RETROFITTING FACADES TO MITIGATE THE URBAN HEAT ISLAND (UHI) EFFECT IN THE NETHERLANDS

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ABSTRACT

With the expansion of cities located in the Randstad in the Netherlands, the magnitude of the urban heat island (UHI) effect will increase further. The changing urban climate has negative consequences for the existing local ecosystems as well as for the urban quality. The UHI effect is a complex phenomenon in cities, therefore in this paper, five mitigation goals are formulated. This paper quantifies the effectiveness of different UHI mitigation strategies for different situations in the Netherlands to determine which strategy is the most appropriate. A comprehensive list is made with different façade mitigation strategies whereby the effectiveness of each strategy is rated based on the proposed goal and the contextual parameters. The goal of this report is to emphasize the urgency to take actions to mitigate the UHI effect in Dutch cities and to inform which mitigation strategy is the most appropriate. To be concluded is that the UHI effect in the Netherlands is the most visible at night, therefore strategies in general should focus on lowering the heat storage capacity of urban materials and reducing the incoming solar irradiation during the day. The complex and context-specific character of the UHI effect makes it not possible to define the most appropriate goal for the Randstad, because this should be examined per case. This paper could be used as a guide for architects to get a better understanding of the various design mitigation methods on facades.

KEYWORDS: *urban heat island effect, facade retrofitting, climate-proof, the Netherlands*

I. INTRODUCTION

With our ever-increasing population growth, the built environment is constantly changing, resulting in more densified urban areas. By 2050 more than 68% of the total world population is expected to live in cities. A population which by then nears 10 billion people (United Nations, 2018). With the ongoing urbanization trend, buildings will become important components that alter existing ecosystems. Urban ecosystems are transformed and reshaped by humans and consist of abiotic elements and organisms (see appendix II, figure 1) whereby the abiotic elements form the habitat for plants and wildlife. The city is therefore considered as: *''An integrated open system of living things interacting with their physical environment''* (Douglas, 1983, p. 229).

Buildings nowadays have a self-centric approach that is focused on fulfilling the needs of future residents only and thereby neglect the consequences on the existing urban ecosystems contributing to urban climates. Urban climates are an example of inadvertent climate modification, where humans unintendedly impact the microclimate of the city. Microclimates impact the infrastructure, safety, and health in cities as they struggle to cope with extreme weather events (Oke et al., 2017b, p. 2). As a consequence of human alterations to existing ecosystems, the temperature in cities is warmer compared to surrounding rural areas, this phenomenon is called the urban heat island (UHI) effect. Higher temperatures in cities can be explained as a net positive thermal balance in the city, which occurred by changes that were made to the surface materials of the city. This includes an increased surface roughness (Oke, 1987, p. 40), the use of low albedo and high storage materials (Taha, 1997), and less evapotranspiration by reduced green and blue spaces (Taha, 1997; Gunawardena et al., 2017).

Also human activities influence the UHI effect by increased heat and pollution in the atmosphere (Oke, 1987, p. 262). The causes of the UHI effect in cities have been long understood, but only since recently, research has been done on possible strategies to reverse or mitigate those effects. Still, there is no widespread application of those mitigation strategies within cities (Gorsevski et al., 1998). Because the intensity of the UHI effect is determined locally, the choice of measures also depends on the local context. Generic measures for an entire city are therefore less effective (Rovers et al., 2014, p. 3).

Facades cover a large amount of surface area in the cities and have a huge impact on the microclimate of the city (Sung, 2016). As regards, this study focuses on mitigating the UHI effects through facade retrofitting in denser populated areas in The Netherlands. This report aims to make architects aware of the consequences of their interventions in the built environment and inform them which mitigation strategies are appropriate for different situations. The research will therefore try to answer the question: *´´What is the most appropriate facade mitigation strategy to mitigate the urban heat island (UHI) effect in the Netherlands?''*

Literature on specific mitigation strategies (Stark et al., 2012; Qin, 2015; Yuan et al, 2015) and overviews of the parameters of the UHI effect (Rovers et al., 2014; Oke et al., 2017b) are already available. However, this literature is mostly rather technical and unknown to architects. This paper tries to combine the knowledge on the specific implementations to mitigate the UHI effect, the UHI effect in the Netherlands and façade implementations in a comprehensive overview for architects. In the end, architects are responsible for designing buildings and thereby altering existing ecosystems. It is therefore important that architects are aware of the consequences of their interventions in the built environment. This research could be used as a guide for architects to get a better knowledge of this phenomenon. This thesis offers a framework for appropriate strategies to mitigate the UHI effect in the Netherlands and aims to create awareness for architects to design appropriate location-specific interactions in the field of architecture. This thesis is written through the lens of an architect for architects and therefore the author does not exclude the negative impacts of the positively depicted design principles. This thesis is written as part of a graduation project and aims to get better knowledge of the possible façade implementations on the project location of Amsterdam Sloterdijk. The goal of this paper was therefore also not to give expert advice instead, the goal was to make an inventory for possible mitigation strategies for an architecture project.

II. METHODS

To determine which facade UHI mitigation strategy is the most appropriate, contextual and climatic parameters are analyzed. To answer the main question, the paper starts by answering the following sub-question: *'What influences the urban heat island effect in the Netherlands?'* The first step in answering this sub-question is to analyze the UHI effect in Dutch cities and the contextual parameters by using literature studies on the UHI effect in the Netherlands. The contextual parameters are collected and categorized by the simplified classification of distinct urban forms by Oke (2004). This categorization is based on the aspects of the scheme of Ellefsen (1990) and physical measures which relate to the wind, moisture, and thermal controls (see appendix II, table 1). Seven urban forms are distinguished, based on their roughness class, aspect ratio, and percentage of impermeable surface area.

To get better knowledge on possible façade mitigation systems to reduce the UHI effect, the second sub-question is formulated: *'What are the current facade mitigation systems to reduce the urban heat island effect?'*. The research analyses several mitigation methods, selected based on the following selection criteria: (i) the method should have a clear focus on mitigating the urban heat island effect, (ii) the method should be applicable on the façade, (iii) the method should be either in the research phase or already being applied on facades and (iv) the method should focus on changing the radiative properties of the surface material, changing the thermal storage properties of the surface material or reducing the incoming solar irradiation. The listed methods give a variety of possible mitigation strategies implemented in facades (see appendix II, table 2).

The third sub-question is: *'What are the possible urban heat island effect mitigation goals and which facade mitigation strategy is the most appropriate for these defined mitigation goals?'*. The UHI effect is a complex phenomenon and therefore, different mitigation goals are formulated based on the information found in the first sub-question from the literature study on the UHI effect in the Netherlands. For the analysis of the project, the template of table 3 (see appendix III) is used. In this table, the effectiveness is determined by the contextual parameters and the proposed goal and subdivided by five gradations which are defined based on the literature research on the strategies, see appendix II table 4. By using a clear simplified drawing language and adding points of attention, the author wants to make the diagram simple and understandable for all readers.

III. RESULTS

3.1 THE URBAN HEAT ISLAND (UHI) EFFECT IN DUTCH CITIES

Climate change will lead to global warming and the more frequent occurrence of extreme weather in the form of heavy rainfalls, drought, and extreme heat events (KNMI, 2012). Without an explosive increase in air-conditioning systems, the temperature in buildings will heat up massively. Heat stress can lead to problems such as illness and additional mortality among sensitive population groups, reduced work productivity, and an increased amount of sleep disorders (Rovers et al., 2014, p. 3). Considering future urbanization and increased effects of climate change, thermal comfort and heat stress will likely become a critical issue in many densely populated areas in the Netherlands (Steeneveld et al., 2011) and in the end, this will become a critical challenge to the continuing urbanization trend (Revi et al., 2014).

In the Netherlands, the UHI effect in cities has not been greatly studied because the impact was to be assumed minor (Steeneveld et al., 2011). This is due to its relatively mild oceanic (Cfb) climate (Köppen, 1931), which is characterized by relatively cool summers and mild winters. And also because Dutch cities consist of a large number of canals, it can be expected that those water bodies help mitigate the UHI effect (Xu et al., 2010). Steeneveld et al. (2011) researched the UHI effect in Dutch cities by comparing them with other European cities and concluded the UHI intensity is as substantial and of the same order as other European cities. On average, 50% of the Dutch urban areas are subject to heat stress for seven days per year (Steeneveld et al., 2011). Cities are densely populated areas and economic capitals, this makes them important centers for a smoothly running economy and society. At the same time, extreme weather events could threaten a large number of people and therefore it makes cities also vulnerable to the effects of climate change (Rovers et al., 2014, p. 8). The Randstad is the densest populated area in the Netherlands (CBS, 2019). With the expansion of cities located in the Randstad, the magnitude of the UHI intensity will also increase further (Steeneveld et al., 2011).

After sunset, the temperature differences between urban and rural areas can reach up to more than 7 °C, especially on clear and windless summer days. During the day, the measured temperature differences are smaller, with maximums of up to 2 °C (Van Hove et al., 2010; Heusinkveld et al., 2010; Van Hove et al., 2011; Heusinkveld et al., 2014). These temperature differences are present during a large part of the year. In the winter the UHI intensities are generally low, but could on some days also be significant. The UHI effect in the winter is mostly short-lived and occurs when the wind turns to the east and brings cold air. As a result in the rural areas, the temperature drops, and the temperature in cities remains unchanged for some time (Rovers et al., 2014, p. 23). The higher temperatures in the winter could even lead to a decrease in heating consumption by buildings (Mehaoued & Lartigue, 2019).

During the day, the UHI is affected locally by the Sky View Factor (SVF), the surface albedo, and the height (H) to width (W) ratio. In Rotterdam, districts with a higher SVF and surface albedo have a lower surface temperature because less solar radiation is absorbed and thus surfaces heat up less during the day (Rovers et al., 2014, p. 28). The ratio between the height of buildings (H) and the distance between them (W) affects: the amount of solar radiation being absorbed (Chokhachian et al., 2017), the thermal radiation of buildings and other surfaces to the atmosphere (Futcher, 2008), and the transport of heat within the street canyon. A higher H/W ratio reduces the airflow, which results in more internal reflections within the canyon and a lower sky view factor (Chokhachian et al., 2017), which leads to more trapped heat in the street canyon (Kleerekoper et al., 2012). The optimal H/W ratio seems to be around 1,0 (Theeuwes et al., 2014). Higher or lower H/W ratios both have advantages and disadvantages in terms of ventilation and shading (Theeuwes et al., 2014). During the day, there is also a reduced thermal comfort in Dutch cities (Van Hove et al., 2015) which can be explained by the lower wind speeds (Rovers et al., 2014, p. 30). During the night, the reduced thermal comfort can be explained by the variation in temperatures. Van Hove et al. (2015) did research on the maximum UHI in the Rijnhaven and concluded that a larger UHI_{max} for a particular location does not automatically mean less thermal discomfort during the day. During the night, the thermal admittance of buildings has a bigger influence on the UHI effect compared to contextual parameters like the Sky View Factor (SVF) and the surface albedo (Rovers et al., 2014, p. 32).

3.2 Current design strategies

The UHI mitigation strategies investigated are (i) changing the radiative properties of the surface material, (ii) changing the thermal storage properties of the surface material, and (iii) reducing the incoming solar irradiation. For each of the strategies, different methods are described, subdivided by static and dynamic solutions. Static is hereby defined as methods that do not change by season or time period and dynamic is hereby defined as methods that do change.

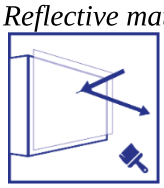
3.1.1. Changing the radiative properties of the surface material

The radiative properties of a surface are determined by the emissivity and the albedo factor (Gunawardena et al., 2019). The emissivity is the ratio of energy that is emitted as thermal radiation. With a high emissivity, the surface starts radiating heat with a slight temperature rise (EPA, 2014). The albedo factor is defined by the integrated wavelength and hemispherical reflectivity of a surface (Taha, 1997). It is also a significant determinant of the surface temperature (Oke, 1987, p. 229; Taha, 1997). Most urban surfaces have an albedo factor that ranges from 0.10 to 0.20. Increasing the albedo of urban surfaces could directly reduce the cooling demand for individual buildings. Large-scale albedo modifications, such as modifications on neighborhood levels, could also reduce the overall ambient air temperature (Taha, 1997; Salata et al., 2015).

This strategy is most effective in hot climates where there is a minimum heating load. In temperate climates such as the Netherlands, more attention should be paid to the rejection of heat gains in the winter (Mastrapostoli et al., 2014). Higher albedo levels lead to colder surfaces. In climates where the heating load is higher compared to the cooling load, the decrease in cooling load always exceeds the increased heating loads, although the reduction in the total energy use could be really small (Synnefa et al., 2006; Kolokotroni et al., 2013).

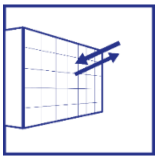
Static solutions

Reflective materials



Cool coatings have high solar reflectance and can be applied to building surfaces to avoid overheating of the building (Upstone, 2019) and help mitigate the UHI effect at a city level (Xie et al., 2019). These coatings can be applied on different surfaces, which include for example metal claddings and wood. On facades, this method is less effective because, it causes multiple reflections within the urban fabric, which results in entrapment of solar radiation (Mills, 1993; Panão et al., 2006; Kastendeuch & Najjar, 2009; Qin & Hiller, 2014; Qin, 2015;). Thereby, surfaces with high reflectivity can create problems like visual discomfort (Chokhachian et al., 2017).

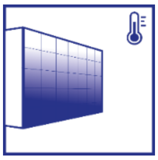
Retroreflective materials



Retroreflective materials have the ability to reflect the incident light towards its source regardless of the direction of incidence and thereby reducing the amount of solar radiation entrapped within the urban fabric. Retroreflective materials could help to reduce the inner reflections within the building canopy, this also applies in situations with a lower height to width factor (Rossi et al., 2015; Rossi et al., 2016; Morini et al., 2017). The application of retroreflective materials as UHI mitigation strategy in the built environment is quite new and a hot topic for researchers for both transparent (Inoue et al., 2017; Ichinose et al., 2017) and opaque building materials (Yuan et al., 2015; Han et al., 2015; Yuan et al., 2016; Qin et al., 2016). Retroreflective facades are still in the research phase and have not been used in practice on building facades, except for the IPKW estate building in Arnhem, where a 'cataphoric film' is used as retroreflective façade material (Material district, 2013), see appendix II figure 3.

Dynamic solutions

Thermochromic paints



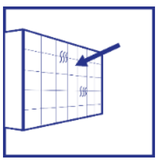
The albedo factor is strongly correlated with the color of the material because 43% of the solar energy is in the visible wavelengths (400-700 mm). Lighter-colored surfaces have a higher albedo factor compared to darker-colored surfaces (Taha et al., 1988; Alchapar et al., 2014; Santamouris & Kolokotsa, 2016, p. 93-112). White-colored buildings compared to black painted buildings can reduce the indoor temperature by 6°C, if no ventilation is considered (Bansal, 1992). Thermochromic paints consist of thermochromic pigments or compounds which according to the surface temperature reversibly change color and optical properties (Desideri & Asdrubali, 2019; Seeboth & Losch, 2013). The change of color happens when the temperature of the surface has reached the transition temperature of the paint. Thermochromic paints have the most impact in temperate climates and there should be a significant seasonal temperature variation to justify the need for thermochromic paints (Granadeiro et al., 2020). Many experiments are done with those thermochromic paints and some show some promising results (Ma et al., 2002; Ye et al., 2012; Ascione et al., 2019). However, still improvements need to be made since thermochromic paints are still quite expensive and the pigments are unstable (Karlessi et al., 2009; Santamouris et al., 2011) and affected by not only the ultraviolet radiation but also by the visible radiation (400-800 nm) (Karlessi & Santamouris, 2013).

3.1.2. Changing the thermal storage properties of the surface material

The thermal storage properties of surface material are affected by the heat capacity, mass, and thermal conductivity (Gunawardena et al., 2019). In general, urban materials have a higher thermal storage capacity compared to natural materials (EPA, 2014). All the solar energy that is not reflected by the surface, is stored within the material. The heat capacity depends on the thermal mass, thermal diffusivity, and thermal inertia (Gunawardena et al., 2019).

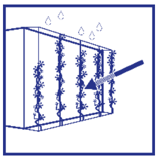
Static solutions

Lightweight materials



Heavyweight materials have a relatively higher diffusivity, heat capacity, and thermal inertia compared to lightweight materials. This means that the heavyweight materials absorb and store the non-reflected energy, which increases the temperature of the material and later on is re-radiated into the environment in the form of longwave diffuse infrared radiation (Gunawardena et al., 2019). Solar absorption by urban surfaces is a dominant cause of the UHI effect in cities (Oke et al., 2017b). At the same time, thermal storage can also effectively reduce the temperature fluctuations during the day (Balaras, 1996; Givoni, 1998; Cheng & Givoni, 2005, Kalema et al., 2008; Zhou et al., 2008).

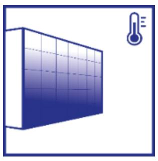
Green facades (GF)



Green facades (GF) can mitigate the UHI effect by: (1) evapotranspiration, (2) increased thermal mass, (3) a thicker insulation layer (4) increase of convective heat transfer, and (5) a higher albedo factor (Van Hooff et al., 2014). Evaporation is the combined term of evaporation and transpiration by vegetation (Kleerekoper et al., 2012). Green facades are not the most effective measure to prevent buildings from overheating. In poorly isolated buildings the effect of green facades is limited and for well-insulated buildings, the effect is negligible (Van Hooff et al., 2014). In a temperate oceanic climate (Cfb), by using a green façade, the surface temperature could be reduced by 16,85°C on the west side of the building (Kontoleon et al., 2010). The reduction in air temperature can only be observed at a very close distance from the façade and depends on the type of green façade. Simulations show that the application of green facades results in relatively low reductions in the air temperature on the street: on average 0,1°C and with a maximum of 3°C (Gromke et al., 2015). The effect of a green façade on the reduction of the air temperature depends on the thickness of the substrate layer (Wong et al., 2010) and the availability of water (Schmidt, 2010). Hoelscher et al. (2016) concluded that green facades should have at least 2,5 L/m2/d water irrigated per wall area. GFs can enable urban cross ventilation if they are situated parallel to the dominant wind direction, when designed perpendicular to the dominant wind direction, they can hinder urban cross ventilation (Szkordilisz, 2014).

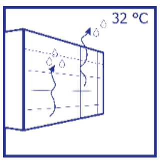
Dynamic solutions

Phase Change Materials (PCM)



Phase change materials (PCM) have a high latent heat capacity, when they are heated the materials will change from a solid-state to liquid, in this endothermic process, they can absorb energy. PCM can be subdivided into four categories: organic (fatty acid and paraffin), inorganic (metallics or salt hydrates), eutectic (a mixture of two or more PCMs), and BioPCM. The choice for the most suitable PCM depends on the melting temperature range and enthalpy variation in relation to climatic conditions and the required comfort temperatures (Lassandro & Di Turi, 2017). Application of PCM on facades is less effective compared to roofs. The solar radiation on the vertical building envelope is not constant during the day, this causes a decrease in their performance (Lassandro & Di Turi, 2017).

Thermoresponsive polymers



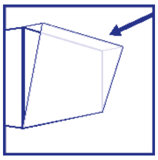
Prof. W. J. Stark et al. (2012) experimented with the thermo responsive material PNIPAM, (poly-N-isopropylacrylamide) on the roofs of buildings to keep the buildings cool. The lower critical solution temperature (LCST) of PNIPAM is 32 °C, which means that below this temperature, the polymer is hydrophilic and above this temperature, the polymer collapses to a hydrophobic state and sweats out water. The material can store water up to 90% of its weight in its swollen state. The experiment showed that the PNIMAP material stayed cooler for a longer period due to fast evaporative cooling. The polymer only works when there is a replenished water supply, by for example precipitation or irrigation. This system of sweating roofs could reduce the electrical consumption by 60% (Stark et al., 2012).

4.1.3. reducing the incoming solar irradiation

Another method to mitigate the UHI effect is to reduce the incoming solar irradiation. Reducing the incoming solar irradiation could decrease the outdoor insolation ratings and reduce the radiant heat exchange. This results in less heating of the facade and a decreased cooling demand of the building (Valladares-Rendón & Lo, 2014).

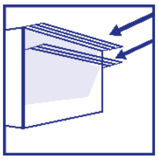
Static solutions

Facade self-shading (FSS)



façade self-shading (FSS) devices aim to lower the insolation on both the opaque and glazing elements of the facade (Valladares-Rendon & Lo, 2014). The effectiveness of this strategy has been analyzed in different locations. In Greece, Zerefos et al., (2012) found that inclined roofs and walls could lower the insolation impacts and energy demands in the summer. The west-facing facade of the calculated building with a Z-angle of 7° could achieve a reduction in annual cooling of (4,64%). In Israel, south-facing facades with a Z-angle of 31° and east and west-facing facades with a Z-angle of 34° could lower the energy consumption by 43% (Capeluto, 2003). It has to be noted that by changing the Z-angle of the facade, more reflected solar irradiation from the urban canopy can enter the building. Thus in a densely populated context, this can negatively influence the energy balance (Valladares-Rendon & Lo, 2014).

Shading devices (SD)



Shading devices (SD) enlarge the shading ratio, especially for windows. Properly designed shading devices should prevent the building from overheating in the summer and at the same time allow enough daylight to enter during the winter (Prowler, 2016). The effectiveness of SDs is examined widely in different locations. In a subtropical climate Valladares-Rendon & Lo (2014) compared several outdoor shading devices and their effectiveness to mitigate the UHI effect, he concluded that horizontal overhangs applied together, as a single, edge and layer was the most effective and could reduce the annual cooling loads by 8,92%. In South Korea (Dwa climate), a south-facing SD with a horizontal overhang was able to reduce the cooling loads by 19,70% (Cho et al., 2014). SDs should be designed properly to be effective. For that, it is necessary to know the sun's altitude and azimuth (Lechner, 2015, p. 145). SDs should be designed carefully, taking into account shading, daylighting, and visibility (Valladares-Rendón et al., 2016).

3.3. Appropriate implementations

The UHI effect is a complex phenomenon in cities. In several studies, different mitigation goals are also formulated. Some studies focus on reaching the lowest indoor temperature to avoid mechanical cooling in buildings (Stark et al., 2012; Kolokotroni et al., 2013; Mastrapostoli et al., 2014; Granadeiro et al., 2020), other studies focus more on creating a pleasant outdoor thermal comfort by reducing the ambient air temperature at the Urban Canopy Layer (UCL) (Kleerekoper et al., 2012; Chokhachian et al., 2017;) and some focus on both (Mehaoued & Lartigue, 2019). Choosing the most appropriate strategy depends therefore not only on the context, but also on the goal. In this paper, five different goals are formulated, see also Appendix II table 5: (i) reducing the energy demand to avoid mechanical cooling, (ii) reducing the ambient air temperature at the UCL at daytime, (iii) reducing the ambient air temperature at the UCL at nighttime, (iv) reducing the thermal comfort during the day and (v) reducing the thermal comfort during the night.

These five goals give another lens towards mitigating the UHI effect in cities. There is a relationship between all of them. Higher air temperatures in cities can, for example, double the cooling load peak of the building (Mehaoued & Lartigue, 2019) and high building surface temperatures can increase the nearby air temperature (Mehaoued & Lartigue, 2019), although this relationship is complex (Crum, 2017). For each goal, parameters are formulated which positively or negatively affect this goal. In Appendix III table 6, the different mitigation strategies, which are mentioned in the fourth paragraph are set out against the goals and urban form, to look at which mitigation strategy is appropriate in which situation. Appropriate is here defined as the strategy with the highest efficiency to reach the chosen goal (criterion).

VI. CONCLUSIONS

The goal of this paper was to find the most appropriate façade mitigation strategy in the Netherlands. Since the UHI effect has a complex and context-specific character, defining one appropriate goal for the Randstad is not effective and accurate and should instead be viewed per case. Literature research on the UHI effect in the Netherlands shows different forms of the UHI effect influenced by different parameters. Therefore, in this paper five goals are distinguished:

(A) Reducing the energy demand to avoid mechanical cooling,
(B) Reducing the ambient air temperature at the UCL at daytime,
(C) Reducing the ambient air temperature at the UCL at nighttime,
(D) Reducing the thermal discomfort during the day and
(E) Reducing the thermal discomfort during the night.

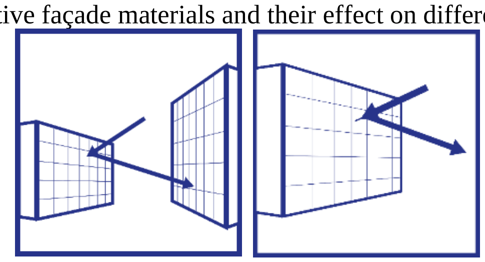
In the Netherlands, the temperature differences at night between urban and rural areas are the highest and can reach up to more than 7 °C. This temperature difference can be explained by the variation in temperatures of surfaces. In this paper three mitigation strategies are formulated:

(i) Changing the radiative properties of the surface material,
(ii) Changing the thermal storage properties of the surface material,
(iii) Reducing the incoming solar irradiation.

To be concluded, in general could be said that more focus in the Netherlands should be put on (ii) ‘changing the thermal storage properties of the surface material’ and (iii) ‘reducing the incoming solar irradiation’ to reduce the temperature difference at night. This can be done by: using lightweight materials, green facades, PCM materials, Thermoresponsive polymers, FSSs, and SDs. Combining multiple strategies can be even more effective. The strategy: (i) ‘changing the radiative properties of the surface material’ can also be applied as a feasible mitigation strategy, but with the Dutch temperate climate and possible problems, like visual discomfort and entrapment of solar irradiation. In most cases, this is not the most appropriate solution and does only slightly reduce the energy demand of buildings in the Netherlands. The comprehensive list (see Appendix III table 5) could be used as a guide for architects to get a better understanding of the various design mitigation methods on facades. The list only provides the basic knowledge and more extensive research should be done per case to determine the most appropriate mitigation strategy.

In reality, every situation is unique and has its own unique existing ecosystem, and by implementing new mitigation strategies, the existing ecosystem is altered. This can also have an unforeseen negative impact on the environment. Ecosystems influence each other, and it is therefore also important to look at different scales. A good example to clarify this, is the use of high surface albedo materials on facades to lower the energy demand of the building. This strategy is proven to be effective when used in a context with a high height to width ratio. If not well implemented, the reflected light could warm up surrounding surfaces causing entrapment of solar radiation. Which in this case could also heighten the temperature of the façade and thus increase the energy use of the building. So on the microscale of the building, this strategy looks effective, but zooming out to the neighborhood, the unforeseen negative effects become clear, see figure 3.

Figure 3. reflective façade materials and their effect on different scales (Source: own).

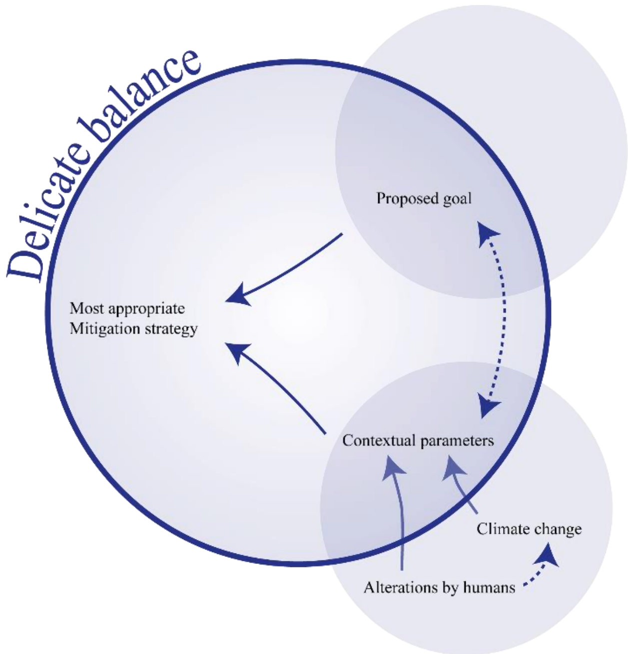


This example is covered in this report but there are other unforeseen consequences that can also be beyond the scope of the architect which will also alter the ecosystem.

In this paper, the focus is on facades and how they can help mitigate the UHI effect. In reality, the problem is far more complex. More research needs to be done on the UHI effect and its interaction on different scales because, with a better understanding of the climatic parameters on specific locations and their effect on the UHI effect, more effective mitigation strategies can be implemented, also because there is a continuous interaction between different ecosystems on different scales. In this thesis, it is assumed that the contextual parameters are fixed. These contextual parameters on mesoscales are crucial for the severity of the UHI effect on microscales and influence the effectiveness of the proposed façade mitigation strategy. To better tackle the problem, this interaction between different scales should be made clear and a combination of different strategies on different scales should be implemented to get the maximum output. This could be explored in further research.

This paper focuses on the most '*appropriate'* mitigation strategy. Appropriate means that the effectiveness of the proposed strategy depends on the goal and contextual parameters. The most appropriate solution is the most effective in answering the goals, (see figure 4). It is important to remember that when the goal or context is changing, the effectiveness will also change. There is no magic formula that can be applied to implement the most appropriate solution because, the context and goal are dynamic. The context can change by human alterations like urbanization or it can change by climate change, which is also an indirect consequence of human alterations. This can also affect the goal because, with a changing context, the nature of the problem can change. The goal of this paper was therefore also not to give expert advice, instead the goal was to make an inventory for possible mitigation strategies for an architecture project.

Figure 4. relationship between appropriate mitigation strategy, proposed goals, and contextual parameters (Source: own).



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APPENDIX

APPENDIX I

GLOSSARY

Glossary term	Glossary definition
Albedo factor	The ratio of the shortwave radiation that is reflected by a surface, to the shortwave radiation reaching that surface (Oke et al., 2017).
Ecosystems	Is a balanced system containing interactions (symbiotic relations) between organisms that maintains the ecology of its surroundings. Ecosystems exists through all scales and are interlinked, every slight change can cause a reaction to maintain this balance.
Mitigation	A human intervention to reduce the causing effect of a problem, to make it less severe or painful (Oke et al., 2017b).
Retrofit	To adapt to a new purpose or need; modify (Merriam-webster, n.d.).
Sky View Factor	The ratio of the radiation received by a planar surface to the radiation emitted by the entire sky hemisphere (Oke et al., 2017).
Urban form	The static, physical properties that shape a city, including the overall dimensions of a city, and at finer scales its urban structure, surface cover and fabric (Rovers et al., 2017).
Urban heat island (UHI)	Characteristic warmth of a city, often resembled by the temperature differences between rural and urban areas (Oke et al., 2017).
Urban canopy layer (UCL)	Is a meso-scale phenomenon beneath roof-level which is produced by micro-scale processes operating on the street level between buildings. It is dominated by a mix of micro-climates which each are dominated by its direct surroundings (Oke, 1987).

Appendix II

Figure 1. The biophysical components that comprise an urban ecosystem. They include all aspects of the pre urban natural environment subsequently modified by the introduction of built infrastructure (Oke et al., 2017a).

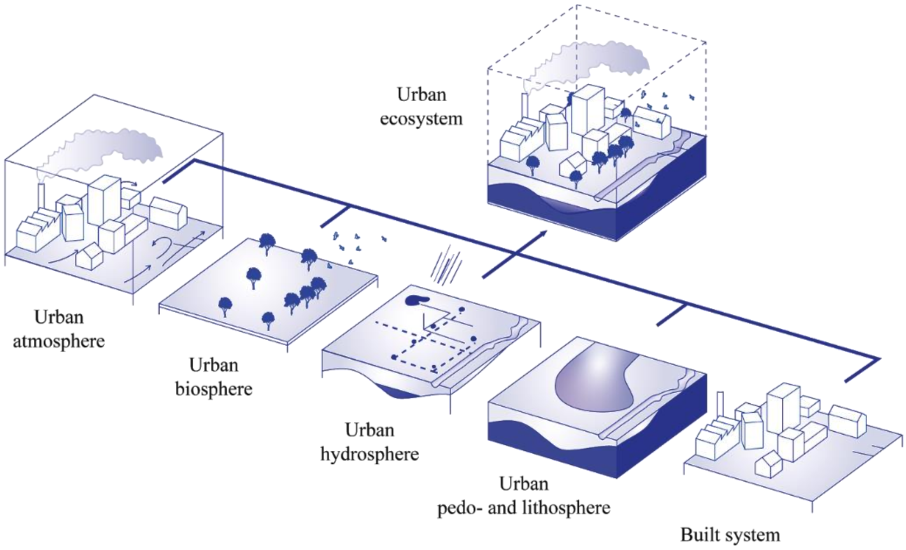
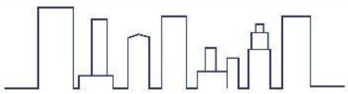
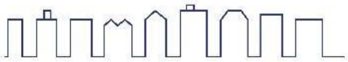
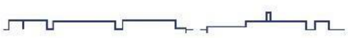


Table 1. Simplified classification of distinct urban forms arranged in approximate decreasing order of their ability to impact local wind, temperature and humidity climate (Oke, 2004).

Urban Climate Zone, UCZ[1]	Image	Roughness class[2]	Aspect ratio[3]	%Built (impermeable)[4]
1. Intensely developed urban with detached close-set high-rise buildings with cladding, e.g. downtown towers		8	>2	>90
2. Intensely developed high density urban with 2-5 storey, attached or very close-set buildings often of brick or stone, e.g. old city core		7	1.2-2.5	>85
3. Highly developed, medium density urban with row or detached but close-set houses, stores & apartments e.g. urban housing		7	0.5-1.5	70
4. Highly developed, low density urban with large low buildings & paved parking, e.g. shopping mall, warehouses		5	0.05-0.2	75-90
5. Medium development, low density suburban with 1 or 2 storey houses, e.g. suburban housing		6	0.2-0.5, up to >1 with tall trees	35-65
6. Mixed use with large buildings in open landscape, e.g. institutions such as hospital, university, airport		5	0.1-0.5, depends on trees	<40
7. semi-rural development with scattered houses in natural or argicultural area, e.g. farms, estates		4	>0.05,depends on trees	<10

Key to symbols: Buildings; Vegetation; Impervious ground; pervious ground

[1] A simplified set of classes that include aspects of the scheme of Ellefsen (1990/91) plus physical measures relating to wind, termal and moisture controls (columns at right)

[2] Effective terrain roughness according to the Davenport classification (Davenport et al., 2000)

[3] Aspect ratio – Z_H/W - related to flow regime types and thermal controls (solar shading and longwave screening). Tall trees increase this measure significantly

[4] Av. fraction of ground covered by built features (buildings, roads, paved and other impervious areas) the rest of the area is occupied by pervious cover. Permeability affects the ability to store moisture and hence the moisture status of the ground

Table 2. Chosen facade mitigation strategies (source, own).

Strategy	Method	Category	Reference
Changing the radiative properties of the surface material	Reflective materials	Static solution, already being applied on facades widely.	Panão et al., 2007, Qin, 2015, Qin & Hiller, 2014, Mills, 1993, Kastendeuch & Najjar, 2009, Chokhachian et al., 2017
	Retroreflective materials	Static solution, first examples are being applied on facades.	Rossi et al., 2015, Rossi et al., 2016, Morini et al., 2017, Yuan et al., 2015, Yuan et al., 2016, Han et al., 2015, Qin et al., 2016
	Thermochromic paints	Dynamic solution, still in the research phase.	Desire & Asdrubali, 2019, Seeboth & Losch, 2014 Ma et al., 2002, Ye et al., 2012; Ascione et al., 2019 Santamouris et al., 2011, Karlessi et al., 2009, Karlessi & Santamouris, 2013
Changing the thermal storage properties of the surface material	Lightweight materials	Static solution, already applied	Balaras, 1996, Givoni, 1998, Cheng & Givoni, 2005, Kalema et al., 2008, Zhou et al., 2008
	Green facades (GF)	Static solution, already being applied on facades widely.	Gromke et al, 2015, Schmidt, 2010, Wong et al., 2010, Hoelscher et al., 2016
	Phase change materials (PCM)	Dynamic solution, already being applied on roofs widely, merely on facades.	Lassandro & Di Turi, 2017
	Thermo responsive polymers	Dynamic solution, still in the research phase.	Stark et al., 2012
Reduce the incoming solar irradiation	Static shading devices	Static solution, already being applied on facades widely.	Valladares-Rendón & Lo 2014, Capeluto, 2013, Zerefos et al., 2012
	Dynamic shading devices	Dynamic solution, already being applied on facades.	Valladares-Rendón & Lo 2014, Cho et al., 2014, Valladares-Rendón et al., 2016

Table 3. Design analysis template. (Source: own)

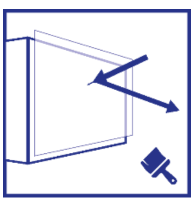
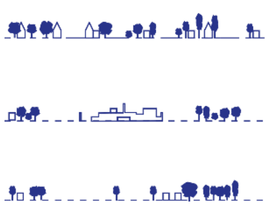
Mitigation strategy	Goal	Effectiveness	Context	Points of attention
Method 	A	+/-		
	B	+		
	C	n.a.		
	D	n.a.		
	E	n.a.		

Table 4. degree of effectiveness (Source: own)

Effectiveness	Meaning
++	very effective
+	effective
+-	neutral
-	negative effect
n.a.	not applicable / not relevant

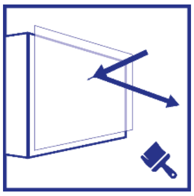
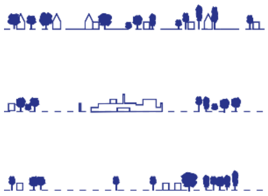
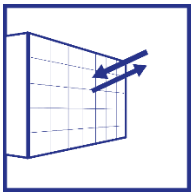
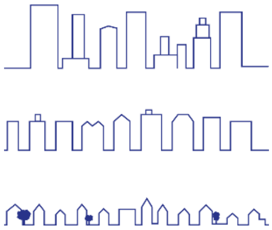
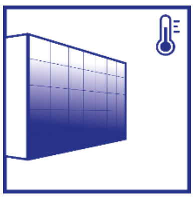
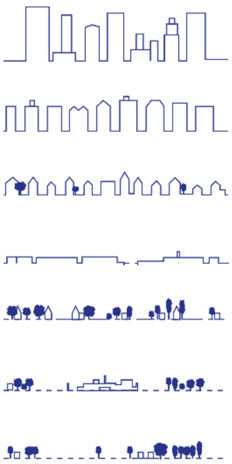
Figure 3. Retro-reflective facade (Musch, 2013)

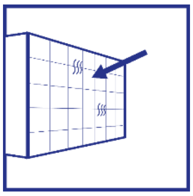
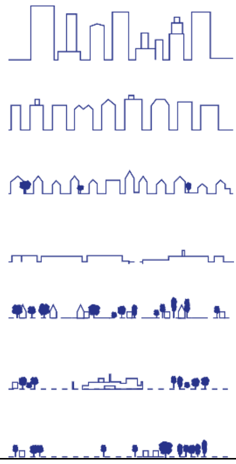
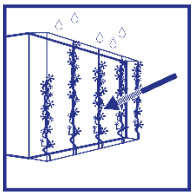
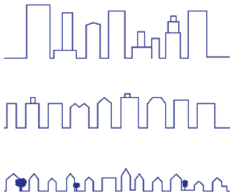
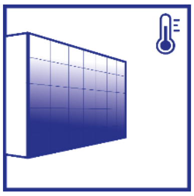
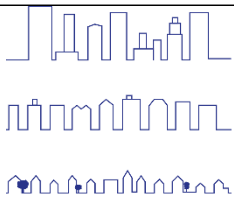
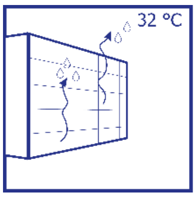
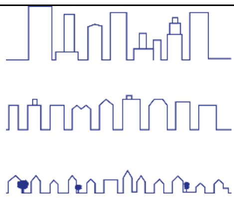
Table 5. diagram with UHI mitigation goals and performance indicators (Source: own)

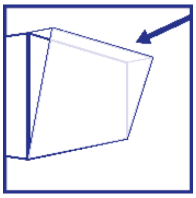
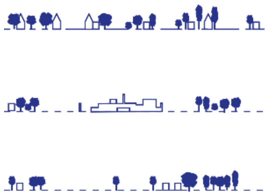
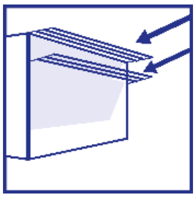
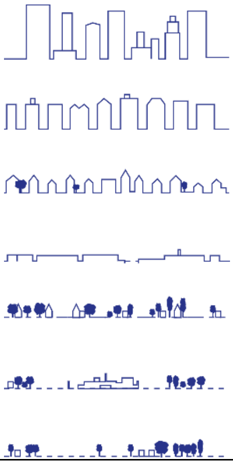
Goal (A)	Goal (B)	Goal (C)	Goal (D)	Goal (E)
Reducing the energy demand to avoid mechanical cooling	Reducing the ambient air temperature at the UCL at daytime	Reducing the ambient air temperature at the UCL at nighttime	Reducing the thermal discomfort during the day	Reducing the thermal discomfort during the night
Parameters	**Parameters**	**Parameters**	**Parameters**	**Parameters**
. The external surface temperature	. The Sky View Factor . Surface albedo . Height to Width ratio	. Thermal admittance	. Windspeed	. Thermal admittance

Appendix III

Table 6. diagram with mitigation strategies and their effectiveness in rural areas in the Netherlands

Mitigation strategy	Goal	Effectiveness	Context	Points of attention
Reflective  materials	A	+/-		When used in higher density areas this strategy causes multiple reflections within the urban fabric which results in entrapment of solar radiation. The total energy reduction can be very small, because the energy demand in the winter is higher. Thereby can this method also cause visual discomfort.
	B	+		
	C	n/a		
	D	n/a		
	E	n/a		
Retroreflective materials 	A	+/-		Retroreflective facades are in the research phase and have not been used in practice on building facades. The study on this material is promising. This strategy also increases the energy demand in the winter, as mentioned in the paragraph on reflective materials. Thereby can this method also cause visual discomfort.
	B	++		
	C	n/a		
	D	n/a		
	E	n/a		
Thermochromic paints 	A	++		This strategy is not far enough developed to implement on facades yet. If the pigments become stable and less expensive, this strategy could be very promising.
	B	++		
	C	+		
	D	n/a		
	E	+		
	A	+/-		This strategy works in the summer, but with the heating demand in the Winter in the Netherlands, there is always
	B	+		

Lightweight materials 	C	++		insulation necessary. Thereby, could lightweight materials have a negative impact on the heating load in the winter.
	D	n/a		
	E	++		
Green Façades 	A	+++		This method can be used in denser populated areas where there is no place for green. The higher the roughness of the façade, the more effect it has on the temperature. Choosing a GF with a thick substrate layer is the most effective. When applied perpendicular to the dominant wind direction, this could have negative effects on the urban cross ventilation.
	B	+/-		
	C	++		
	D	-		
	E	++		
Phase change materials 	A	+		Application of PCM on facades is less effective compared to roofs. The solar radiation on the vertical building envelope is not constant during the day, this causes a decrease in their performance.
	B	+		
	C	+		
	D	n/a		
	E	+		
Thermo responsive polymers 	A	++		This strategy is still in the research phase, also the consequences of freezing temperatures is unsure. Which should be researched further for implementations in the Netherlands.
	B	+		
	C	+		
	D	n/a		
	E	+		
	A	+++		It has to be noted that with changing the Z-angle of the

Facade shading system (FSS) 	B	+		facade, more reflected solar irradiation from the urban canopy layer can enter the building, this makes the strategy less suitable in densely built-up areas.
	C	+/-		
	D	n/a		
	E	+/-		
Shading devices (SD) 	A	+++		Shading devices need to be designed properly to be effective. SDs should be designed, taking into account shading, daylighting and visibility. Expected is that the SD could also have effect on the windspeed, when designing vertical elements this should be taking into account.
	B	+		
	C	+/-		
	D	n/a		
	E	+/-		