergweg

Figure 5.30: Bergweg, street section C-C. Shadows are shown for 14:00, summer time

Figure 5.31: Bergweg, street detail - "Green Umbrella"

 *Buildings with inner yards*

 *Exiting trees*

 *Viaduct*

 *New trees*

 *"Green umbrellas"*

 *Permeable surface for parking lots*

Figure 5.32: Bergweg, street experience

Figure 5.33 Insulindestraat and Voorburgstraat

Insulindestraat and Voorburgstraat. Both of the streets are N-S orientated in the Northern part of the district and NW-SE orientated in the Southern part of the street. Both of the streets have height to width ratio 1:2 or even higher and just partly face urban heat problems caused by street canyon geometry.

At the same time, both streets have similar functions within the area of Bergpolder-Zuid. They provide transit in the district. Almost all car owners use those streets to get to their houses or to the parking lots. Moreover, both streets have parking lots on both sides as well and it is very important for the district inhabitants.

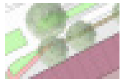
Due to the fact that street still need shadows for heat mitigation it is decided to sacrifice some of the parking lots for trees' planting beds. Roots of planted trees will be covered with the permeable surface like the part for the parking lots. That allows to keep more parking spaces. Trees trunks will be additionally protected by special metal constructions from the clumsy car owners.

South-West facing facades of the street are shaded by green facades and constructions for climbing plants. In some parts of the streets street facades are formed by the railway Viaduct that once was connecting Rotterdam and Den Hague. Nowadays it is a monument and the viaduct area is a part of city green infrastructure. The purpose of the design is to integrate viaduct to the Begpolder–Zuid even more by providing access to the top and create view points for Bergpolder-Zuid area.

Figure 5.34 Insulindestraat, Section D-D. Shadows are shown for 14:00, summer time

 *Buildings with inner yards*

 *Viaduct*

 *Exiting trees*

 *New trees*

 *Green facades*

 *Permeable surface for parking lots*

Figure 5.35: Insulindestraat, street experience

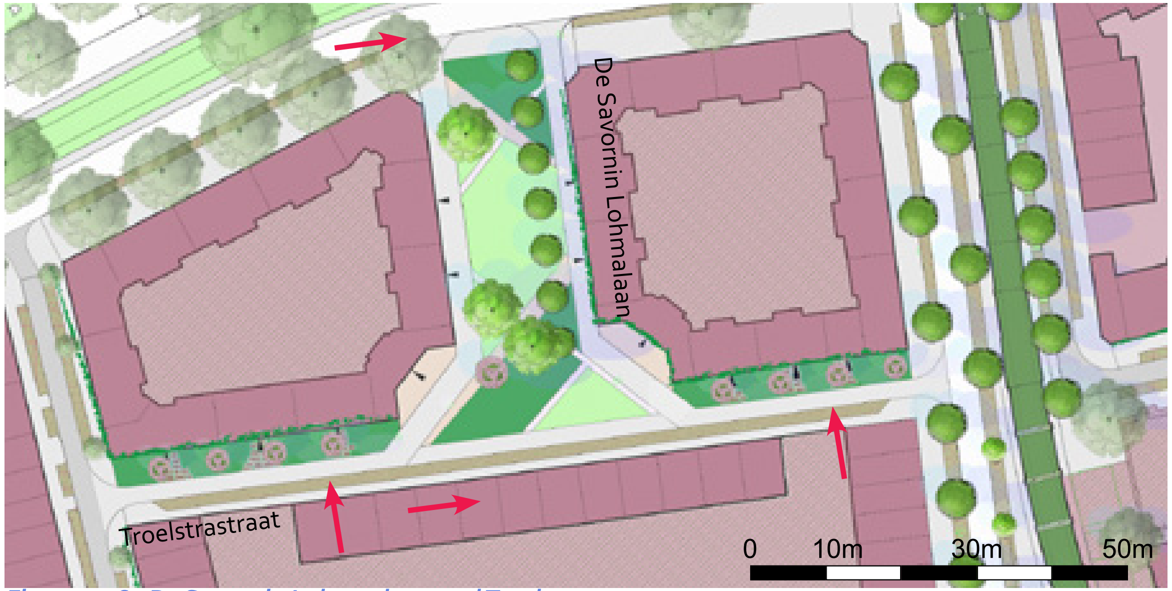


Figure 5.36: De Savornin Lohmanlaan and Troelstrastraat

Comfort diversity of the pocket park

De Savornin Lohmanlaan is N-S orientated street canyon with height to width ratio 1:2. ***Troelstrastraat*** is E-W orientated street with ratio 1:1. Both streets are inner streets that play more parking and access function rather than transportation. Bergpolder-Zuid development plan in 2011 suggest development of the pocket park in the area of these streets.

De Savornin Lohmanlaan Street outside the area of Bergpolder-Zuid has large green areas and form so called green axis of the district. Partts that belongs to Bergpolder-Zuid can become successful extension of this green axis. Troelstrastraat is small one way street that is perpendicular to De Savornin Lohmanlaan. It is suggested to move the parking lots away from the street to the common parking area underground and make the street completely pedestrian with open green areas and children playgrounds (Ginter, Hornis et al. 2011).

Figure 5.37: Panorama along De Savornin Lohmanlaan. Shadows are shown for 14:00, summer time

To improve the microclimate in the context of this research the areas of both streets will be considered as a street canyons, as long as they actually still remain canyons. At the same time, the main activities of the areas will shift from movement (like walking or biking) into more calm and recreational. Sitting, reading, relaxing, slow walking or children plays requires more higher PET values than strong movements. Shadows, so desirable on the big streets where people walk, may create too cool environment for people who want some leisure and rest. Therefore, the design of these street canyons will focus not only on the heat mitigation strategies but also on diversity of the thermal conditions for diversity of human activities.

The design evaluates all the possible functions of the area and relocates them according to the canyon shadow patterns.

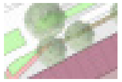
Although it was decided to eliminate traffic functions from the streets, vehicles access to the buildings still should be provided and parking lots will still remain on the streets. Accoring to the solar exposure/shading analysis it is decided to locate all the access roads and parking lots into the most shaded parts of the area (along the North facing façade of Troelstrastraat and along the East facing façade of De Savornin Lohmanlaan). Access road along the West facing facade of De Savornin Lohmanlaan will be additionally shaded by row of medium size trees.

One of the most important aspects of the design is to provide pedestrian access to all building entrances. Several paths are strategically placed in the area will solve the situation. South facing part of Troelstratstraat will be transformed into green areas with shrubs and meadow vegetation complemented with ornamental trees and green facades. The access to the entrances will be provided by stone pavement placed in the lawn.

The middle area of De Savornin Lohmanlaan canyon will be an open green lawn. Some tarts of it will be intensively managed (mowed and


Buildings with inner yards


Viaduct


Exiting trees


New trees


Green facades


Grass/lawn


Meadow


Permeable surface for parking lots


Permeable surface for building entrances

Figure 5.38: Panorama along Troelstrastraat Shadows are shown for 14:00, summer time

watered) and used for the recreational purposes – like playing sport games, or lying and resting in it. These parts are designed with small slopes, to enlarge the area and provide some relief. This will also help to manage rainwater drainage for rainy days and helps to avoid puddles in the middle of the grass surface.

he other parts of the canyon are designed as meadows, with extensive management and diversity of perennials and grasses. They will retain the access water, and provide the cooling effect through slow evaporation. Meadows will be easily accessible, but they won't be used as much as the areas with smooth lawns that are located nearby and are much more convenient for recreational purposes. Both, lawns and meadows will be partly shaded, partly exposed to the sun. The reason of this is to create different patterns of sun and shade, so people can chose where to go according to their personal thermal preferences and current activities.

Park, formed by these two streets is easily accessible for area inhabitants, workers and visitors, children and their parents, teenagers and grown-ups and should provide safe natural playground or place for the recreation for the entire Bergpolder-Zuid, so called "pocket size nature" just behind the corner.

Figure 5.39: De Savornin Lohmanlaan, experience. View from Bergselaan street.

Figure 5.39: De Savornin Lohmanlaan and Troelstrastraat, experience

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6. Conclusions and future steps

6.1. Research objectives and questions

6.2. Approach to the research and study cases

6.3. Shadow simulation method

6.4. Results and conclusions of the research outcomes.

- Solar exposure/shadow patterns of the street canyon
- Research on street green elements
- Combinations of street canyons and trees for design principle development.
- Site specific adaptation of design principles

6.5. Possible future steps

- Validation and testing of the design principles
- Heat mitigation strategy integration with other climatic components

6.1. Research objectives and questions

The main objective of this study was to find the ways how to mitigate urban heat in the street scale and create thermally pleasant outdoor environment.

The answer to the main research question and the chosen strategy for heat mitigation is ***to prevent solar radiation gains in the streets by providing shadows of the trees or other green elements in the places where it is necessary.***

This strategy development requires several steps that were mentioned in the research sub-questions:

1. ***Analysis of the parameters of street canyon geometry itself:*** H to W ratio and orientation towards the sun, to figure out the areas that are more or less exposed to the sun and which areas of street canyons require additional shading.
2. ***Analysis of the parameters of green elements*** – particularly trees, to understand their shading geometry and factors that influence it.
3. ***Find the optimal combinations of street canyons and trees*** to provide enough shadows to mitigate urban heat ***and use them for development of the design principles*** for further design.
4. And finally ***to apply design principles to the design case.***

All the taken steps result certain outcomes that can be applied by landscape architects for microclimatic analysis or design for urban heat mitigation individually or in combinations.

6.2. Approach to the research and study cases

Pragmatic and quantitative approach determined all the research process.

Strategy meant to improve the existing streets conditions. Therefore, first of all street canyon form itself was analysed for the amount of shaded/solar exposed areas, the additional shading is provided by urban green elements. Shaded/solar exposed areas from the street canyon and trees can be quantitatively evaluated and visualised.

Streets that are chosen for development of the design principles and final design case are typical in the Netherlands. The reason behind this choice - to make the strategy for urban heat mitigation more relevant not only for the case study area but for the other areas in the Netherlands as well.

Heat mitigation strategy can be also applied for the new developed areas during the design process. This way, street layouts and functions can be developed according to the heat mitigation principles which will help to implement these principles in easier and more efficiently.

6.3. Research method

The main research method was based on shadow pattern simulations by Sketch Up program software. It is freely available, commonly used by designers, and allows to simulate shadows instantly for every point of the world and any time of the day.

Shadows were simulated separately for street canyons with different aspect ratios and orientation toward sun and trees with different shapes and sizes. Simulations were made for 4 times during the day: ***10:00, 12:00, 14:00*** and ***16:00*** and for ***summer and winter solstices*** Figure 6.1 and 6.2. Due to the fact that the case study are of the research was located in Rotterdam, this city was taken as a location for shadow pattern simulation. But in general, hours of the day, date of the year and location of the area are adjustable for any other requirement.

After shadows were simulated, their patterns for 4 times of during the day were overlapped together and resulted diurnal solar exposure/ shadow analysis of street canyon or diurnal shadow pattern of a single tree. ***The further analysis or manipulations with street canyons or trees were done taking these diurnal patterns into account.***

6.4. Results and conclusions of the research outcomes

Solar exposure/shadow patterns of the street canyon

Shadow simulation for street canyons were made for ***4 H:W ratios (2:1, 1:1, 1:2 and 1:3) and 4 possible orientations towards the sun (N-S, E-W, NE-SW and NW-SE).*** The results of canyon solar exposure are organised in a table according to street canyon geometry parameters - figure 6.3 .

Previous literature research described the influence of street canyon H to W ratio and orientation towards the sun on street thermal conditions. Studies, conducted independantly in the different places of the world with moderate or hot climates proved that the more street is exposed to the sun the more urban heat it generates (Ali-Tourdert and Mayer 2006; Ali-Toudert and Mayer 2007; Futcher 2008; Herrmann and Matzarakis 2012).

Based on canyon solar exposure results and literature studies of canyon geometry impact on street thermal conditions it was concluded that streets with more than ½ of horizontal surface exposed to the sun for more than 6 hours a day during the summer time face urban heat problems.

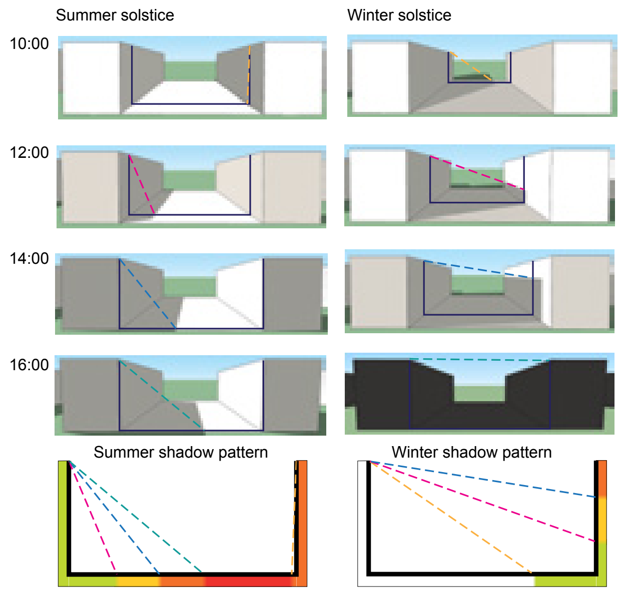

Figure 6.1 Example of shadow pattern simulation and diurnal solar exposure calculation in street canyon.

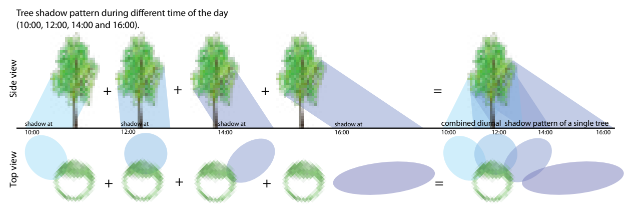

Figure 6.2 Example of diurnal tree shadow pattern calculation.

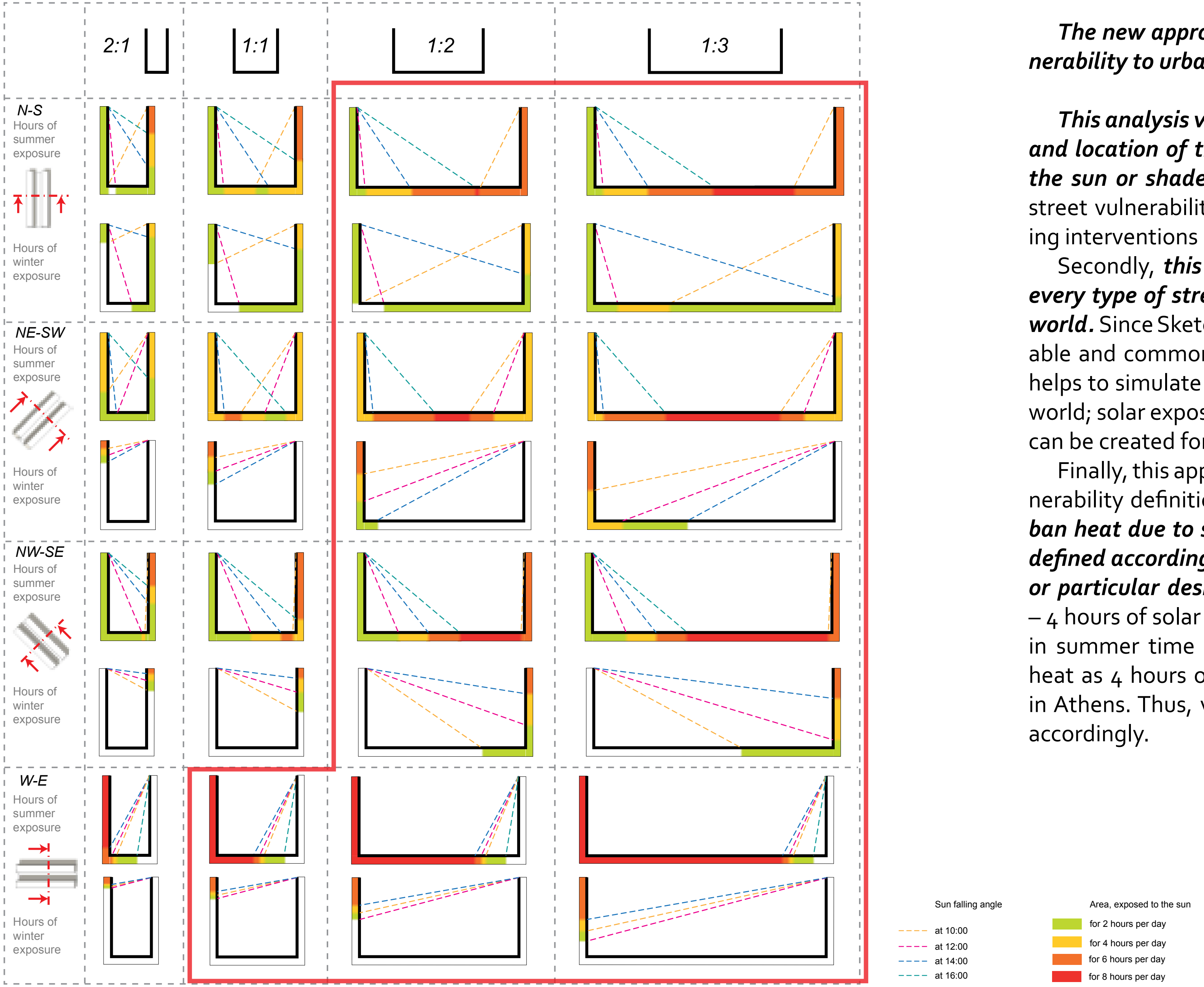

Figure 6.3 Diurnal solar exposure analysis of street canyons.

The new approach to analysis of street vulnerability to urban heat is developed.

This analysis visually illustrates the amount and location of the areas that are exposed to the sun or shaded. Based on this information street vulnerability can be defined and according interventions can be proposed.

Secondly, ***this approach can be applied for every type of street and every location on the world.*** Since Sketch Up simulations is easy available and commonly used design software that helps to simulate shadows for every part of the world; solar exposure/ shadow patterns analysis can be created for any desirable location.

Finally, this approach gives a freedom for vulnerability definition. ***Street vulnerability to urban heat due to solar exposure can be always defined according to the local climate specifics or particular design preferences.*** For example – 4 hours of solar exposure in Rotterdam Street in summer time won't cause too much urban heat as 4 hours of solar exposure of the street in Athens. Thus, vulnerability can be redefined accordingly.

Research on street green elements

Trees and street vegetation are the easiest, most effective and cheapest way to improve aesthetical qualities in the street. Green is a psychologically restful and agreeable colour (Jacobs 1995). At the same time urban vegetation affects air pollution, works as a noise barrier, and even shapes the urban development and provides number of general ecological functions and environmental services (Givoni 1991; Bolund and Hunhammar 1999).

The climatic impact of plants in urban areas is quite certain and performs in a different ways and even city scales. One of the major contributions of trees to street climate is shading (Heisler 1986; Mayer and Martzarakis 2006; Mayer, Kuppe et al. 2009).

The outcomes of this research on green elements shows the ways how to locate green elements especially trees in the most efficient way to shade the area under them. These outcomes can be applied for existing or newly developed streets, as well as for open areas, parks or squares that need shading.

Combinations of street canyons and trees for design principle development

Shadow patterns in street canyons shows the areas that are exposed to the sun for the certain amount of hours. Shadow patterns of the trees will help to find the optimal distances, arrangements and locations of trees. It is important to understand how to combine these elements together, so they can shadow street in for urban climate improvement.

Based on the preliminary research on street shading guidelines, energy savings and conservation (Heisler 1986; Brown and Gillespie 1995; Erell, Pearlmutter et al. 2011) and according to the specifics of Rotterdam climate, street solar exposure analysis and shading abilities of the trees it is decided to develop street shading requirements:

- areas of the streets that are exposed to the sun for 6 or 8 hours a day should be shaded,
- areas that are exposed for 2-4 hours a day should be exposed to the sun as much as it is possible, and
- street facades shouldn't be shaded by trees even if they are exposed to the sun for all day long (walls can be shaded by green facades, but windows should remain open for solar penetration) (Figure 6.4).

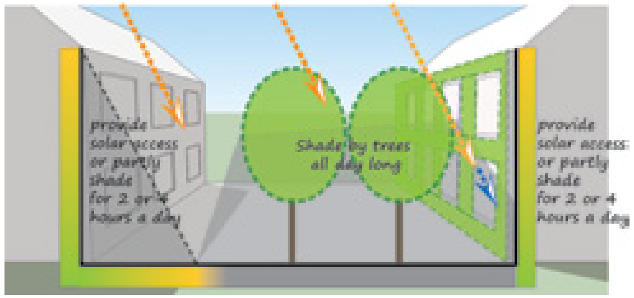

Figure 6.4 Shading requirements for trees in the canyon

To find these requirements 4 orientations of the certain street canyon with fixed ratio (1:2) was combined with 18 possible combinations of 3 trees sizes to figure out combinations with the most suitable shading solutions. The example of one of such combination and shadow pattern calculation is shown on the Figure 6.5.

The full overview of the combinations is presented in the appendix while the most suitable combinations for street shading and leaving the solar access to the windows were selected into separate table in the Figure 6.6 (a).

The most suitable combinations can be used as design principles for actual design process with microclimate. Application of these principles is a fast way to find the most efficient solution for street shading according to existing street geometry (Figure 6.6 (b)).

Site specific adaptation of design principles

The design principles have an idea of global thinking, but the design of the area should act on the local scale (Koh 2010).

Design process requires site analysis besides the analysis of street geometry. Design principles are applicable for almost all street geometries, but they do require certain modifications according to the street layouts and functions. ***Careful analysis of the design area has to be made***, especially if the final design outcome has to be detailed and elaborated.

Streets won't allow design principle application without any modifications due to their sizes, existing layouts and functions. Some streets do not allow to plant trees, due to the lack of space, some streets are too wide or too narrow to apply the design principles right like they are presented in the selection table. That is why, ***selected design principles have to be modified according to existing street layout and conditions.*** The example of such modification is shown on the figure 6.7.

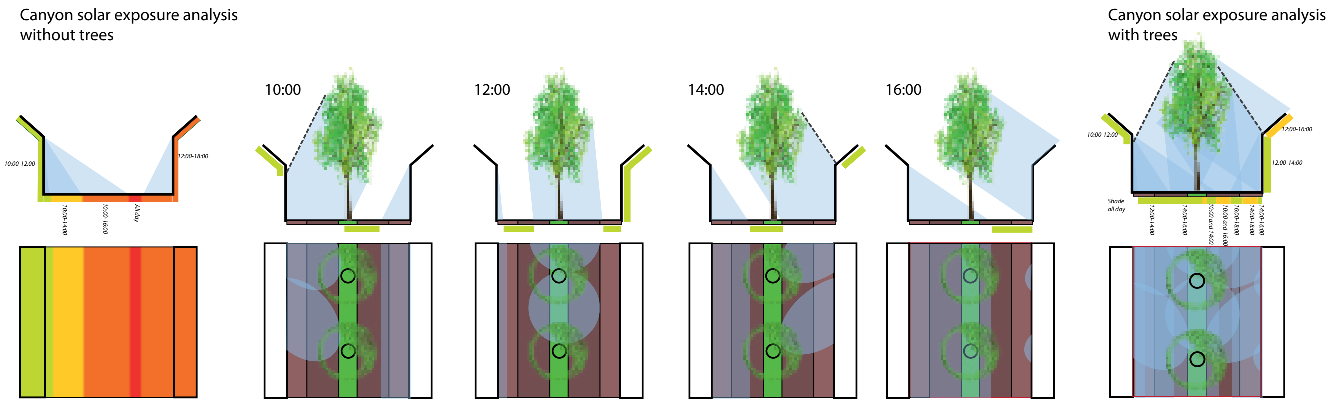

Figure 6.5 Example of solar exposure analysis calculation for street canyon with trees.

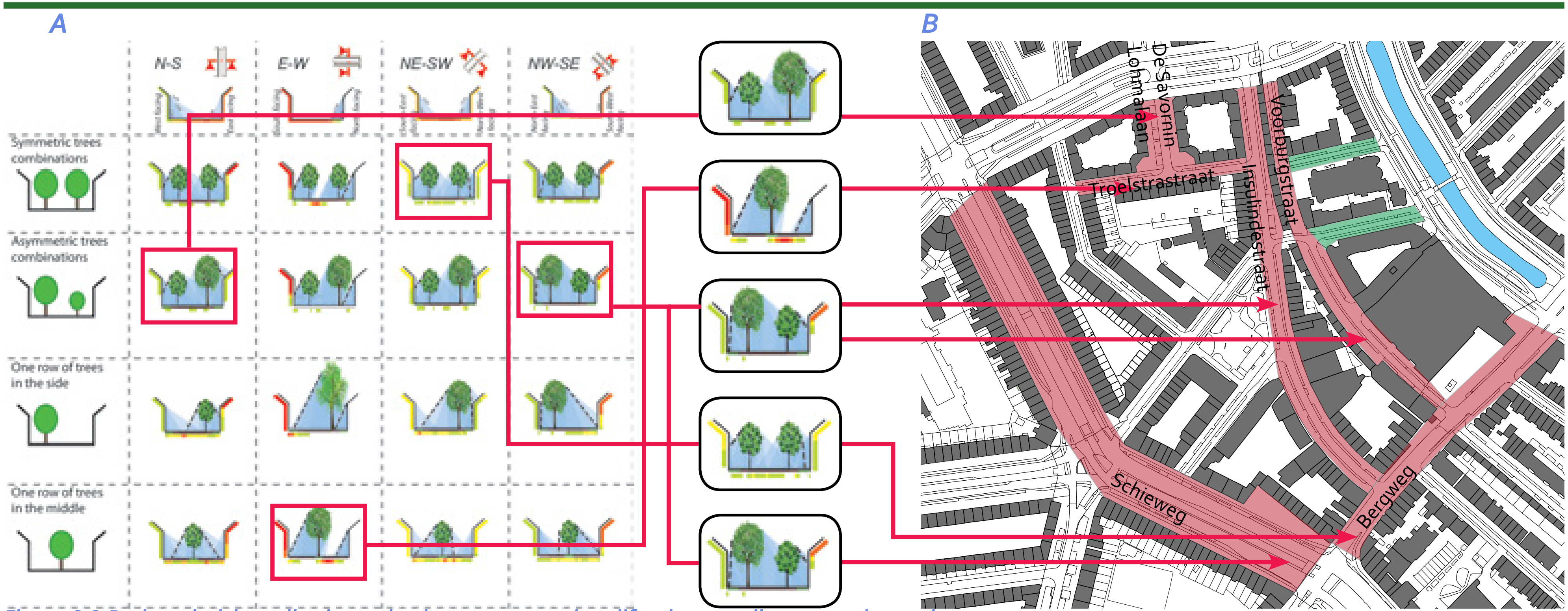

Figure: 6.6 Design principle application to the chosen streets and modification according to actual street layout

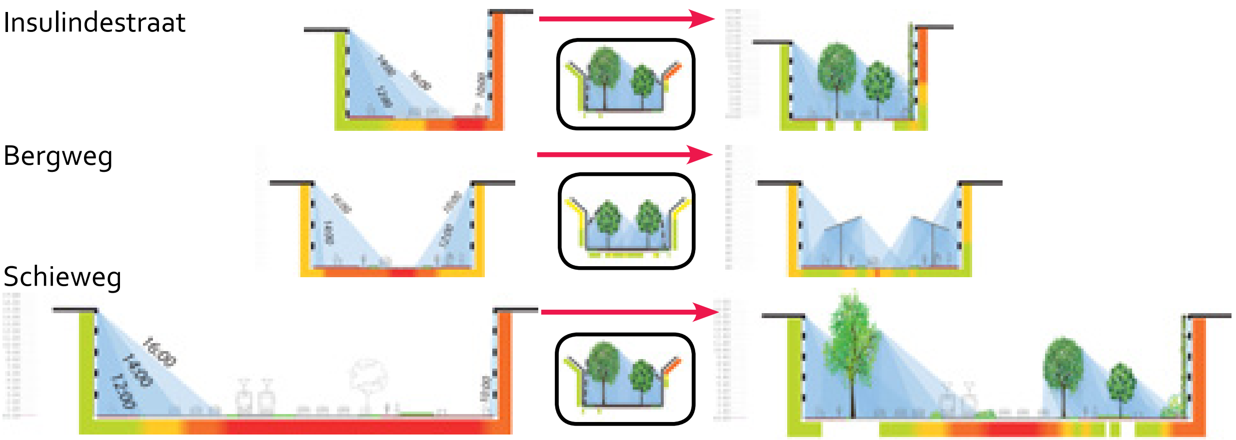

Figure: 6.7 Design modification according to actual street conditions

Trees are located as close to the middle of the street as possible to allow solar access to the windows.

Street does not have space to plant trees that is why shading constructions in the shape of umbrella are proposed.

Canyon H to W ratio is very low, it is impossible to shade street with 2 rows of trees complitely, additional trees to shade the surface are added where it is possible.

6.5. Possible future steps

Although this master thesis research is finished, it definitely can be extended. Urban heat in the streets can be discussed in many different ways. Here are mentioned two ways of how is it possible to extent this particular research beyond the frames of current thesis. Both ways are interesting and valuable but unfortunately can't be implemented in the master thesis frames due to their complexity and large amount of data required.

Validation and testing of the design principles

Heat mitigation strategies and design principles are developed theoretically, based on the literature research and with help of shadow simulation software. Therefore it would be extremely interesting to investigate the effect of those design principles with climatic simulation software and in the real life situation.

With help of special microclimatic simulation software amount of reduced radiation in streets might be translated into micrometeorological aspects like humidity, air temperature. Physiological Equivalent Temperature (PET) can also be calculated and evaluated according to existing street functions and required thermal conditions.

In the same way combinations of street canyon and trees can be found in the real life situations. This way, climatic conditions can be measured with special instruments and people can be questioned about their thermal perceptions.

Heat mitigation strategy integration with other climatic components

There are a lot of factors that influence thermal conditions in urban areas. I choose to work with solar radiation modification and shadow patterns. At the same time, there are a number of other factors that have an impact on urban heat – for example: sky view factor and reflection abilities of the materials, wind access to the area, location of the water elements, geographical location of the area and many more.

That is why another way of this thesis extension can be integration of the described Urban Heat Mitigation strategy with other heat formation factors. This could help to develop even more complex and comprehensive model for design with microclimate.

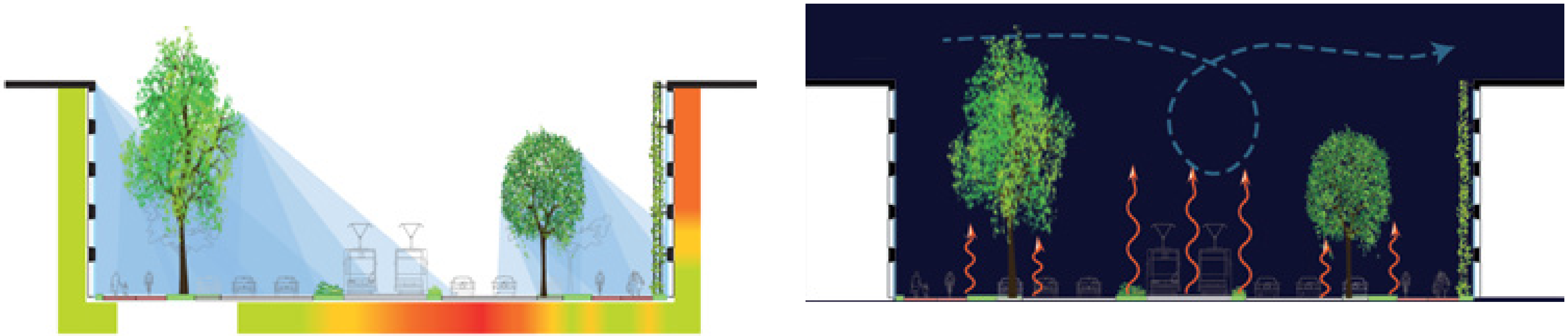

Figure: 6.8 Heat mitigation strategy integration with other climatic components

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Combination of street canyons:

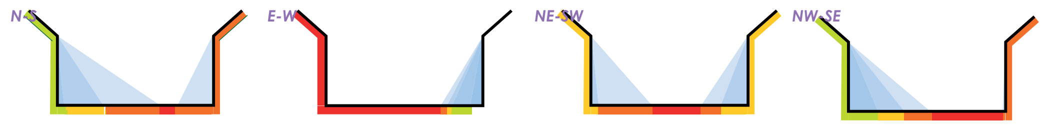
- H to W ratio: 1:2, (H=6m, W=12m)
- orientations: N-S, E-W, NE-SW, NW-SE

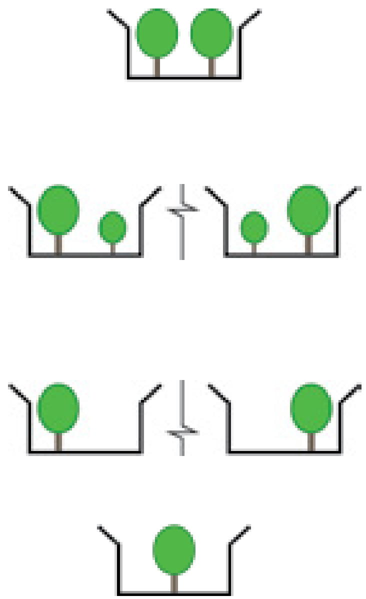
with groups of trees:

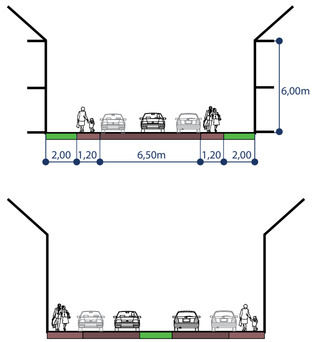
- 2 rows of trees with the same sizes: Large, Medium and Small. (3 combinations)
- 2 rows of trees with the different trees sizes: Large and Medium, Large and Small, Medium and Small in this case trees combinations are asymmetrical and therefore will be studied twice with a mirror reflection option. (6 combinations)
- 1 row of the trees from the each side of the street. 3 sizes of trees and 2 sides of the street. (6 combinations)
- 1 row of trees in the middle of street canyon for each size of trees. (3 combinations)

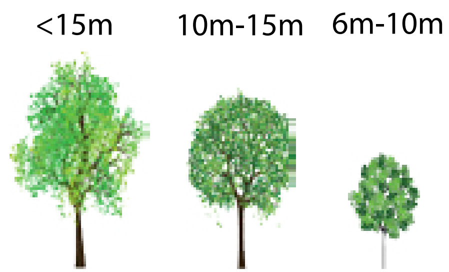
In total 18 combinations of street canyon and trees will be tested for 4 possible street orientations.

- Trees will be arranges coherently for the N-S and E-W orientated street canyons and oppositely for NE-SW and NW-SE canyons.
- The distance between rows of trees is 6,5 m (in case of 2 rows). The distance between trees is 8m.







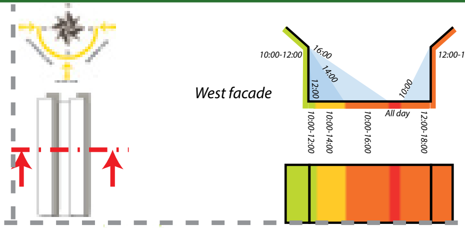


Area, exposed to the sun

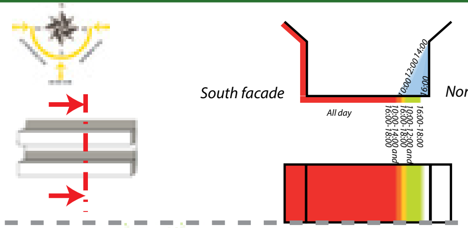
- for 2 hours per day
- for 4 hours per day
- for 6 hours per day
- for 8 hours per day

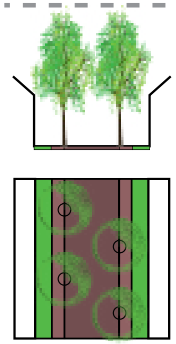
N-S and E-W
2 row with the same tree height.

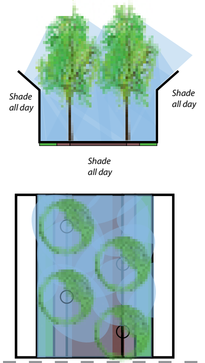
N-S



E-W

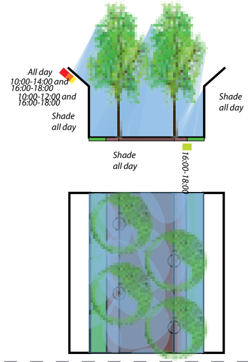






Solar access reduced complitely

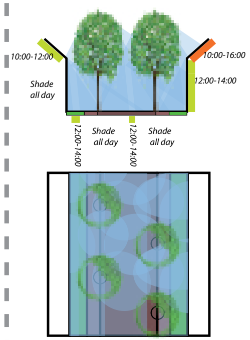
Street is shaded for the whole day



Solar access reduced complitely

Street is shaded for the whole day

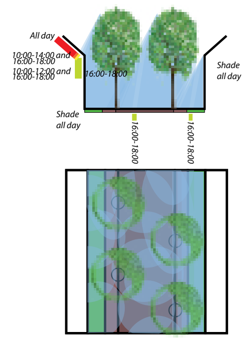
Some sun can reach Southern roofs, a little bit of sunlight is accessible between 16:00 ad 18:00



Solar access reduced complitely, or to 2 hours in a day

Street is mostly shaded for the whole day

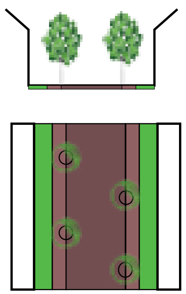
Some sun is allowed for roofs and walls

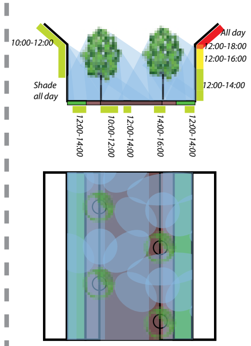


Solar access reduced complitely

Street is shaded for the whole day

Some sun can reach Southern facade walls and roofs, a little bit of sunlight is accessible between 16:00 ad 18:00

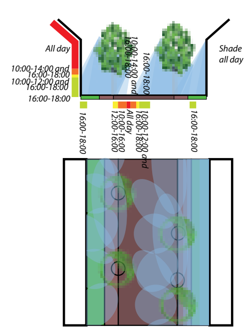




Solar access reduced complitely, or to 2 hours in a day

Street is partly shaded for the whole day

Some sun is allowed for roofs and walls

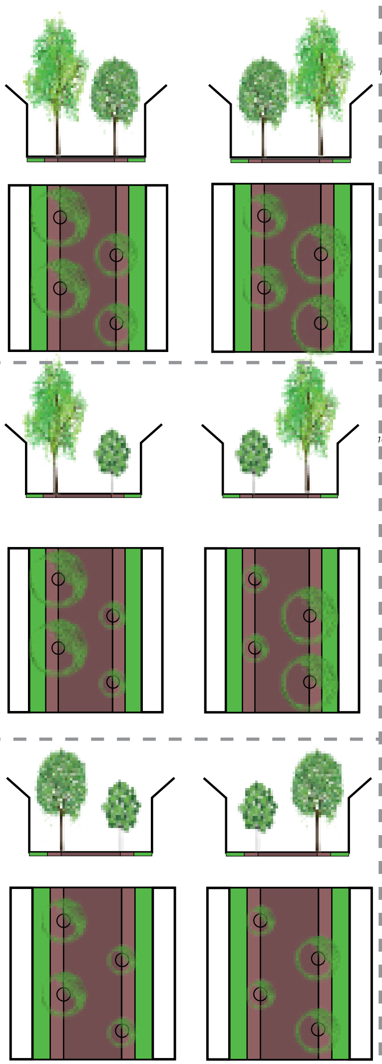


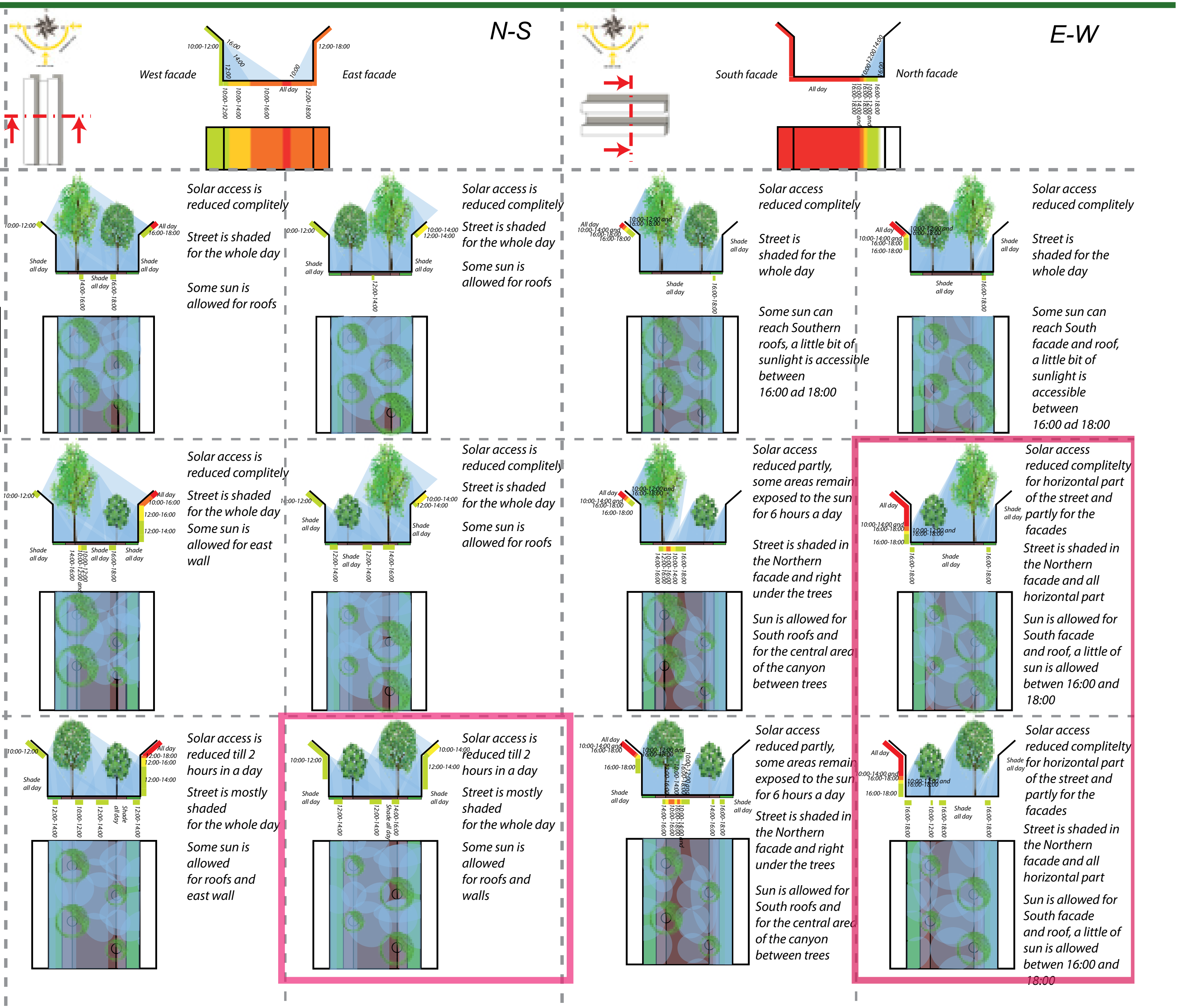
Solar access reduced partly, some areas remain exposed to the sun for all day

Street is shaded in the Northern facade and right under the trees

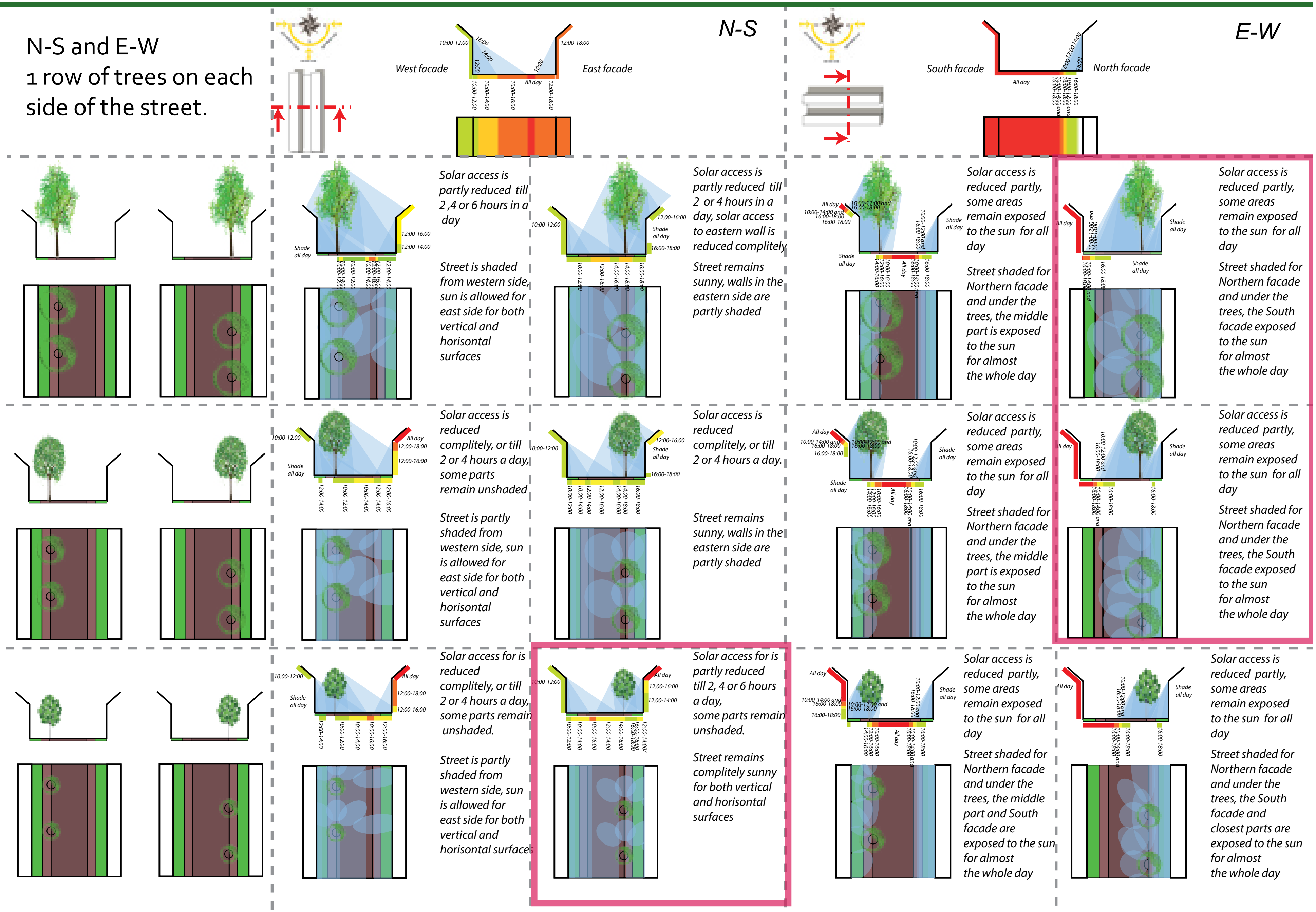
Sun is allowed for South facade and for the central area of the canyon between trees

N-S and E-W
2 rows with different tree height.

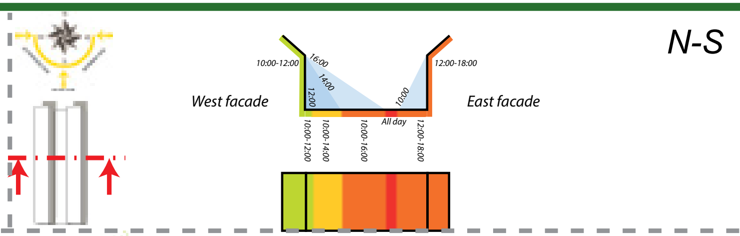


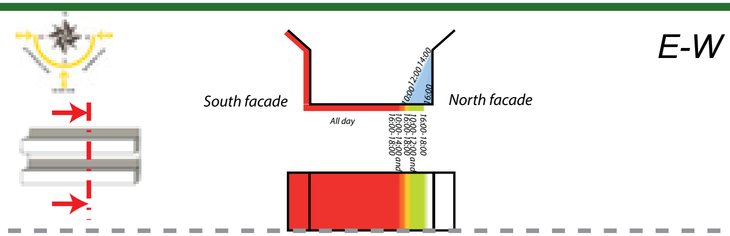


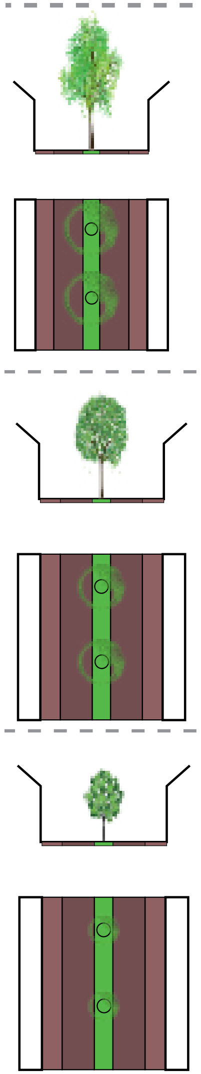
N-S and E-W
1 row of trees on each side of the street.

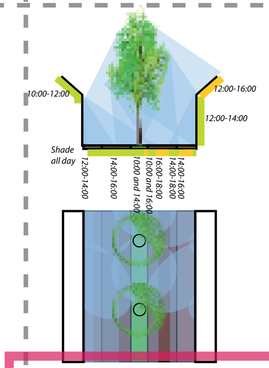


N-S and E-W
1 row of trees in the middle of the street.



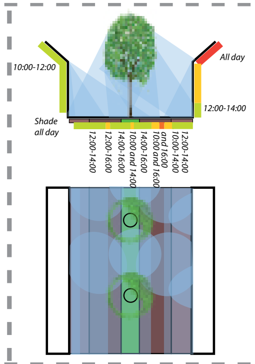






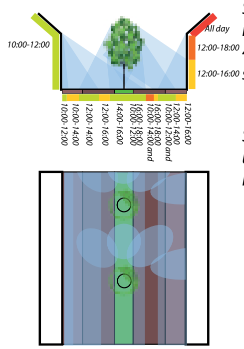
Solar access for is reduced complitely, or till 2 or 4 hours a day.

Vertical street surfaces are partly shaded from western side, sun is allowed for the rest of the street for both - vertical and horisontal surfaces



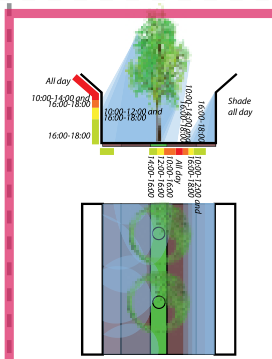
Solar access for is reduced till 2, 4 or 6 hours a day, some parts remain unshaded.

Street is sunny for both, vertical and horisontal surfaces



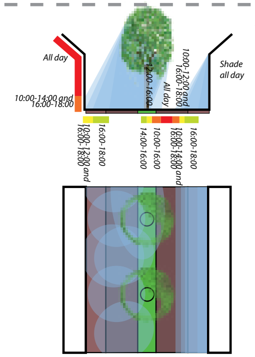
Solar access for is reduced till 2, 4 or 6 hours a day, some parts remain unshaded.

Street is sunny for both vertical and horisontal surfaces



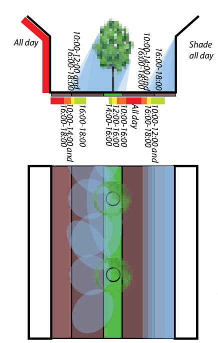
Solar access is reduced partly, some areas remain exposed to the sun for all day

Street shaded for Northern facade and under the trees, the middle part and South facade are exposed to the sun from 2 hours to all day long



Solar access is reduced partly, areas remain exposed to the sun for all day

Street shaded for North facade and under the trees, the middle part is exposed to the sun from 2 hours to all day long, South facade is exposed to the sun almost all day long

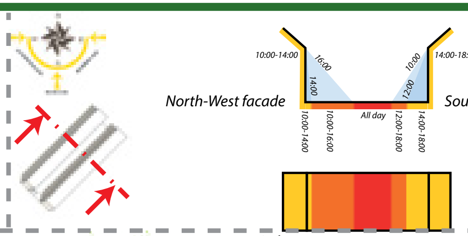


Solar access is reduced insignificantly, areas remain exposed to the sun for all day

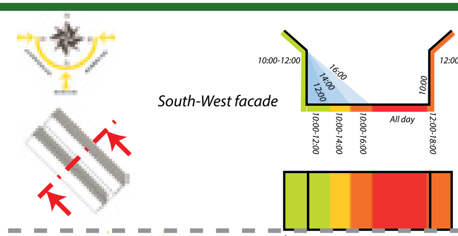
Street shaded for North facade and under the trees, the middle part is exposed to the sun from 2 hours to all day long, South facade and nearest part of the street are exposed to the sun almost all day long

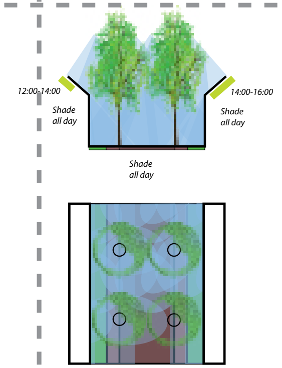
NE-SW and NW-SE 2 row with the same tree height.

NE-SW



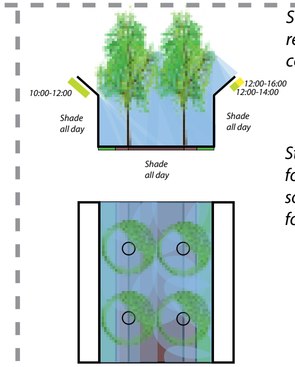
NW-SE





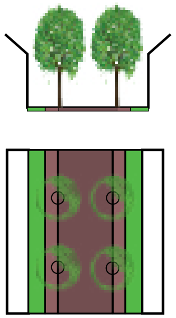
Solar access is reduced complitely.

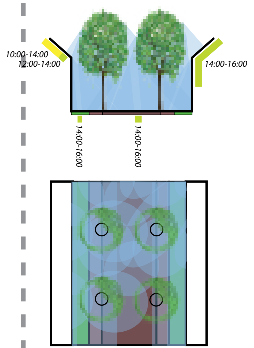
Street is shaded for the whole day, some sun is allowed for the rooftops



Solar access is reduced complitely.

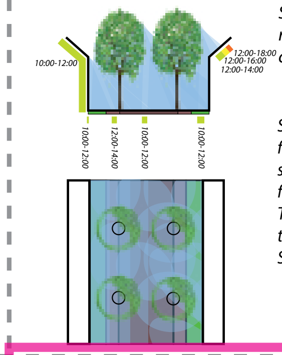
Street is shaded for the whole day, some sun is allowed for the rooftops





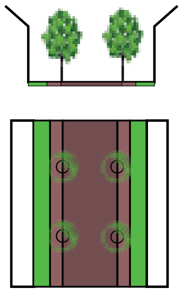
Solar access is reduced complitely.

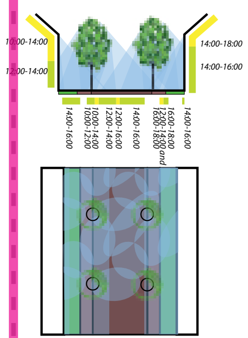
Street is mostly shaded for the whole day, some sun is allowed for the roofs and facades for 2 to 4 hours a day; a little of sun is allowed between 14:00 and 16:00



Solar access is reduced complitely.

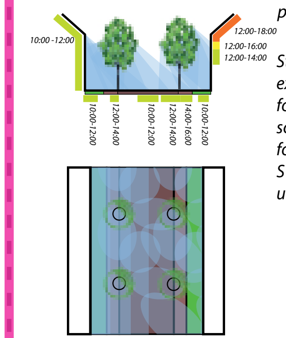
Street is shaded for the whole day, some sun is allowed for the rooftops. Tiny parts are exposed to the sun for 2 hours a day. SW facade remain unshaded.





Solar access is reduced form 8 - 6 to 2 - 4 hours in a day

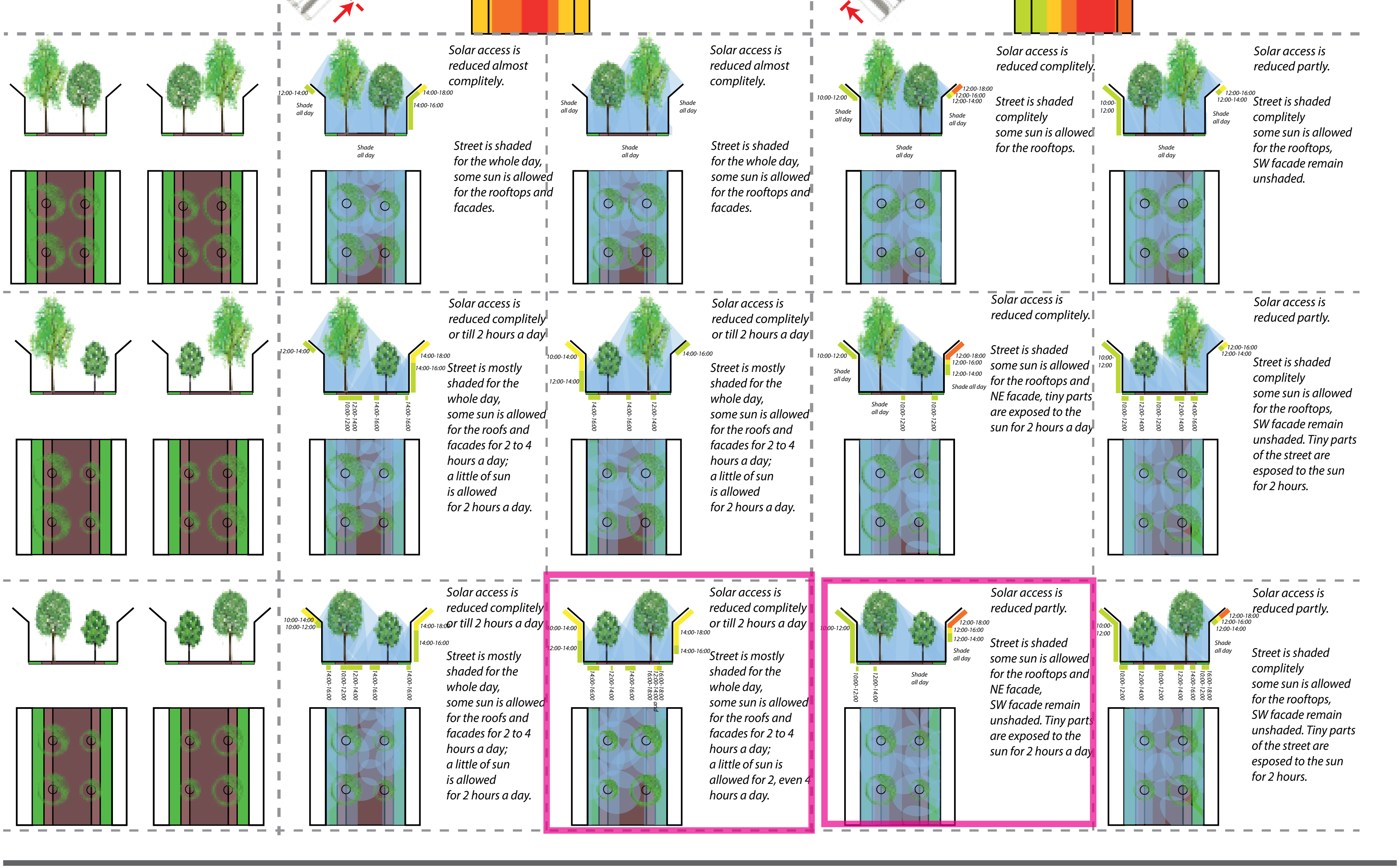
Street is partly shaded - and exposed to the sun for 2 till 4 hours a day solar access to the facades is reduced partly from 4 to 2 hours a day



Solar access is partly reduced.

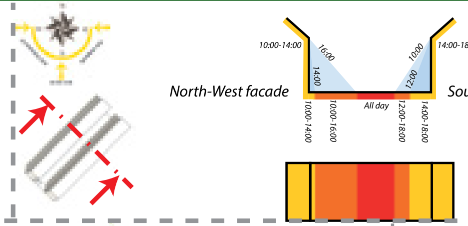
Street is shaded or exposed to the sun for 2 hours, some sun is allowed for the rooftops, SW facade remain unshaded.

NE-SW and NW-SE 2 rows with different tree height.

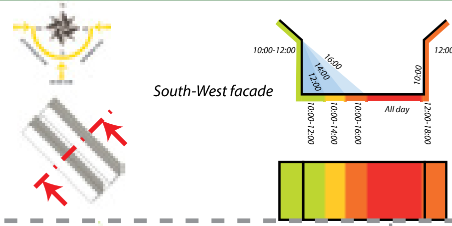


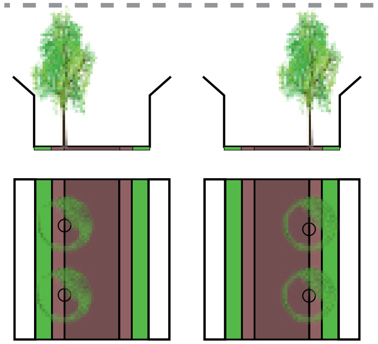
NE-SW and NW-SE
1 row of trees on each side of the street.

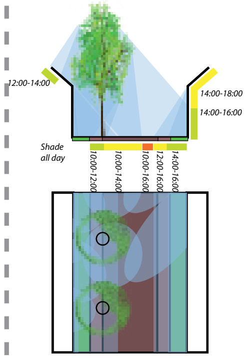
NE-SW



NW-SE

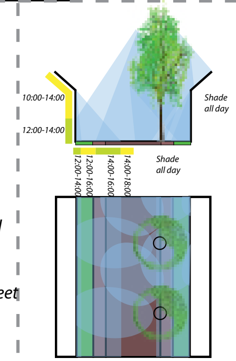






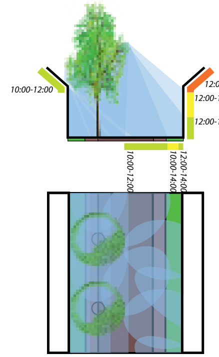
Solar access is reduced till 2, 4 or 6 hours a day.

Street is shaded complitely from NW side, for SE side solar access is reduced from 4-6 to 2-4 hours a day. Middle of the street is exposed to the sun for 6 hours.



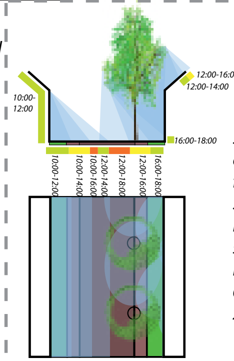
Solar access is reduced till 2 or 4 hours a day.

Street is shaded complitely from SE side, for NW side solar access is reduced from 4-8 to 2-4 hours a day.



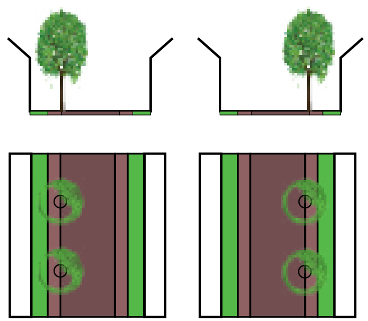
Solar access is reduced partly till 2 or 4 hours a day.

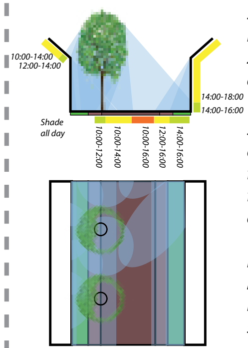
Street is shaded complitely from SW side, for NE side solar access is partly reduced from 6 and 8 to 2-4 hours a day.



Solar access is reduced partly till 2,4 or 6 hours a day.

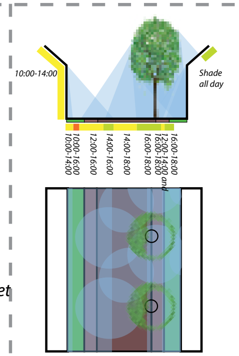
Street is shaded complitely from NE side, SW stay unshaded, in central part solar access is partly reduced from 6 and 8 to 2-6 hours a day.



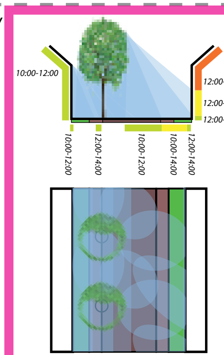


Solar access is reduced till 2, 4 or 6 hours a day.

Street is shaded complitely from NW side, for SE side solar access is reduced from 4-6 to 2-4 hours a day. Middle of the street is exposed to the sun for 6 hours.

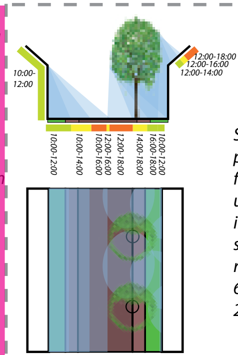


Solar access is partly reduced till 2, 4 or 6 hours a day. Street is shaded complitely from SE side, for NW side solar access is partly reduced from 4-8 to 2-4 hours a day. Part of the street remain exposed to the sun for 6 hours. NW facades remain unchanged



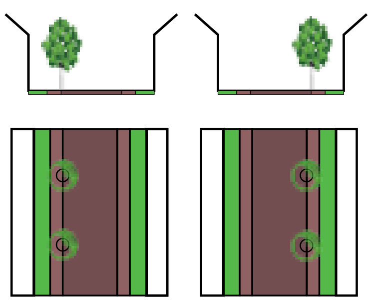
Solar access is reduced partly till 2 or 4 hours a day.

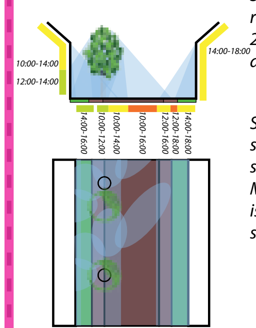
Street is shaded from SW side, SW facade remain unshaded. For NE side solar access is partly reduced from 6 and 8 to 2-4 hours a day.



Solar access is reduced partly till 2,4 or 6 hours a day.

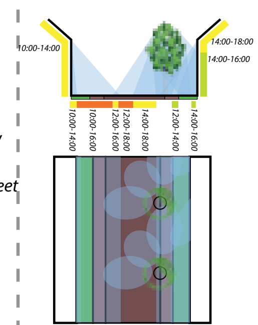
Street is shaded partly from NE facade, SW stay unshaded, in central part solar access is partly reduced from 6 and 8 to 2-6 hours a day.





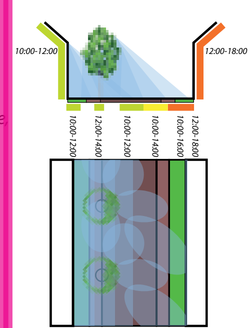
Solar access is reduced till 2, 4 or 6 hours a day.

Street is a bit shaded from NW side. Middle of the street is exposed to the sun for 6 hours.



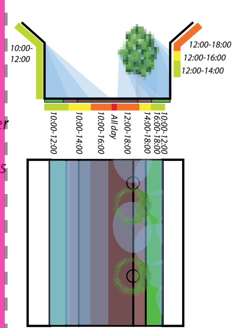
Solar access is partly reduced till 2, 4 or 6 hours a day.

Street is partly shaded from SE side for NW side solar access is reduced partly till 4 or 6 hours a day. Part of the street remain exposed to the sun for 6 hours.



Solar access is reduced partly till 2 or 4 hours a day.

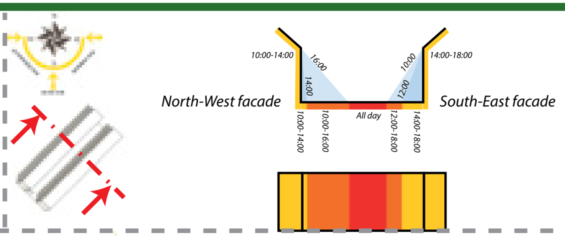
Street is shaded from SW side under the tree, SW and NE facades remain unshaded. For middle of the street side solar access is partly reduced from 6 and 8 to 2-4 hours a day.



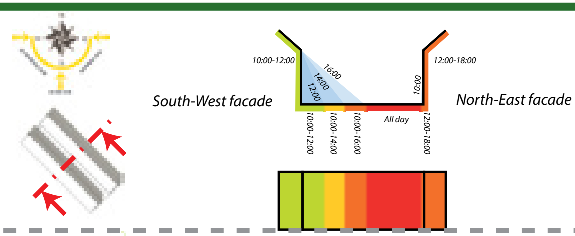
Solar access is reduced partly till 2,4 or 6 hours a day. Street is shaded from NE side under the tree, SW facade and part of the street remain unshaded. For middle of the street side solar access is partly reduced from 6 and 8 to 2-6 hours a day.

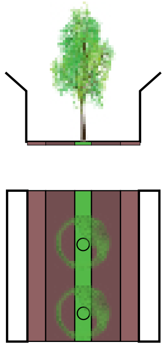
NE-SW and NW-SE 1 row of trees in the middle of the street.

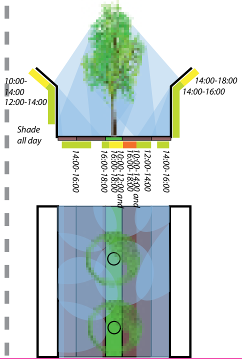
NE-SW



NW-SE

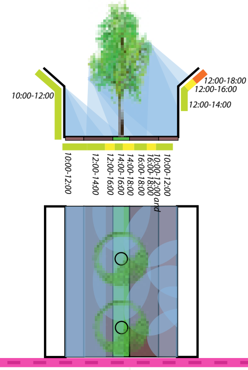






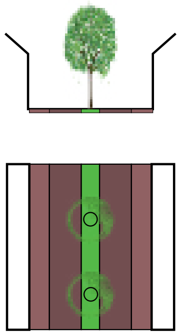
Solar access is reduced till 2, 4 or 6 hours a day.

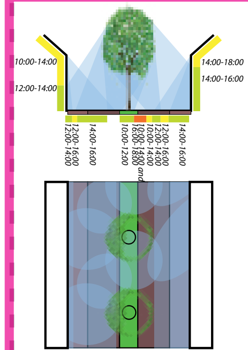
Solar access reduced for both facades from 4 to 2 hours a day; Horozontal surface is exposed to the sun mainly for 2 hours, only small parts are exposed for 4 and 6 hours a day.



Solar access is reduced till 2 or 4 hours a day.

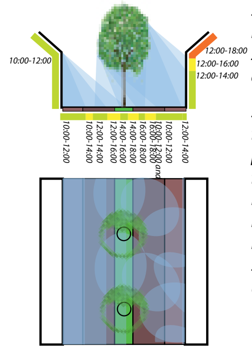
Solar access reduced for NE facade and part of the street from 6 to shade or 2-4 hours a day; Horozontal surface is exposed to the sun mainly for 2-4 hours. SW facade remain unshaded.





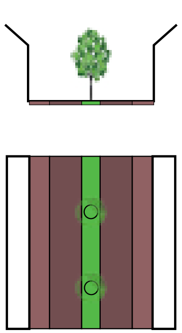
Solar access is partly reduced till 2, 4 or 6 hours a day.

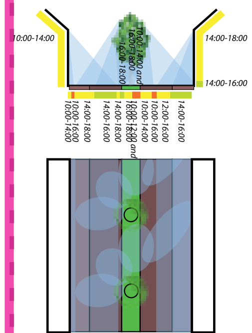
Solar access reduced partly for both facades from 4 to 2 hours a day; Horozontal surface is exposed to the sun mainly for 2 and 4 hours, only small parts are exposed for 6 hours a day.



Solar access is reduced till 2 or 4 hours a day.

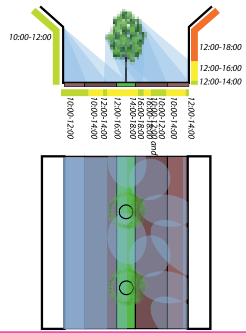
Solar access reduced for NE facade and part of the street from 6 to 2-4 hours a day; Horozontal surface is exposed to the sun mainly for 2-4 hours. SW facade remain unshaded.





Solar access is partly reduced till 2, 4 or 6 hours a day.

Solar access is not reduced for the facades. Horozontal surface is exposed to the sun mainly for 4 hours, only small parts are exposed for 6 hours a day.



Solar access is partly reduced till 2 or 4 hours a day.

Solar access reduced partly for NE facade and part of the street from 6 to 2-4 hours a day; Horozontal surface is exposed to the sun mainly for 2-4 hours. SW facade remain unshaded.