THESIS REPORT

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INTRODUCTION

Abstract
Bioreceptivity in building envelopes is a new type of facade greening system which thrives to improve the urban climate. In this type of facade greening the building envelope acts as a mediating layer between indoor and external conditions. This research focuses on the impact of the implementation of bioreceptive facade panels in the urban climate of The Netherlands; this includes designing in the urban climate and measuring what benefits these plants can bring, and how they can contribute to their own existence in their habitat.

INTRODUCTION

SOCIETAL RELEVANCE

What is bioreceptivity?

Guilitte was the first one in 1995 to describe bioreceptivity as a material property as follows; "*the aptitude of a material to be colonised by one or several groups of living organisms without necessarily undergoing any biodeterioration*"(Guilitte, 1995).
The colonisation of building facades by microorganisms is a known phenomenon and is usually seen as 'biofouling' because it changes the aesthetic appearance of the materials. The microorganisms can cause corrosion or physical degradation. Several factors such as climate, environment, facade design and materials have influence on the bioreceptivity of the facade(Tran et al., 2014).

Greening of cities

The average global temperature has risen about 1,1°C globally when compared to the pre-industrial era. The past decade has been characterised by retreating ice, rising sea levels, increasing ocean acidification and temperatures and more extreme weather(World Meteorological Organisation, 2019). Our modern cities have become major sources of greenhouse gasses and are also one of the most vulnerable places for global warming impacts. With more than half of Earth's population living in cities - and this number is expected to rise - the climate of our urban cities becomes increasingly important to our lives(United Nations, 2018).
Our industrial past and present urges us to find new ways of designing our cities to improve the environmental quality. The present urban greening is a response which thrives to improve the urban biodiversity, air quality, temperatures and water retainment of urban areas. This greening is especially challenging in cities where there is a pressure for space, resources and development.

The architectural surfaces - roofs and facades - which so far have been designed to repel biological growth, are now seen as opportunities for additional greening(Cruz & Beckett, 2015). The greening systems also have economical and social benefits. The green layer can function as both an acoustical and thermal barrier, while the presence of green induces psychological wellbeing. Furthermore the presence of vegetation improves the city image and can improve property value(Manso & Castro-Gomes, 2015).

Bioreceptive facades; a new typology of green wall systems

Besides contributing to a better climate in cities, the greening of building envelopes is also used as an aesthetic feature in the built environment(Manso & Castro-Gomes, 2015). Green wall systems can be divided in two categories: green facades and living wall systems. Green facades are based upon the application of climbing or hanging plants, allowing them to grow vertically, covering the facade. A living wall system is an additional external layer on the facade into which plants are inserted, held by a support structure. Research on green walls is mostly focussed on the improvement of the sustainability aspect of the systems; currently the wall systems need lots of additional material and maintenance(Manso & Castro-Gomes, 2015). The existing green wall systems function as a 'vertical garden' attached to a supporting structure. The bioreceptive panels, however, function as a host where microorganisms, cryptograms and other plants can propagate. There is a shift from the notion that the facade functions as the boundary layer of a building to that of a mediating layer between internal and external conditions, see figure 2 for vertical greening typologies. Where biological growth on facades was described before as biofouling or biodeterioration, it is now seen as the preferred (aesthetical) state of the facade panels(Cruz & Beckett, 2015). Due to this redefinition, it is possible to design vertical green in a rather simplistic manner which reduces material use and possibly the maintenance of the vegetation.

What are Bryophytes?

Bryophytes are nonvascular plants like liverworts, mosses and hornworts. Bryophytes are small scale which makes them able to inhabit microsites in otherwise unfavorable habitats(Vanderpoorten, 2009). Most of the Bryophytes are also epiphytes, which means they grow on other plants.
Cryptograms - algae, fungi, lichens,mosses, among other biotic things - are a plant type which thrives best in temperate or tropical climates. They distinguish themselves as plants without roots and propagate with spores instead. This makes them suitable for bioreceptive facades since roots can damage a facade assembly. Furthermore, cryptograms are able to survive in extreme environments which is often the case in dense urban environments(Cruz & Beckett, 2015).

Why concrete as base material?

It is well known that rocks, either in a natural or urban environment, are habitat for numerous microorganisms. Natural and man-made stone materials (concrete, brickwork, mortar) are particularly susceptible due to their physico-chemical properties(Miller et al., 2012). Cementitious materials are of great significance in architecture and design; especially concrete. Nowadays, concrete is one of the world's most used building materials in cities, making it an ideal material for the development of green areas in cities(Manso, Calvo-Torras, De Belie, Segura, & Aguado, 2015).

The urban environment

As mentioned before, cities are on the frontline of climate change since climate change is aggravated in urban areas. Due to the alterations of the natural environment in city's, distinct urban climates are formed. These climate alterations are a result of the physical structure of the city and the energy and pollution generated. (Coutts, Beringer, & Tapper, 2007).
Cities contribute to climate change and atmospheric pollution at local, national and global scales. In turn, the cities cope with extreme weather events such as droughts, storms, floods ect. Urban development affects the biological and physical components of the ecosystems that used to exist in that area (ie., vegetation, animals, soil, landform and water)(Oke, Mills, Christen, & Voogt, 2017).

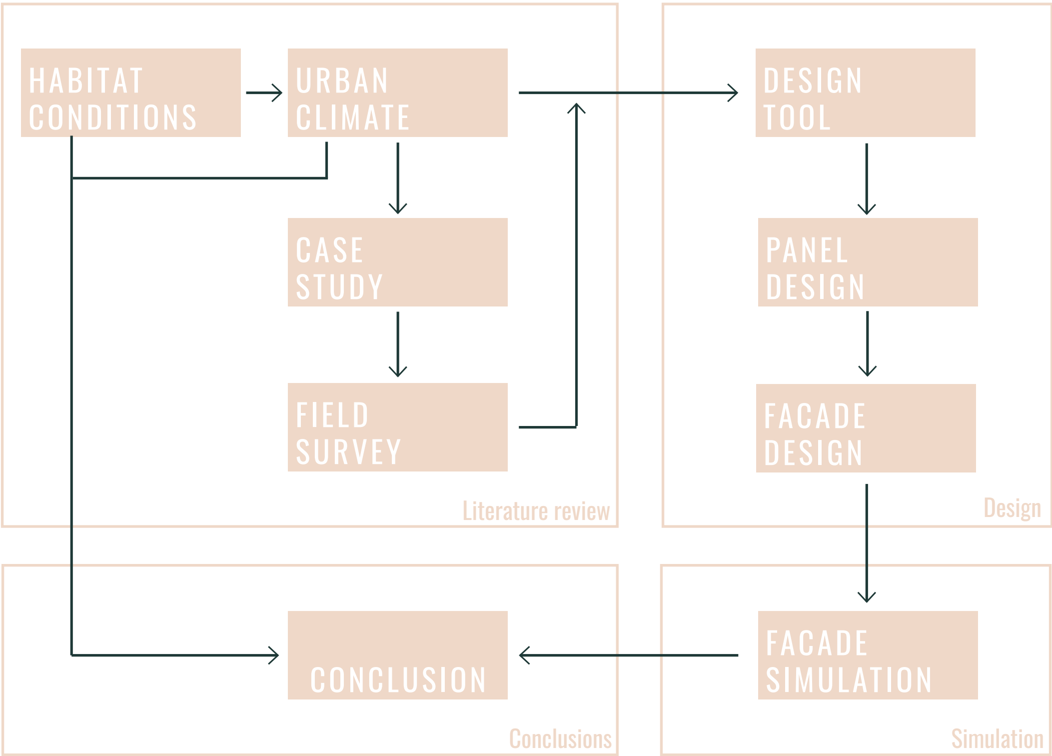
The most notable climate change effect in urban area's is the increase in temperature compared to rural areas, the so called Urban Heat Island effect (UHI). The two primary causes for the UHI effect are difference in materials (vegetal removal) and structure between rural and city areas (Eliasson, 2000).

Current research on bioreceptivity

Bioreceptive design is a relatively new phenomenon in architecture. Current research on bioreceptive facade panels focuses mostly on the material properties of the concrete panels (Tran et al., 2014; Huang et al., 2018; Gambino

RESEARCH FRAMEWORK

Figure 1 - Thesis research framework



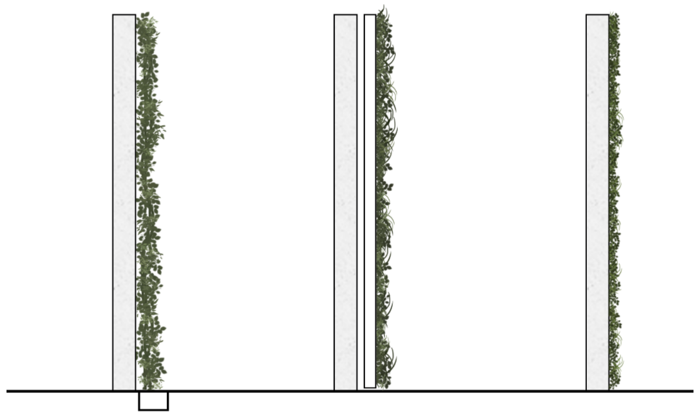


Figure 2 - Green wall systems. Left: green facade. Middle: living wall system. Right: bioreceptive facade.

et al., 2019; Manso & Aguado, 2016) and less on the impact of environmental conditions on bryophytes and the contribution of bryophytes to the environment. Most of the research that has been conducted uses accelerated laboratory tests - imitating 'optimum' conditions - which are significantly different from field conditions. Field investigations have a long duration which makes them unfavourable to perform(Tran et al., 2014).

PROBLEM STATEMENT

Due to alterations of the physical structure of the city, energy and pollution generated, distinct urban climates have formed. In these urban climates, the climate change effects are aggravated causing cities to cope with extreme weather events such as high temperatures (UHI effect). Although bioreceptive panels contribute to the improvement of hostile urban climates, they are also affected by it. Bioreceptive facades contribute to the urban biodiversity, air quality, temperatures and water retainment and it has economical-, social-, and aesthetical benefits. Currently, measuring the impact of urban climates on bioreceptivity is lacking in research and also how effectively such bryophytes contribute to improving a city's climate, especially in temperature reduction. In order to find out if bioreceptive facade panels are a feasible measure to improve the city climates, their impact on the environment needs to be assessed with the main focus on their ability to reduce the outdoor temperature.

RESEARCH QUESTION

Following from the problem statement, the main research question is formulated; *Are bioreceptive facade panels an effective measure to improve the city climates in The Netherlands?* Where the effectivity of the panels is assessed in urban biodiversity, air quality, temperatures and water retainment and economical-, social-, and aesthetical benefits, with the main focus on temperature. Since adding bioreceptive panels contributes to biodiversity, this benefit won't be further discussed. Furthermore, the economical-, social-, and aesthetical benefits are merged in solely aesthetical benefits, since the economical and social benefits rely on the aesthetical condition of the facade. This main research question is subdivided into three subquestions(see figure 1);

Subquestion 1: How to develop a design tool for bioreceptive facade panels to account for the bryophytes' habitat conditions in The Netherlands?
Chapter 1; The habitat conditions and limits of bryophytes in a natural and urban environment.
Chapter 2; The relation of urban climate to the physical structure of the case study area.
Chapter 3; Field survey.

Subquestion 2: How to design a bioreceptive facade panel in urban environmental conditions of The Netherlands?
Chapter 4; The translation of habitat conditions into panel geometry; development design tool.
Chapter 5; Panel design.
Chapter 6; Facade design.

Subquestion 3; What is the impact of bioreceptive facade panels on the urban environment in The Netherlands?
Chapter 7; Simulating the urban environment and bryophytes.
Chapter 8; Assessment if bioreceptive facade panels are an effective measure to improve the city climates in The netherlands.

METHODOLOGY

Literature review

Subquestion 1: How to develop a design tool for bioreceptive facade panels to account for the bryophytes' habitat conditions in The Netherlands?
The first part of the research contains orientation and research into the available literature on the topic. Based on the literature a specific case study area is selected. The literature is substantiated with field observations, this combination is used to translate the habitat conditions into design factors.

Design

Subquestion 2: How to design a bioreceptive facade panel in urban environmental conditions of The Netherlands?
All aspects influencing the panel design are elaborated in order to develop a design tool. This tool is used to crease two different facade panel designs. At last, the application of this facade panel system in the case study area is shown.

Simulation

Subquestion 3; What is the impact of bioreceptive facade panels on the urban environment in The Netherlands?
The proposed design in the case study area is used to simulate the influence of the facade on its environment. The simulation tool ENVI-met is used together with literature in order to define the simulation model and settings.

PLANNING

Figure 3 - Thesis planning academic year 2019/2020

		Nov	Dec	Jan				Feb				Mar					Apr				May					June		
WHEN?				1	2	3	4	--	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Activity																												
Research topic		P1																										
Research question				P2																								
Research framework				P2																								
Research planning				P2																								
Literature review				P2																								
Case study selection																												
Field survey																												
Processing results																												
Compute urban geometry																												
Analyse design site																												
Development design tool																												
Design concepts																P3												
Panel design																P3												
Model panels																												
Assessment final design																												
Facade design																												
Define context geometry																												
Define greening parameters																												
Run final simulations																									P4			
Processing results																									P4			
Conclusions																									P4			
Reflection and conclusion																												P5
Adjustments																												P5
Visualisations																												P5
Reflection																P3												
Presentation preparations																P3									P4			P5
Completion report																P3									P4			P5

LITERATURE REVIEW

Chapter 1

LITERATURE REVIEW

In order to understand the climatic conditions in which bryophytes grow, their natural habitat must be understood. Below the habitat conditions for bryophytes are elaborated, divided in different factors: nutrients, water, wind, temperature and solar radiation. Furthermore, the limits for bryophytes and their relation with environmental factors is described. The natural habitat conditions are compared to the challenges in the urban climate and finally the conclusion is drawn.

1.1 HABITAT OF THE BRYOPHYTES

Nutrients

Bryophytes have rather low nutrient requirements. They can receive their nutrients from substrate as well as precipitation and dust. The nutrient availability in precipitation varies widely, with the lowest concentrations in the open (precipitation becomes more nutritious through canopy throughfall). Bryophytes are essentially limited in nutrient supply by their poikilohydric method (hydration controlled by environment) of water regulation. The need for nutritions is greater in young shoots, usually the concentrations of N, P and K are higher(Glime, 2017).

Water

Bryophytes are poikilohydric, this means their hydration state is controlled by the environment. This trait makes it necessary to grow in a moist environment and to be desiccation tolerant. The structure of the habitat and microhabitat of bryophytes is important in conferring their hydration state. According to Voortman the optimal water content for respiration and photosynthesis as measured for several bryophyte species is around 87% to 305% of their own dry weight, which is high compared to other plants(Voortman, 2018). Bryophytes have the ability to recover from dehydration and resume photosynthesis. The dry habitat bryophytes are able to withstand long periods of desiccation, but drought sensitivity varies according to species. That is obvious in the study of Pardow & Lakatos in 2012, twenty-one species are tested against their desiccation tolerance. All species didn't show signs of dessication after being exposed to 85% humidity. At 75% humidity, difference between species existed and became more pronounced at 43%. From the desiccation tolerant species 16/18 recovered more than 50% of their photosynthesis after being exposed to 43% humidity for 9 days(Pardow & Lakatos, 2012). Approximately the same results are described by Johnson and Kokila, where desiccation tolerant species showed 4.8 - 8.3 % of damaged cells after four hour exposure to 55% humidity, and in the desiccation sensitive species 14.0 - 42.3 % of their cells were damaged after four hour exposure(Johnson & Kokila, 1970). Generally, >50% relative humidity is desired for bryophyte growth even if desiccation tolerant species are chosen for application on the facade. Additionally, some bryophytes are capable of drawing considerable quantities of water from atmospheric vapour, using it as a water source (Barkman, 1958). In most bryophytes water availability is the most limiting factor for growth(Glime, 2017).

Dry mosses are typically much more heat resistant than hydrated mosses. Glime describes that Norr found eight European mosses which reached lethal temperature limits at 42-51 degrees Celsius when wet whereas these limits were 85-110 degrees Celsius when dry(Glime, 2017).

Wind

Bryophytes use evaporation until a minimum amount of hydration is reached. Evaporation is dependent on the temperature, humidity and wind. Evaporation is significantly reduced in forests due to lower temperatures, less wind and higher relative humidity. It has been shown that the evaporation is minimized on the North side and maximized at the side most exposed to sun (provided that wind does not interfere)(Barkman, 1958).

In a laboratory study on the Sunagoke moss species it became evident above a wind velocity of 2 m/s the convection heat transfer on a moss roof remains identical (Amir et al., 2018).

Temperature

For most of the bryophytes the optimum temperature is 15-25 °C, even for tropical species. Often, their minimum temperature for photosynthetic gain is -10 °C and seldom have a net gain at temperatures above 25°C (for most of them the optimum is near 20°C and for many others it is much lower). They experience a sharp decline for net photosynthetic gain just past the optimum, where changes in temperature below their optimum have only modest effects on their productivity. Usually, they become dormant in summer heat (above 25°C) and drought (suffer from reversible depression of photosynthesis) or die (irreversible damage to photosynthesis). The bryophytes are generally able to handle temperatures until 40°C before it becomes lethal. For dry mosses this value is much higher. Also during cold winters and when there is no free water available bryophytes go dormant(Glime,2017).

The temperature of a bryophyte is not necessarily the of the ambient. The bryophytes can use evaporative cooling in order to cool themselves down. In addition, they use color to either reflect or attract the sun. In well established moss cushions the temperature of the moss and its surroundings can differ about 30°C. Bryophytes likewise alter soil temperature as thick moss covers can act as insulation layers preventing the soil from warming up via the sun or heating up the soil by trapping geothermal heat(Glime,2017).
Bryophytes seem to be able to acclimate to temperature differences suggesting that temperature is not necessarily the signal for photosynthesis(Glime, 2017).

Solar radiation

Generally, bryophytes are adapted to low light conditions relatively to other plants. They are, due to their chlorophyll a: chlorophyll b ratio able to withstand bursts of high light intensity. Liverworts seem better adjusted to shade than mosses. There is a broad range of light compensation points among bryophytes, ranging from 0.03% of full sunlight in deep water species to 7.5% in sun species. Light saturation points are likewise low, although some bryophytes seem to be able to use bursts of high light intensity and can increase their saturation points when higher levels of CO_2 are present(Glime, 2017).

The saturation of photosynthesis in bryophytes is often shown at low irradiance levels, <20% of full sunlight, even in species in bright lit habitats. During bright and dry sunny weather most bryophytes are in a dehydrated, metabolically inactive state (dormant). Their photosynthesis takes place in rainy or cloudy weather(Tuba et al., 2011). Moreover, in dehydration state too much sunlight can damage the bryophytes. Generally bryophytes are better resistant against solar radiation damage whilst being moist(Glime, 2017). Some sun adapted species are known to handle several hours of sunlight(Pugnaire & Valladares, 1999).

Bryophyte conditions

Temperature	15 - 25 °C
Nutrients	Low requirement
Water (precipitation)	Moist climates
Solar radiation	Low light conditions
Humidity	High humidity levels (>50%)
Wind	Intermediate wind speeds

Table 1.1 - Bryophyte conditions in a natural environment

Limits

The most significant climatic stress inducers for bryophytes in a natural environment are drought, high temperatures and frost(Glime, 2017). Some bryophyte species are able to survive in extreme environments like iron stoves, caves and glacial surfaces. Bryophytes have many stress-tolerants and ruderals. The plants can behave differently under different environmental circumstances due to inducible proteins which can respond to climatic changes(Glime, 2017).

Relation bryophytes and the environment

Most of the bryophytes are also epiphytes, which means they grow on other plants. Barkman described three causes of the horizontal zonation on tree trunks; 1. illumination, 2. prevailing wind directions and 3. inclination. See image appendix A for the factors and their relations influencing epiphytes. According to Barkman, illumination and wind play a key role in the epiphyte relations, though Barkman did not add photosynthesis to the diagram and argues the influence solar radiation on relative humidity.

Conclusion

An interpretation of barkman's scheme is illustrated in figure 1.1 to show the relation of bryophytes with their environment. In this scheme, photosynthesis is also added since it is known that temperature influences the photosynthesis and the factors only concerning trees are left out. From this scheme we can conclude that illumination and wind are important indirect factors for bryophyte growth, where temperature and humidity are important direct factors.

The most significant climatic stress inducers for bryophytes in a natural environment are drought, high temperatures and frost. As mentioned above, usually water availability is the limiting factor in growth in bryophytes. Bryophytes have the ability to go dormant, metabolically inactive state, when their habitat is too dry and/or the temperatures are too low or high(usually >25°C). Generally, >50% relative humidity is desired for bryophyte growth even if species are desiccation tolerant. Dormant bryophytes often turn brown and can resume their photosynthesis and evaporation after dormancy. Furthermore, too much solar radiation can damage the bryophytes. Generally, bryophytes are better resistant against radiation whilst being moist.

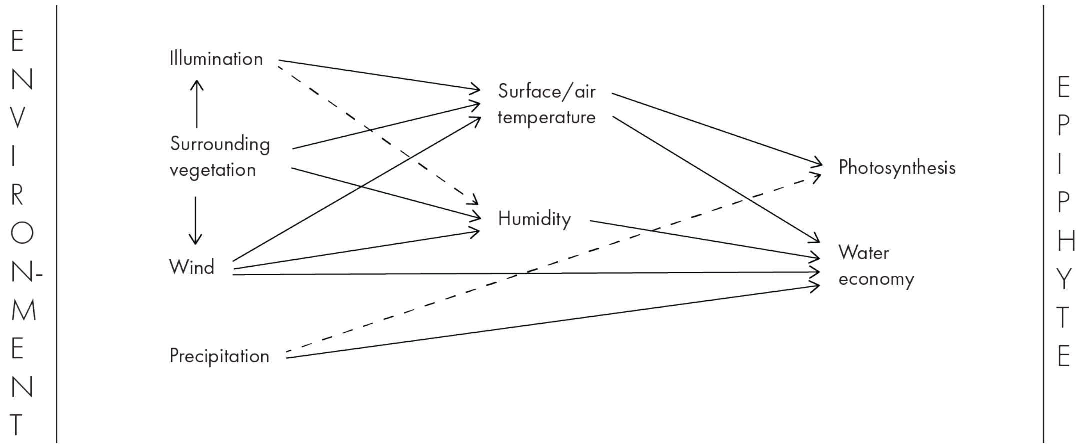


Figure 1.1 - Relation epiphytes and their environment, interpretation from Barkman, 1958

1.2 THE URBAN CLIMATE

Urban ecosystems differ from natural ones in terms of their climate, soil, hydrology, species composition, population dynamics, and flows of energy and matter(Alberti, 2007). This section describes how the urban climates are formed and the limiting factors for bryophytes in an urban setting.

Due to the alterations of the natural environment in a given city, distinct urban climates are formed. These climate alterations are a result of the physical structure of the city as well as the energy and pollution generated. In these urban climates, the air pollution is increased aiding in the formation of the UHI (Urban Heat Islands)(Coutts, Beringer, & Tapper, 2007).
Coutts, Beringer, & Tapper describe in 2007 the factors that contribute to the formation of the UHI; the emissions of atmospheric pollutants that increase longwave radiation and/or induced absorption of shortwave radiation, anthropogenic heating, decreased horizontale airflow due to increased friction, absorption and retention of solar energy due to canyon (H/W ratio) geometry (see figure 2.1 chapter 2 for description H/W ratio), reduced longwave loss due to limited sky-view factor (SVF), and reduced evapotranspiration because of lower fraction of vegetative cover(Coutts, Beringer, & Tapper, 2007).
Cities contribute to climate change and atmospheric pollution at local, national and global scales. In turn, the cities cope with extreme weather events such as droughts, storms, floods etc. Urban development affects the biological and physical components of the ecosystems that used to exist in such areas (ie., vegetation, animals, soil, landform and water)(Oke, Mills, Christen, & Voogt, 2017).

Bryophyte conditions

Temperature

The urban warming effects are similar to the global warming issues. Global warming forecasts predict a temperature increase of 1.9 to 3.5 °C over the next century whereas urbanised areas already routinely measure an increase of 3.3 to 4.4 °C (Coutts, Beringer, & Tapper, 2007).

The UHI effect is the most well documented effect showing huge temperature differences between urban and rural areas. The two primary causes for the UHI effect are difference in materials (thermal admittance) and structure (street geometry). The sky view factor (SVF) is a measure for the street geometry and has a good correlation with UHI effect since it is well correlated with surface temperature(Eliasson, 2000). A low SVF correlates with low exposure to the sky, which means less cooling (especially at night). The magnitude of UHI effect, compared to rural areas, is usually maximum at nighttime(Oke et al., 2017).

Wind

In general, the urban landscape decreases the regional wind speeds compared to rural areas. The geometry of the city, trees and buildings, increases friction which changes wind patterns, usually reducing the wind speeds but also creating local areas with high wind speeds and eddy circulations. The urban wind pattern also includes weak airflows induced by temperature differences within the city, or differences between the city and its surroundings(Eliasson, 2000).

Water

Urban influences on clouds and precipitation are often subtle - conditions vary with season and location - generally, the effects on clouds and precipitation are due to the UHI effect, surface roughness and aerosols. During summer time, increased cloudiness and precipitation is found in and downwind from urban areas as well as increased frequency of thunderstorms and hail. In many cases, urban effects enhance or suppress existing clouds or storms instead of forming new ones(Oke, Mills, Christen, & Voogt, 2017).

Humidity

Towns are relatively low in humidity levels compared to forests. The evaporation in towns is higher compared to the countryside due to the opposite reasons in forests; temperatures are higher and humidity is lower in spite of reduced wind velocities(Barkman, 1958).

Eliasson describes in 2000 that the humidity in cities during daytime is often lower compared to rural areas and the opposite prevails at night(Eliasson, 2000). Additionally, Oke, Mills, Christen, & Voogt describe in 2017 that the atmospheric humidity is generally lower in urban climates during daytime and in summer compared to rural areas, induced by a lower fraction of vegetative cover. During nighttime and in winter, the atmospheric humidity generally exceeds that of rural areas. Additionally, in some urban neighborhoods with extensive irrigation the humidity can exceed that of surrounding areas(Oke, Mills, Christen, & Voogt, 2017).

Nutrients

As mentioned in section 1.1, the vegetation makes the precipitation more nutritious in nature, whereas in urban areas the vegetation fraction is decreased which typically makes the nutrient supply lower. The principal differences between rural and urban areas is the altered load of pollutants in the air. SO2, NO, NO2 and CO gasses are among the principal urban atmospheric pollutants as well as some organic compounds, a variety of solids and photochemically produced products. The emission of all the particles is not primarily the problem since there is a lively chemical interaction taking place. Many of the anthropogenic products are catalysts for chemical reactions and together with solar radiation a lot of photochemical reactions can take place(Landsberg, 1981).

Solar radiation

Due to the urban cloud of particulates in the air which scatter and absorb the sun's rays, the solar radiation reaching cities is less when compared to their surrounding rural areas. In industrial cities, the loss in solar radiation can be between 10% and 20%. Similar losses are measured in terms of energy received below the urban dust cloud. In winter and autumn the radiation loss is greatest and in summer the loss is reduced or nearly vanishes(Landsberg, 1981).

Limits in the urban environment

Table 1.2 gives an overview of the bryophyte growth conditions and how these factors change in an urban environment. At first, it can be stated that wind, solar radiation and precipitation generally change in favour of bryophytes in urban conditions. Especially of the factors wind and solar radiation, it must be noted that this is on a large scale, in cities microclimates will vary enormously and with solar radiation it is only seasonally. Additionally, the nutrient requirement and precipitation varies among different cities and locations. Since additional irrigation is most probable necessary, precipitation and nutrient factors in the environment are less of influence on the effectiveness of the bryophyte panels.

Pollutants

The presence of air pollution can potentially be a problem for bryophytes in an urban area since some pollutants are toxic for vegetation. In the mid-nineteenth century it was noted by botanists that lichens and bryophytes were scarce in the vicinity of large towns(LeBlanc & Rao, 1973). In some literature, towns are referred to as epiphyte deserts(Barkman, 1958). Although this fact was almost universally recognized, opinions differed about the cause of this phenomenon. In literature, three hypotheses arose; the decline is caused by pollution, by drought, or by a combination of both(LeBlanc & Rao, 1973).

Later on, in other studies, the importance of pollution fades. Hohenwallner and Zechmeister describe in 2001 that habitat and substrate diversity in urban environments turn out to be the most influential parameters, environmental pollutants seem to be of minor importance on species richness and distribution. Nevertheless, air pollution affects reproduction (as mentioned in other studies) and such pollution has probably resulted in the extinction of at least one species in urban areas, which was made evident in a study in Vienna. This species is known in literature to be sensitive to pollutants (Hohenwallner & Zechmeister, 2001).

As mentioned in the introduction, bryophytes have the ability to purify the air. In more recent studies moss bags are used as biomonitoring in urban settings, to measure the existence of major and trace elements. In the study is mentioned that poor vitality was evident after exposure because of the hot and dry continental climate the moss bags have been placed in. In this specific study, the passive uptake of major and trace elements of the mosses is tested, suggesting the mosses were (partially) dormant during exposure(Aničić et al., 2009; Goryainova et al., 2016).

Temperature

Furthermore, it was mentioned in section 1.1 that bryophytes are sensitive to drought, high temperatures and frost. Particularly high temperatures and drought can be a problem in urban climate, since these factors are known to be increased. As mentioned before, bryophytes seldom have a net gain for photosynthesis at temperatures above 25°C, since temperatures are known to rise in the urban climate, this will be a limiting factor on the effectiveness of bryophyte panels. In a study in Japan for the influence of microhabitats on bryophyte diversity in urban Japanese garden landscapes, they correlated bryophyte diversity with low temperature and high humidity microclimate, probably due to large vegetation cover and water surface(Oishi, 2018).

Humidity and solar radiation

Drought can as well be challenging in the urban climate, especially since during daytime and in summer the humidity levels are low and bryophytes propagate best in humid climates. Field studies have shown additional irrigation was necessary in a continental climate in order to keep the mosses from dehydration(Aničić et al., 2009; Goryainova et al., 2016).

Furthermore was mentioned solar radiation can be damaging to bryophytes, additionally it influences temperature and moisture(indirect factor). Bryophytes are better resistant against radiation whilst being moist. Isermann described bryophyte flora in Germany in 2007 on stoney surfaces and soft substrates and related the bryophytes' growth with intermediate levels of light availability(Isermann, 2007).

Universidad de Politecnika de Madrid performed outdoor testing of bryophytes on all orientations as part of a smart building envelope system. They mention the humidity levels and solar radiation as the two most difficult parameters to take over and developed a system that, depending on the weather, provides the right shading and moisture conditions. They found that the vertical panels needed more conditioning compared to the horizontal ones, where the south facing facade panels needed 60° inclination to provide enough shading and the north facing ones remained in the same position(Bryophyte Building Envelope Project, 2015).

Bryophyte conditions	Urban conditions
Temperature 15 - 25 °C	Huge increase
Nutrients Low requirement	Decreased, pollutants present
Water (precipitation) Moist climates	Slightly increased
Solar radiation Low light conditions	Decreased up to 10-20% (except summer)
Humidity High humidity levels (>50%)	Decreased
Wind Intermediate wind speeds	Decreased (except locally)

Tabel 1.2 - Bryophyte conditions in a city climate

1.3 CONCLUSION

Precipitation, pollutants and wind have modest influence in the habitat of bryophytes. As mentioned in section solar radiation is an important direct factor in moss growth, where humidity levels and temperature are important indirect factors.

If the conditions for bryophytes aren't reached in their habitat, they can be damaged (or die) and go dormant. Dormant bryophytes can lose their aesthetic value - turn brown, and lose the ability to recover damages(photosynthesis) - and their ability to cool down and humidify the surrounding area by evaporation. Because of the poikilohydric character of bryophytes, additional irrigation of vertical facade panels will be necessary in order to create an effective greening facade. Water availability is the limiting factor in their natural habitat. According to Voortman the optimal water content for respiration and photosynthesis as measured for several bryophyte species is around 87% to 305% of their own dry weight(Voortman, 2018). Furthmore, in field studies it was mentioned irrigation is necessary to keep the bryophytes from going dormant.

Relating back to the question as stated in the beginning of the chapter. We can conclude that improving the temperatures, water retainment and aesthetical benefits (thus also social- and economical benefits) are dependant on the irrigation and whether the bryophytes turn dormant. High temperature and desiccation induce dormancy and become more challenging in an urban environment.

Uptake of major and trace elements by bryophytes also takes places passively, this means air purification of such elements is not dependant on whether bryophytes are in an active or passive state. Research does imply active bryophytes are more effective in uptake of these elements. Since photosynthesis (C02 uptake) takes place when bryophytes are active, air purification is still partially dependant on the state of the bryophytes. High temperatures are an important influence on the activity of bryophytes. As mentioned before, most of the bryophytes the optimum temperature is 15-25 °C, even for tropical species. Often, their minimum temperature for photosynthetic gain is -10 °C and seldom have a net gain at temperatures above 25°C (for most of them the optimum is near 20°C and for many others it is much lower). They experience a sharp decline for net photosynthetic gain just past the optimum, where changes in temperature below their optimum have only modest effects on their productivity. Usually, they become dormant in summer heat (above 25°C) and drought (suffer from reversible depression of photosynthesis) or die (irreversible damage to photosynthesis).
The hydration state of bryophytes is controlled by the environment. Water content can be controlled by irrigation but humidity levels are known to be reduced in urban environments. As concluded in chapter 1 the relative humidity levels below 50% can damage even desiccation tolerant species(without irrigation). Induced relative humidity can reduce the irrigation amount, thus making the panels more effective.

Solar radiation is the important indirect factor on bryophyte growth. Generally, bryophytes prefer low light conditions which, in an urban setting, is not always the case. Also in dehydration state too much sunlight can damage the bryophyte cells but bryophytes are better resistant against solar radiation damage whilst being moist. Some sun adapted species are known to handle several hours of sunlight.

From these observations can be concluded that shading and irrigation important design aspects in bryophyte facade panels, as also mentioned by other studies. Furthermore can be concluded that the presence of bryophytes in their habitat contributes to improving it by altering the direct factors temperature en relative humidity.

CASE STUDY

Chapter 2

CASE STUDY

Previously the habitat conditions and limits in urban climates are understood for bryophytes. This chapter will focus on defining the case study area to develop and implement a design tool for bioreceptive panels. The case study area needs to be challenging and have potential for bioreceptive panels, furthermore it needs to be representative in The Netherlands.

2.1 ROTTERDAM

For this research the city of Rotterdam is chosen as a case study area. Rotterdam has an urban character, a variety of neighborhood typologies and well documented weather data which makes it a suitable location for bioreceptive research.

At first, the weather conditions in Rotterdam are briefly described. Secondly, a classification method is proposed on how to classify certain urban scenarios according to their impact on the city climate, called Local Climate Zones(LCZ's). At last, urban scenarios in Rotterdam will be selected where bioreceptivity is suspected to be challenging but also where it has the most potential to influence the local climate. These urban scenarios are classified according to the LCZ's. Later on the specific neighborhoods will be selected on their representivity in the Netherlands, and their properties documented for further research.

General weather conditions

The Netherlands has a temperate climate, characterised by modest winters and summers. Below the direct factors in the climate of Rotterdam as described in chapter 1, are elaborated.

In the study of *Hotterdam*, is mentioned the amount of summer days in The Netherlands (temperatures >25 °C) currently totals 21 days, this can increase up to +130% in fifty years(+/- 28 days). This would mean approximately a month per year temperatures will be too high for bryophytes(Van der Hoeven & Wandl, 2015).

Average relative humidity (RH levels) in Rotterdam during summer 76 - 78 %(KNMI, n.d.). These averages are measured over 1981-2010. The high RH levels are positive for bryophyte growth. More specifically, the amount of days during meteorological summer (1st of June till 1st of September, measured) of 2019 where the minimum RH levels drop below 50% numbers 28 days (of 92 days). In 2018 this number is higher, 38 days, and in 2017 it was 27 days. In 2016 and 2015 this number was around 30 days (KNMI, n.d.). This means the average humdity is suiting for bryophytes, though their limits can be reached.

2.2
CLASSIFICATION URBAN CLIMATE

As mentioned in chapter 1, the distinct urban climates are formed because of the physical structure of the city as well as air pollution plus energy generated. In this chapter, the city climate will be related to the physical structure of the city.

Physical structure of the city

The physical structure of the city can be described by urban surface properties which are fabric, metabolism, land cover and structure. Several parameters to describe urban properties such as urban cover, length scales and urban structure are shown in figure 2.1 (Oke, Mills, Christen, & Voogt, 2017).

A method to classify the climate on a neighborhood scale is the LCZ (Local Climate Zones), see figure 2.2. The criteria on which the classification is based, are known to control micro- and local climates (temperature, moisture and wind). The different zones can be distinguished by their ability to modify local climates due to their fabric, metabolism, land cover and structure(Oke, Mills, Christen, & Voogt, 2017).

The different local climate zones have their typical properties illustrated in table appendix B, page 113.

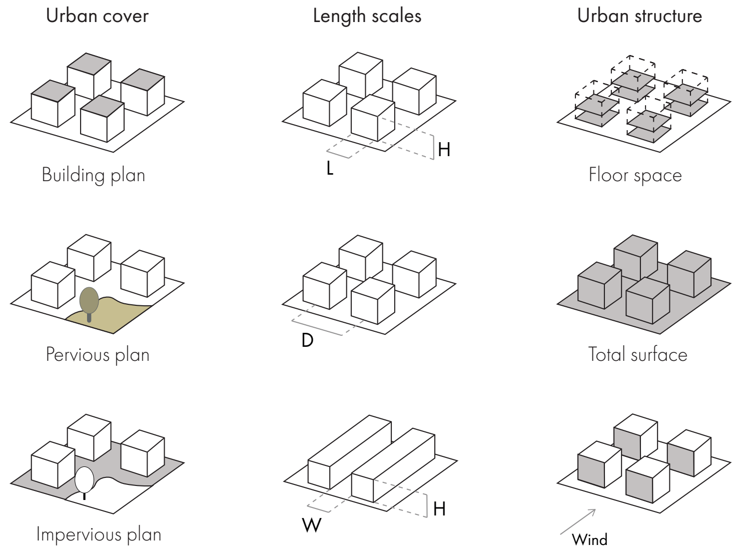


Figure 2.1 - Urban properties, reproduced from Oke, Mills, Christen, & Voogt, 2017

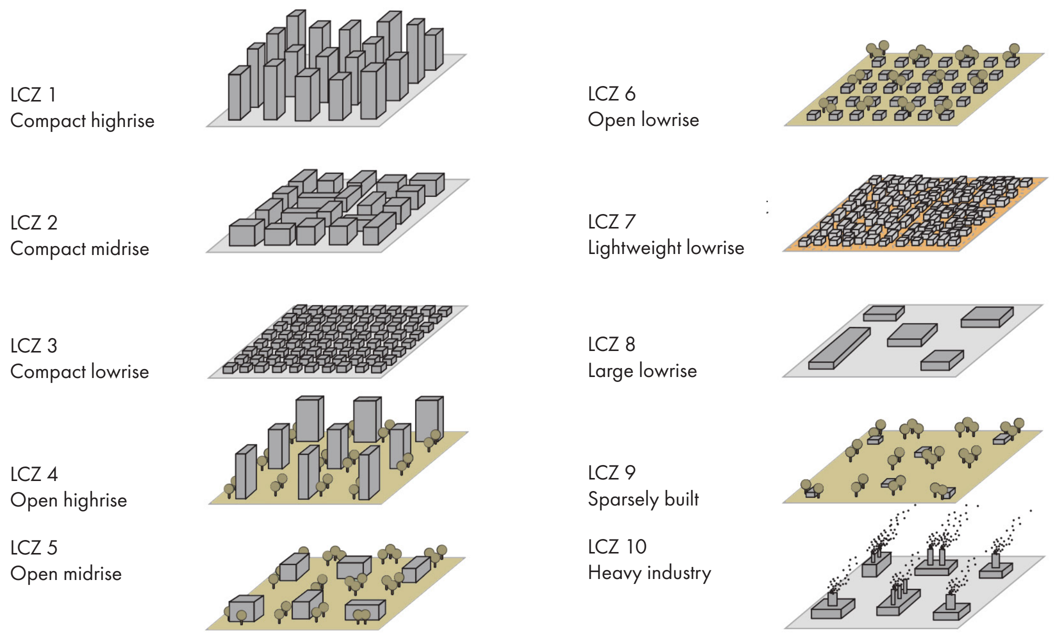


Figure 2.2 - LCZ's, reproduced from Oke, Mills, Christen, & Voogt, 2017

2.3 SELECTION URBAN SCENARIOS

Challenging area

In the research *Hotterdam* by Van der Hoeven and Wandl in 2015, the physical characteristics of Rotterdam have been analysed to determine the influences that contribute to the UHI effect in the city. They produced several maps based on satellite images, GIS and 3D models which have resulted in the 'Warmtekaart fysiek' (heat map physical), which is shown in appendix C. These maps are used in defining different neighborhoods which are sensitive for the urban heat island effect in Rotterdam.

In the heat map, eight physical clusters are developed, defining areas that are sensitive for the UHI effect. The dark red areas shown on the map reference industrial zones, stating that their sensitivity to urban heating is mainly due to the amount of paved surfaces and lack of vegetation/ water. For this study the industrial zones are disregarded.

The bright red color shows the second cluster, this area is shown in figure 2.3 Here, the heat island is mainly caused by the amount of building surface and pavement, as well as the lack of vegetation/ water. This area concerns the entire central district of Rotterdam and its neighboring areas.

Bioreceptive potential

Within this cluster the neighborhoods need to be defined where facade greening can contribute to the city climate. As mentioned in chapter 1, SVF is correlated with surface temperature. The SVF map of Rotterdam is shown in appendix C. In this map, the sky coverage with leaves is also integrated, which one would like to rule out in case of bioreceptive facades. Once these areas are disregarded, the neighborhood (1) Kralingen becomes obvious as an area with potential for facade greening, see figure 2.4

The measurement of surface area of a given building is often indicative of the heat stored by the building throughout the duration of a day, which influences the UHI effect. Furthermore, bioreceptivity can potentially have a huge impact in places with large building surface fractions. See appendix C for the building surface map. The building surface ratio is especially high in the north (2) Cool district in Rotterdam, see figure 2.5.

The two neighborhoods (1) Kralingen and north (2) Cool district have been selected for their potential sensitivity for the UHI effect in addition to their potential for the implementation of bioreceptive facade panels. The next section will zoom in at these two neighborhoods.

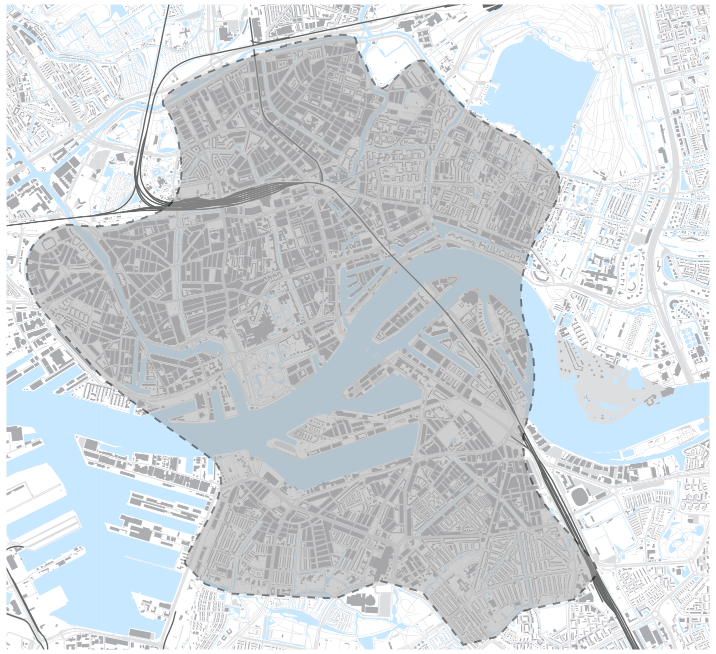


Figure 2.3 - Indication second cluster area in Rotterdam

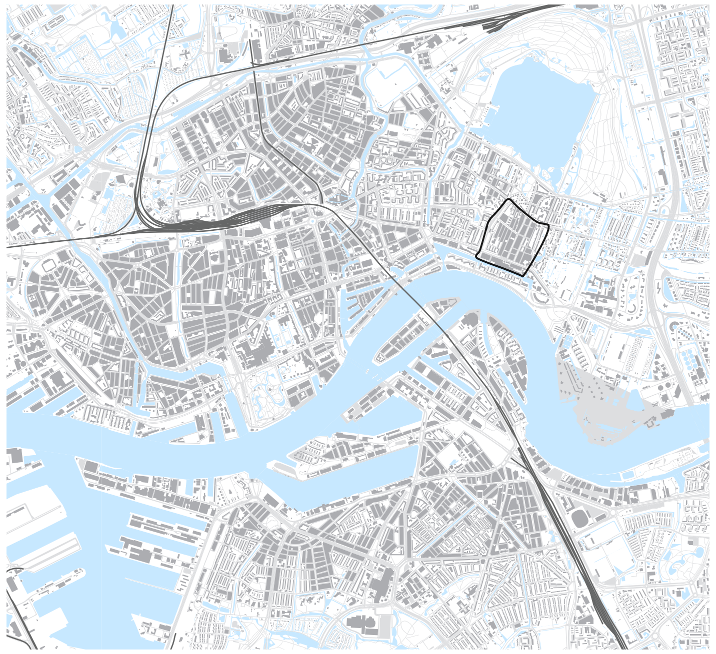


Figure 2.4 - Indication area with high sky view factor within second cluster

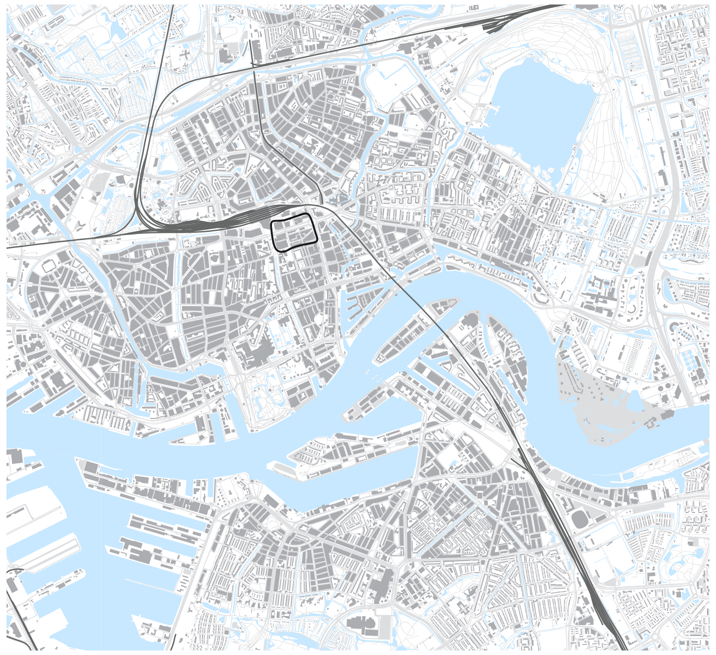


Figure 2.5 - Indication area with high building envelope within second cluster

2.4 MAPPING URBAN SCENARIO'S

The neighborhood of Kralingen is illustrated in the figures 2.6-2.10.

2.8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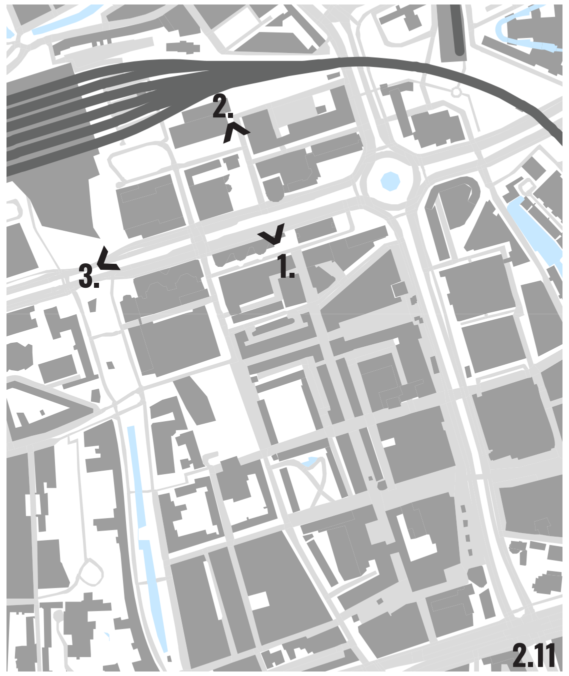
2.4 MAPPING URBAN SCENARIO'S

The neighborhood of Cool District is illustrated in figures 2.11-2.14.



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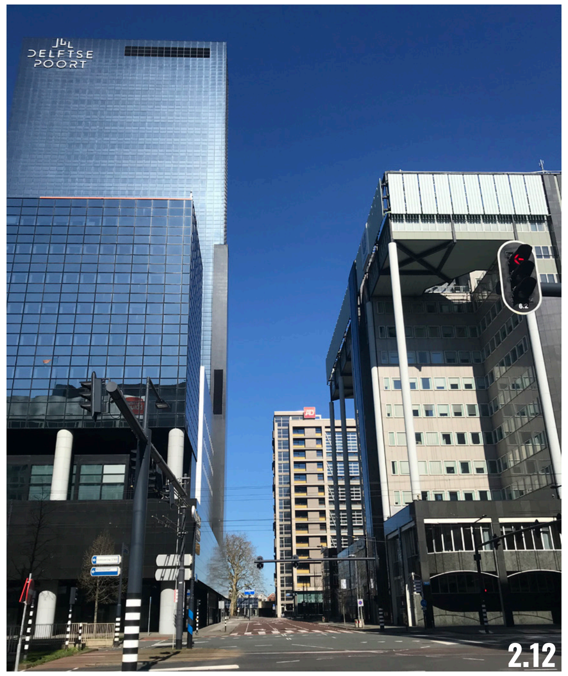

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2.5 CLASSIFICATION URBAN SCENARIO'S

The geometrical properties of the two neighborhoods are shown below in tabel 2.1. Concluding from these observations in street geometry, pattern and configuration of two different local climate zones can be distinguished in Kralingen, LCZ 3 Compact lowrise (Kralingen 1 in tabel 2.1) and LCZ 5 Open midrise (Kralingen 2 in tabel 2.1). Both climate zones have their typical properties illustrated in table appendix B.

In the Cool district, one climatic zone can be distinguished which is LCZ 1 Compact highrise, see plan view and images above. This climate zone has its typical properties illustrated in table appendix B, such as mean height >25 m, canyon aspect ratio >2 and building plan fraction 40-60%(see tabel 2.1).

For further research, the neighborhood of Kralingen will be studied since this neighborhood is representative for neighborhoods in The Netherlands. As explained above, Kralingen consists of two different LCZ's which contain a variety of common neighborhood typologies in The Netherlands, see figures 2.6-2.10. LCZ 1 on the other hand, which is found in Cool District, is a more rare typology in The Netherlands.

Neighborhood	Building plan fraction %	Impervious plan fraction %	Canyon aspect ratio H/W	Mean building hight (m)
Kralingen 1	60	20	1	+/- 7.5
Kralingen 2	37	20	0.5	+/- 13
Cool district	50	35	2.2	+/- 50

Tabel 2.1 - Selected neighborhoods in Rotterdam and their properties

2.6 NEIGHBORHOOD PROPERTIES

For comparison of the two climate zones in Kralingen the differences must be stated. As mentioned before, the different zones describe different micro- and local climates (temperature, moisture and wind). The two climate zones of the neighborhood of Kralingen are simplified in the image below, figure 2.15-2.16. In table 2.1, an estimation of the geometric properties are illustrated.

Urban cover

The lowrise and midrise zone both have the same amount of impervious plan fraction, though the building plan fraction in the lowrise area is much higher, leaving little space for vegetation. In other words, the vegetation fraction cover is much higher in the midrise area.

Length scales

The canyon aspect ratio is much higher in the lowrise area compared to the midrise. This is mainly due to the building spacing (W) which is much higher in the midrise area.

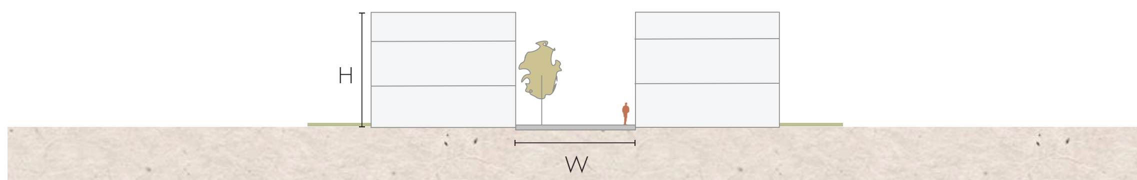


Figure 2.15 - Scheme of street profile in LCZ 3 - lowrise

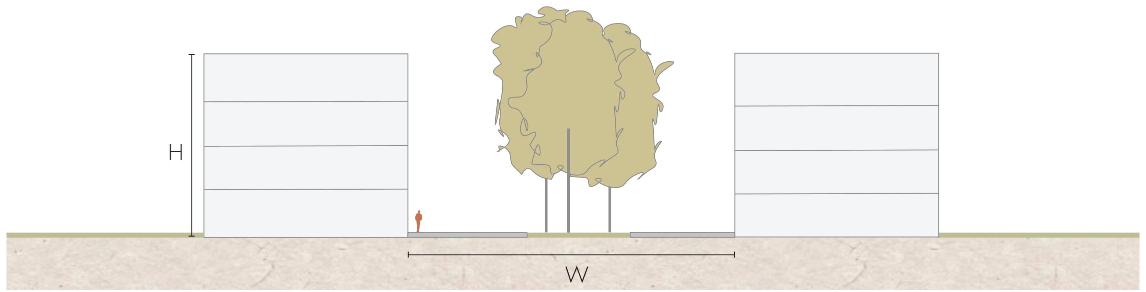


Figure 2.16 - Scheme of street profile in LCZ 5 - midrise

FIELD SURVEY

Chapter 3

FIELD SURVEY

In order to validate growth factors and limits described in literature, a field survey is conducted. In this chapter the conducted field survey will be described. The case study area Kralingen, as described in chapter 2, will be used for the field survey.

3.1 HYPOTHESIS

As analysed in chapter 2, there are two different local climate zones in Kralingen; LCZ 3 Compact lowrise and LCZ 5 Open midrise. For the field research two areas are selected which are most representative for their LCZ and comparable in building orientation and surface area. The two analysed areas are depicted in the figures 3.1-3.2. In the areas the cases of bryophytes on stoney materials are documented.

As described in chapter 2, the lowrise area has a high building plan fraction, low pervous plan fraction and a higher canyon ratio compared to the midrise area. These urban characteristics make the area more prone to UHI. As mentioned in literature review, temperature is one of the important limiting factors in bryophytes since it influences the water economy and photosynthesis. The decrease in vegetative cover also influences humidity levels in the lowrise area. Low humidity levels have a negative impact on bryophyte growth, making the area less favourable for bryophytes. At last, the vegetation in the street profile in the midrise area creates more shading. This decrease in solar radiation reaching the ground surface will positively influence the bryophyte growth.
Based on these observations, the hypothesis is formulated as follows; *The bryophyte growth in the midrise area will be more abundant.*

The full field survey is documented in Appendix D.

Field observations date from 22/01/2020 - 24/01/2020 - 11/02/2020 - 14/02/2020

Figure 3.1 - Area LCZ 5 - midrise, building blocks highlighted.

Figure - 3.2 Area LCZ 3 - lowrise, building blocks highlighted.

3.2.1 OBSERVATIONS LCZ 5

LCZ 5 area 1

In the appendix D page 118 the first area of the survey is documented, the findings are systematized in the left side, central part and right side of the street. A selection is shown in the figures 3.3-3.8. By comparing the street sides, the following observations are noted:

+ Generally, less abundant growth is present on the south-east facing side than on north-west.
+ In the central reservation the south facing surfaces show the least growth, north facing surfaces most growth, then north-east facing and thereafter south-east facing surfaces.
+ More vertical bryophyte growth on the north-west compared to south-east, on one spot next to rainwater pipe(see figure 3.4).
+ Largest moss growth patches can be found on the central part or north-west area.
+ Bryophytes show no decolorization.
+ Bryophyte growth in cracks and niches(figure 3.3).

LCZ 5 area 2

In the appendix D page 121 the second area of the survey is documented, the findings are systematized in the left side, central part and right side of the street. A selection is shown in the figures 3.3-3.8. By comparing the street sides, the following observations are noted:

+ In the central reservation north-east facing surfaces show more growth than south-east facing surfaces(figure 3.5 and 3.8).
+ Less abundant growth on the south-east facing side than on north-west.
+ Most vertical growth can be found in the central part, in other areas little vertical growth can be observed.
+ One patch in the south-east facing area shows decolorization.

Comparison

From the analyses of these two areas the following can be concluded:
+ In both area's the north-west facing surfaces show more growth than the south-east facing surfaces.
+ In the central reservation the bryophyte growth is most abundant in both areas.
+ The bryophyte growth in area 1 seems more abundant than in area 2.
+ In area 1 more vertical growth is observed than in area 2.

Conclusions

+ On north-west facing surfaces the bryophyte growth is more abundant compared to south-east facing surfaces.
+ Bryophytes prefer horizontal surfaces over vertical surfaces.
+ In area 1, the conditions for bryophytes are more favourable than in area 2.
+ Bryophyte growth in cracks and niches(figure 3.3 and 3.7).
+ If the growth conditions are better for bryophytes they show more vertical growth.

Figures 3.3 - 3.8 - Edited photographs of bryophyte growth from LZC 5, taken during field survey.

3.2.2 OBSERVATIONS LCZ 3

LCZ 3 area 1

In the appendix D page 124 the first area can be found. The findings are systematized on the left side and right side. A selection is shown in the figures 3.9-3.14. From the comparison the following observations are noted:

+ Some of the patches in this area show decolorization.
+ On the north-west side one vertical spot is more moisturous (next to air outlet) and rough surface, see figure 3.9.
+ North-west surfaces show more growth than south-east facing surfaces.
+ South-east facing surfaces show no vertical growth.

LCZ 3 area 2

In the appendix D page 126 the second area can be found. The findings are systematized on the left side and right side. A selection is shown in the figures 3.9-3.14. From the comparison the following observations are noted:

+ Some of the patches in this area show decolorization, see figures 3.9 and 3.11.
+ North-west surfaces (figure 3.12) show more growth than south-east facing surfaces.
+ South-east facing surfaces show no vertical growth.
+ On the north-west side one vertical spot on a more moisturous and rough surface (next to the air outlet), see figure 3.10.
+ Low area of north-west facing surfaces more abundant bryophyte growth; next to open area.
+ Bryophyte growth in cracks.

LCZ 3 area 3

In the appendix D page 128 the third area can be found. The findings are systematized on the left side and right side. A selection is shown in the figures 3.9-3.14. From the comparison the following observations are noted:

+ Some of the patches in this area show decolorization.
+ North-west surfaces show more growth than south-east facing surfaces.
+ South-east surface shows vertical growth in a shaded area, see figure 3.13.
+ Low area of north-west facing surfaces more abundant bryophyte growth; next to open area. See figure 3.14.

Comparison

+ Area 1 least favourable for bryophyte growth.
+ Surfaces next to green areas show more bryophyte coverage than elsewhere.
+ In both area's the north-west facing surfaces show more growth than the south-east facing surfaces.

Conclusion

+ On north-west facing surfaces the bryophyte growth is more abundant compared to south-east facing surfaces.
+ Surfaces next to green areas show more bryophyte growth.
+ Bryophytes prefer horizontal surfaces over vertical surfaces.
+ If the growth conditions are better (rough surface, moisture availability) the bryophytes show more vertical growth.


3.9


3.12


3.10


3.13


3.11


3.14

Figures 3.9 - 3.14 - Edited photographs of bryophyte growth from LZC 3, taken during field survey.

3.3 GENERAL CONCLUSIONS

Comparison LCZ 5 and 3

Comparing the LCZ 3 with LZC 5, it becomes obvious that there is more bryophyte growth in LCZ 5. Furthermore, the bryophytes patches present in this area are larger in area and thickness, and the patches show less decolorization as in LCZ 3. Therefore, the hypothesis as stated in the beginning of this chapter, *the bryophyte growth in the midrise area will be more abundant*, is proven to be true.

Conclusion LCZ 5 and 3

From the field observations the characteristics of the bryophyte conditions can be derived.

+ More vertical bryophyte growth is observed on rough surfaces.

+ As suspected from literature review, solar radiation is important in bryophyte growth. Bryophytes are better adapted to low light conditions. In the field survey the difference is observed between surfaces facing different orientations; where north is most favourable and south the least. Furthermore, bryophyte growth is observed on shaded surfaces in the two neighborhoods.

+ Bryophytes prefer moist areas as stated in the literature review as well(figure 3.4).

+ Bryophytes prefer horizontal surfaces over vertical surfaces. This observation is associated with moisture as well (on vertical surfaces water runs off more easily) but also gravity on the bryophytes plays a role in this aspect. It seems as when the growing conditions are more suitable for bryophytes, more vertical growth is observed.

+ Bryophytes grow more abundantly next to green areas.

These conclusions are visualised in the following scheme, figure 3.15.

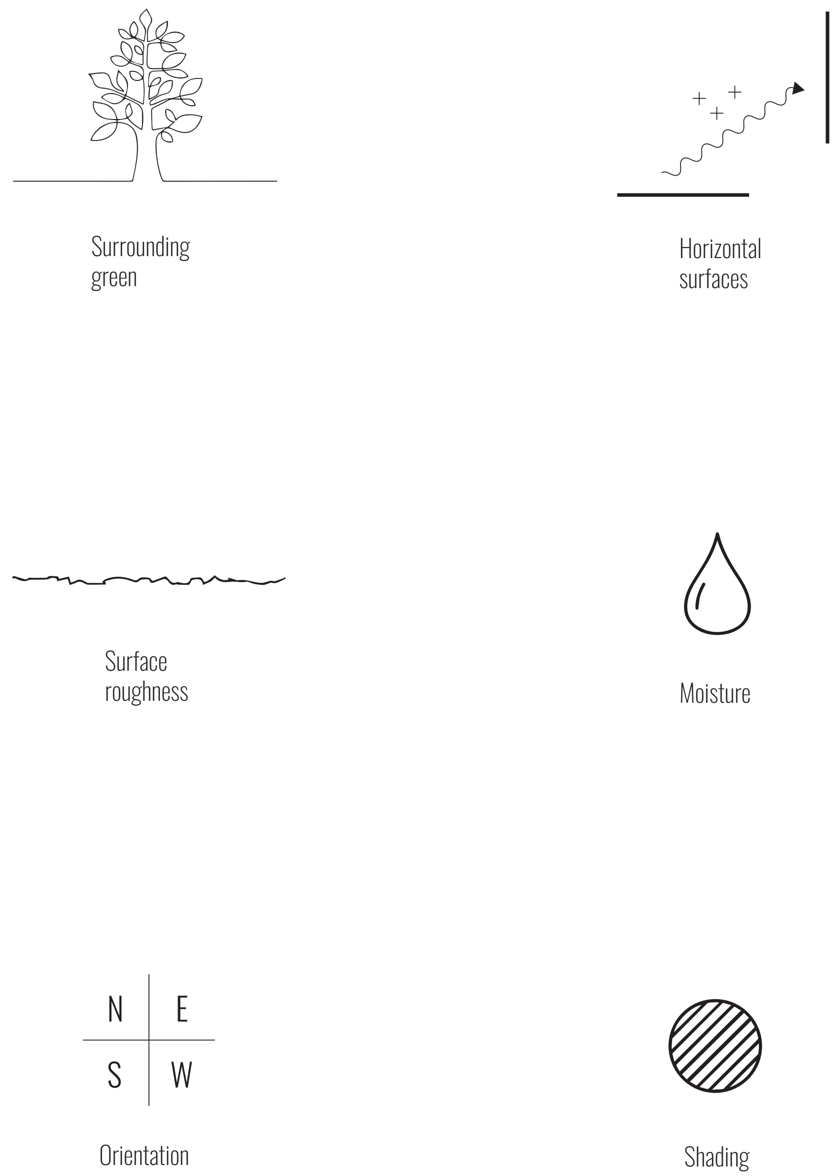


Figure 3.15
Scheme of main habitat characteristics derived from field survey

DESIGN TOOL

Chapter 4

DESIGN TOOL

In this chapter, the results of the bryophyte growth analyses (field survey + literature) will be used to develop a design tool. At first the design factors are elaborated in order to use them as a design tool for the geometry. As well a specific location will be selected for the panel design.

4.1 LOCATION

A more specific location is needed for the design since the microclimate influences the design factors. For the design the 'worst case scenario' location is chosen in Kralingen, this means a south-west facing facade in LCZ 3, in order to design a panel which is applicable in the whole neighborhood. See figure 4.1. The facade is pointing 22,5 degrees to east (if north is 0). One representative building facade is chosen as a specific design site, this will be further elaborated later on.

Figure 4.1 - Design location highlighted by two building blocks.

4.2 BRYOPHYTE FACTORS

Surrounding green

The presence of surrounding green has a positive effect on bryophyte growth. In this case a specific location is chosen to implement the design, ruling out the influence of this factor. The design site is characterised by low vegetation fraction (see table 2.1, section 2.5).

Surface angle

Bryophytes prefer horizontal surfaces over vertical surfaces. In the design the angle of the surfaces preferably are as low as possible (0 degrees for horizontal, 90 for vertical). Surface angle also influences moisture, which will be discussed next. Since surface angle is also implemented in moisture and radiation, it won't be discussed as a separate factor.

Moisture

Moisture is one of the main design factors for bioreceptive facade panels, as stressed in the previous chapters. The factor moisture has influence in different scales, as will be elaborated below.

Surface roughness
Surface roughness influences the moisture content of the panels on a mesoscopic scale. The porosity of the concrete is a material property which can create small water 'pockets' on the surface that hold water. The panel design on such small scale is beyond the scope of this research, for the design will be given that a concrete mixture creating a rough surface will be used.

Moisture by geometry
On a larger scale the surface shape influences moisture on the panel. Water runoff from building facades is a complex phenomenon induced by multiple urban, building, material and meteorological parameters. Field observations indicate that surface soiling patterns generally show quite a uniform wetting surface, although it has been reported that runoff tends to occur in streams. Instabilities are visible as fingers and do not extend from top to bottom on the facade surface(Blocken, Derome, & Carmeliet, 2013).

The shape of the panel can influence the ability of the surface to retain water. This is best described in section through the panel (figures 4.2-4.3), where different surface shapes and water runoff is shown. The geometry can create water pockets, as visible in section 3 in figure 4.2; the geometry can retain volumes of water trapped on the ledges of the facade panel. The relation of moisture and surface angle is also visible in this image; the water retention ability is induced as more surface angle is equal to 0(horizontal). Furthermore, the influence of the typology of the geometry (section 1 and 2 in figure 4.2) is made obvious.

By altering the surface geometry of the panel, the rainwater won't form a uniformly wetted surface. The 'water path' through the panel can be described in plan view of the facade panel(figure 4.4). Extending the water path means the panel will retain water longer and increase the area in which water is in contact with. The downside of this is that too much current in the panel might affect the bryophyte growth negatively.

Additional irrigation system
Additional irrigation is presumed necessary for bryophyte facade panels, as discussed in section 1.3 Defining the amount of irrigation needed can be derived from field studies of the (later on) designed panels. Unfortunately, such field tests do not fit within the time frame of this research.

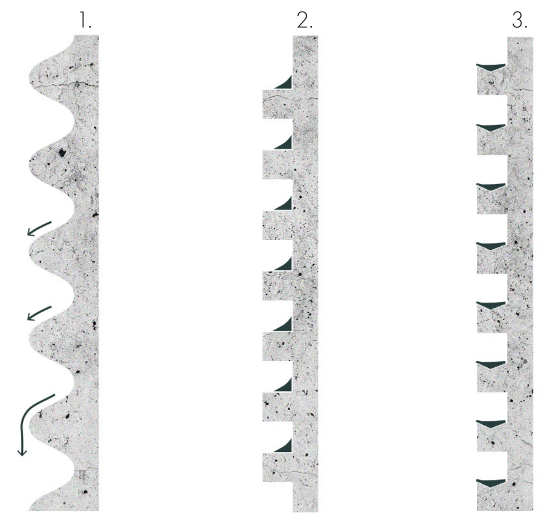


Figure 4.2 - Moisture strategy in vertical section

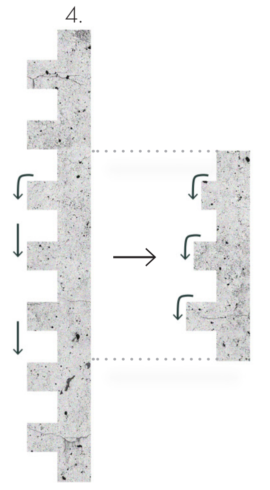


Figure 4.3 - Moisture strategy in vertical section

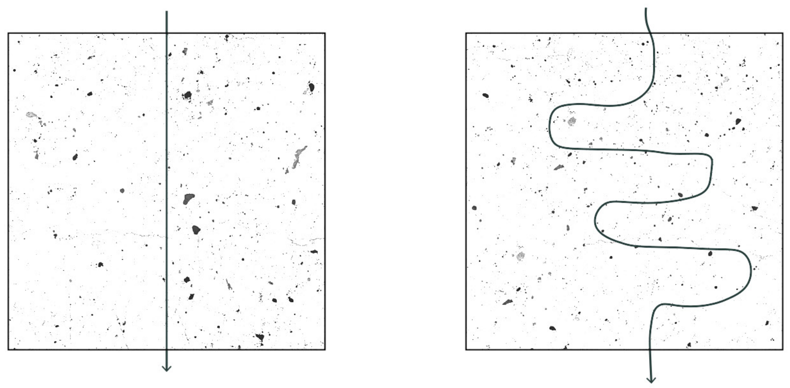


Figure 4.4 - Moisture strategy in plan view

Solar radiation

Solar radiation is an important aspect in bryophyte growth and can be categorized in three variables; context, orientation and shading. In further research, the sun hours on the facade will be calculated for 21st of June since the maximum amount of solar radiation on east and west facing facades is highest in mid summer(Stephenson, 1963) and this is also the most crucial timing in bryophyte growth since in summer humidity levels are lower, there is less precipitation and temperatures are higher. As mentioned in chapter 1, in dry and sunny weather bryophytes generally are dormant. The difference in sun hours on the facade for different seasons is also visible in the sun hour analysis, figures 4.5-4.8. The analysis is performed using Ladybug plug-in for Rhinoceros. The Ladybug script of the radiation analysis shown in appendix E, page 130.

Context
The context geometry of the facade influences the sun hours reaching the facade and can differ per location of the facade panel, see figures 4.5-4.8. The street canyon ratio, orientation of the street and the presence of trees are important factors of the context. In this case the street canyon ratio numbers 1 and the building facade is facing 22.5 degrees east (if north is 0). The height on the building is important in terms of sun hours and is site specific. One representative building is chosen in the street, as visible from figures 4.5-4.8 the building is representative in terms of solar radiation in this specific street(the specific building is marked with a white triangle).

Orientation
Orientation is the second factor influencing radiation amount. The chosen facade of the site has a fixed orientation but the panel orientation can be altered and the orientation of the panel surface. This changes the amount of sun hours reaching the panel and can be used to reduce it.

Shading
The surface geometry of the panel can be altered to cast shade on its own surface, this is called self shading. Self shading geometries reduce the amount of sun reaching its surface. This effect can be measured in sun hours reaching the panel. The self shading quantity of the panel geometry is associated with panel depth.

Analysis
As observed during the field survey (figure 3.13), vertical bryophyte growth is present at the design location. In appendix F the radiation analysis of the observed spot is shown, which is a shaded surface at the site, this is also the largest bryophyte spot on a vertical surface in this area. This specific location will be used to measure the difference in sun hours by height difference.

The surface is shaded by the window frame, which overlaps approximately 3 cm compared to the shaded surface. In other words, the surface is pulled back, approximately 3 cm, compared to the facade surface. In appendix F the sun hour analysis is shown of the shaded surface. The left image shows the location of the surface (0.2 m height) and the right image shows the radiation amount. The surface reaches <4.80 sunhours on a day. The top part (where bryophytes growth is observed) even <3.60. This also matches with the 'few hours of sun' a day - as mentioned in chapter 1 - for bryophyte species that are known to be better resistant to solar radiation. If the pulled back surface is located higher on the building (the same three centimeters depth is chosen), the amount of fully shaded area decreases.

This analysis substantiates the previous statements about the 'few' sun hours bryophytes can withstand throughout the day. These values will be used later on when the radiation amount on the panel designs will be assessed. Furthermore, the analysis shows the influence of the height on the building on the radiation amount in the design location.

In the previous, the design factors which accommodate bryophyte growth in a facade panel design are described separately. These factors often lead to contradictory outcomes in terms of shape, see figure 4.9. This image depicts that downward facing surfaces are shaded and more visible, but less preferable because of the moisture retention and surface angle. Preferably, the shaded areas in the panel design are most horizontal, visible (which will be discussed later on) and moisturous.

Figure 4.5 - Radiation analysis design site, 21th of June

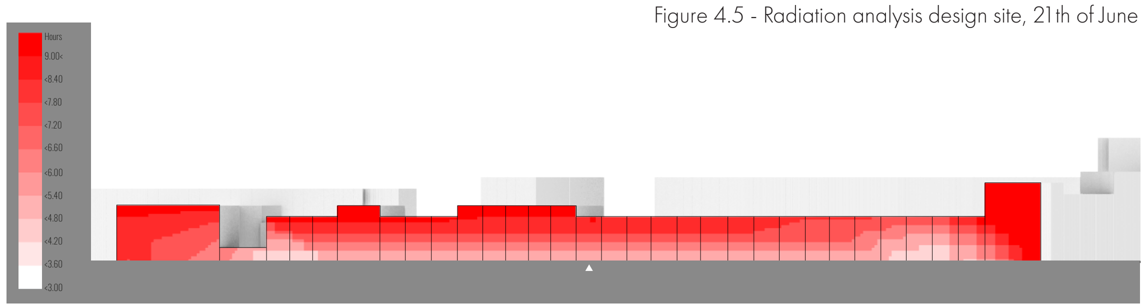


Figure 4.6 - Radiation analysis design site, 21th of September

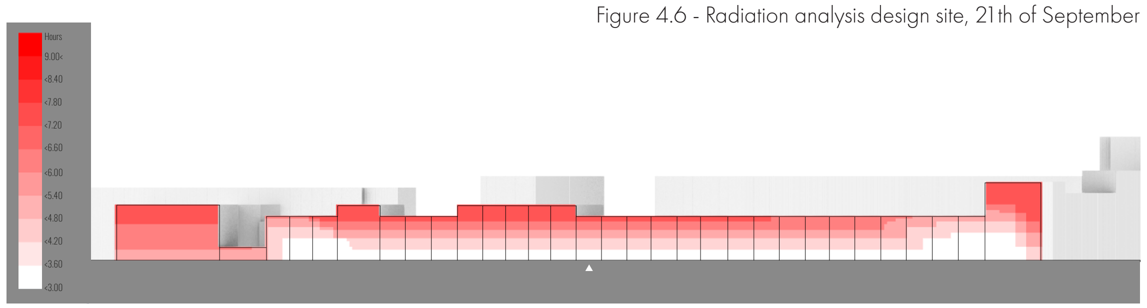


Figure 4.7 - Radiation analysis design site, 21th of December

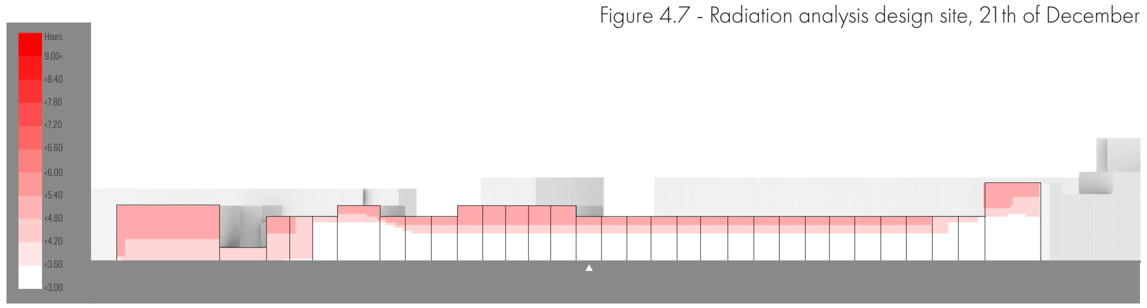
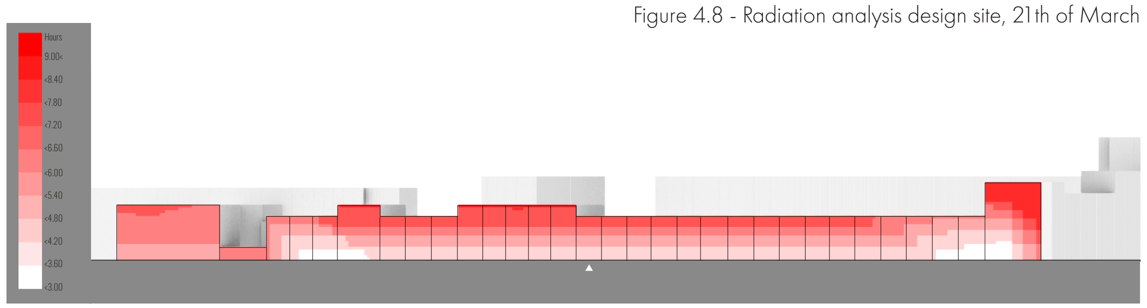


Figure 4.8 - Radiation analysis design site, 21th of March



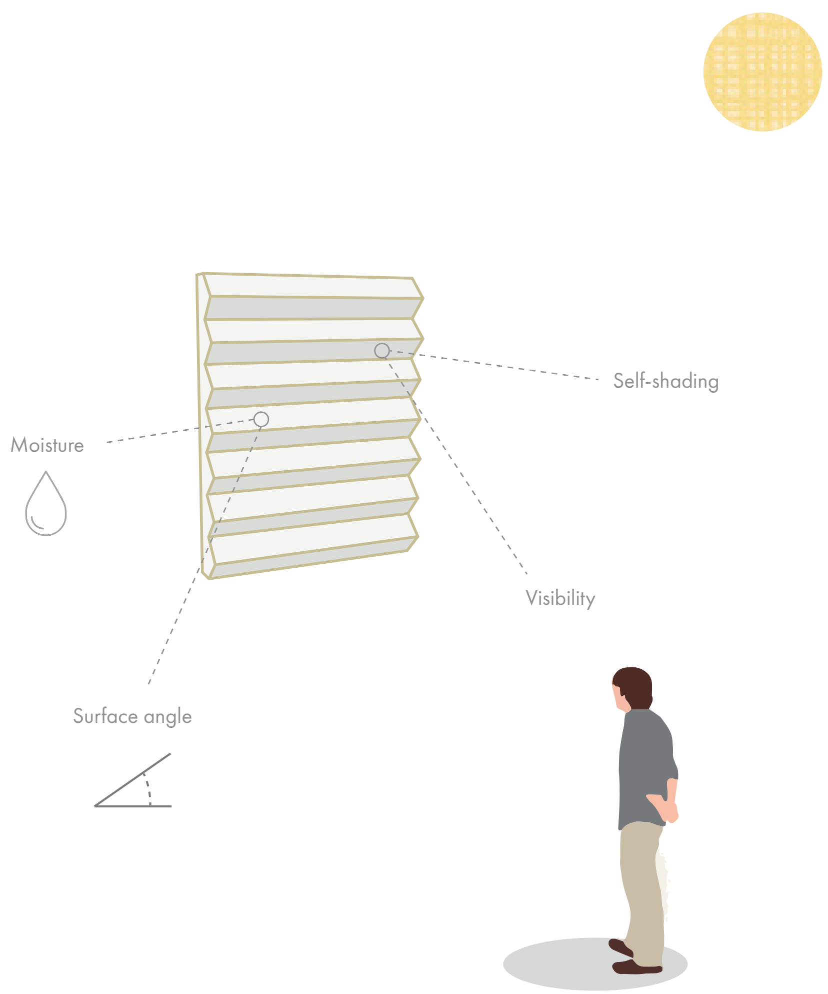


Figure 4.9 - Contradictory design factors for the panel design.

4.3 DESIGN FACTORS - AESTHETICS

Besides the design factors to provoke bryophyte growth on the panels there are also design factors relating to the aesthetic aspects, which need to be considered for the geometry design.

Panel typology

The panels are part of a panelized facade system, as further elaborated in chapter 6. The panels are casted concrete elements, limiting the geometrical possibilities of the surface. The panel geometry needs to be designed in such manner that it allows for unmoulding after the casting process. Due to these limitations for example the shape of section 3, figure 4.2, is not possible.

The intrinsic properties of the concrete is, besides climatic conditions, another factor in bioreceptive facade panel development. This is beyond the scope of this research.

There are also limitations in the thickness of the panels. The panels have a minimum thickness of 130 mm (measured from shallowest point in the panel) and if the panels become too thick (measured at most profound section) the facade becomes heavy. The maximum thickness also depends on the shape on the panels. In general can be stated a thickness of 10 cm shouldn't be exceeded.

Visibility

The visibility of the moss growth on the panels is of importance since preferably the facade system is perceiced as green. Increasing the panel depth decreases the visibility of the bryophyte growth on the panels. Especially the panels at the top of the building are challenging since they are less visible (angle from bottom to top increases). The visibility of the moss growth is perceived differently - because of the geometry - from the front of the building or from the sides. Therefore, the visibility on the bryophytes needs to be considered from the different angles; top-bottom and from the sides.

Personal sensitivity

The aesthetical preferences of the designer dominate the design decisions in terms of geometrical typologies, for example whether the shapes are geometric or organic forms. The panel design also includes the design of the facade as a whole, whether the facade pattern is horizontal or vertical and the type of pattern created by the panels together on the facade, for example a randomised or regular pattern.

Coverage

The panel coverage is the presumed amount of panel surface being suitable for bryophyte growth. The coverage of the panel is important in terms of effectivity of the panel; coverage increase means an increase of the benefits of bryophyte facade panels. The coverage of the designs will be further elaborated in the next chapters.

4.4 DESIGN STRATEGY

The order of applying the different design factors will influence the final result, since some of the factors have contradictory outcomes in terms of shape, as visualized in figure 4.9. Therefore a hierarchy in the factors needs to be applied, creating a stepwise design tool. At first, the design concept is described. This relates to the initial geometry and the aesthetics of the panel. The initial design concept influences all decisions concerning geometrical typology. After the design concept, moisture is the first factor. Since the 'base' geometries (which will be described in the next chapter) initially are both self-shading shapes thus radiation is already implemented, the factor moisture is implemented first. After moisture, the radiation on the surface is analysed and the shaded surfaces assessed. At last, visibility and the coverage of the mossess on the panel have a final say over the geometry, since preferably the panel is perceived as a 'green' facade. The factor surface angle is not seen as a separate factor, since it will already be discussed in moisture, radiation and visibility.

[1] Design concept
[2] Moisture
[3] Radiation measurements / shading assessment
[4] Visibility
[5] Coverage

PANEL DESIGN

Chapter 5

PANEL DESIGN

In this chapter, the design factors are used as a design tool to create a bioreceptive facade panel for the neighborhood of Kralingen. As mentioned previously a specific building location is chosen, the 'worst case scenario', in order to design a panel applicable in the neighborhood of Kralingen. Two different panels will be designed and assessed on their applicability.

5.1 GEOMETRICAL POSSIBILITIES

The two different panel designs originate from two different 'base' geometries, derived from the initial design concept; one vertical continuous pattern and the other horizontal continuous, see figure 5.1-5.2. Both geometries are a self shading shape, but due to their difference in configuration the shading ability of the panels takes place under different light inclinations. The two geometries create a different pattern on the facade; one vertical and the other horizontal. These geometries are altered according to the design factors, as is described in the previous chapter.

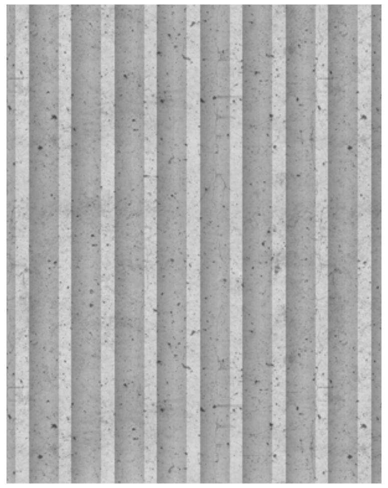


Figure 5.1
Base geometry 1

Figure 5.2
Base geometry 2

5.2 PANEL 1 HORIZONTAL CONTINUOUS

[1] Design concept

In forests bryophytes often grow vertically on tree bark, which forms the inspiration for this panel design. A tree bark is a self shading geometry due to the ribbed surface. The shading ability of the panel is mostly during lower sun which reaches the panel under an inclined angle(from the sides). This inspiration for the panel dictates an organic geometry typology for this panel design, see figure 5.3. Therefore the vertical lines on the panel will be described by a curvature instead the straight section as shown in fugure 5.6.

Figure 5.3 - Shading in tree bark (Pinterest, 2011)

The shape is described by two lofted sine curves(lofted in vertical direction) with both the same starting point. In table 5.1, the frequency and amplitude of this curve are described (curve 1). See appendix G for geometry script of the final panel design.

[2] Moisture

In terms of moisture retention capacity, this shape performs very poorly; if this shape is considered in vertical section the surface is flat. Trying to improve this shape organically in vertical section will not make a significant difference; the surface will be shaped like figure 4.2 (section 1), see figure 5.6 for the moisture geometries. However, the surface angle created by this variation will change in favour of the bryophytes. The curvature in moisture option 3(fugure 5.6) is such that instead of a vertical continuous pattern, a 'block' pattern is formed. Moisture option 3 can be an interesting geometry but it is not representative for a vertical continuous pattern and the design concept, this variation won't be elaborated further. Additionally, a discontinuous curvature pattern in vertical section can be created - the moisture effect as shown in figure 4.3 - but due to the organic shape the water still easily runs off.
In plan view this shape also behaves poorly in terms of moisture retention, see figure 5.4. The water path through the panel could be prolonged by altering the horizontal flow in plan view by 'zigzagging' the section curve from top to bottom in an organic manner. In other words; the section of the panel is swept along a sine curve instead of a straight line(rail curve). See figure 5.5 for this variation. In appendix G the Grasshopper script of this panel is shown. This variation also changes the surface angle, partially in favour of the bryophytes.

The amplitude and frequency of the curvature describes the extension of the water path through the panel. Increasing the amplitude or frequency increases the path. Several variations are created by defining the rail curve differently. See table 5.1 for the properties of curve 2 in these variations. In appendix H the plan view of the variations are found. The water path length is described by the curve length of the rail curve. In terms of moisture, variation 8 will be performing best (longest path) where the water path has increased with almost 50% compared to the previous variation (panel 1). As visible in table 5.1, both amplitude and frequency have a linear relation to water path; increasing the frequency of the rail curve has the greatest impact on the water path extension.

[3] Radiation measurements / shading assessment

Radiation

For the eight variations described under 'moisture', the radiation analysis is performed. The input of the analysis is similar to the input of appendix F, the results can be found in appendix H. In the table 5.1 the total amount of sun hours per variation is given. From the table it can be concluded that solar radiation doesn't have a linear correlation with changing amplitude or frequency of the rail curve in this geometry. The total sun hours of variations 1 and 2 are similar, despite the increase in amplitude and in variation 7 and 8 the total sun hours are also similar despite the increase in amplitude. It seems that there is a range where amplitude and frequency influence the sunhours on the surface in the given simulation setting. In terms of sun hours variation 7 or 8 perform best; their average radiation values are lowest.

Shading assessment

The surfaces that are shaded on panel 7 compared to panel 1 are at the locations where

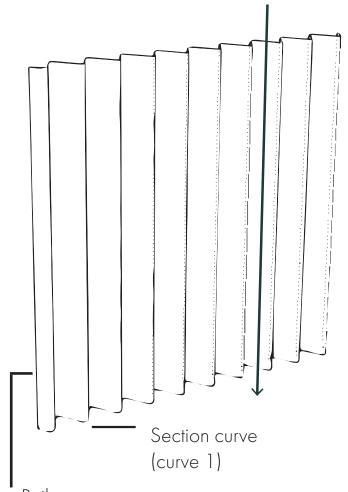


Figure 5.4
Geometry description

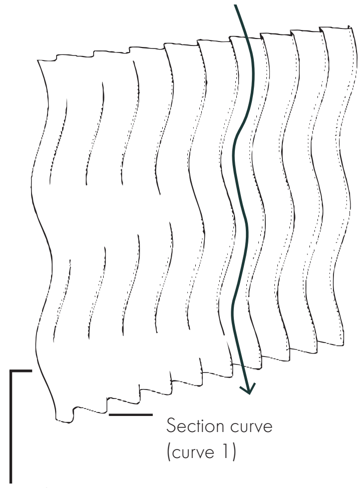


Figure 5.5
Geometry description moisture variation

Variation		01	02	03	04	05	06	07	08
Curve 1	A	30	30	30	30	30	30	30	30
	F	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Curve 2	A	0	20	30	40	10	20	30	40
	F	0.02	0.02	0.02	0.02	0.04	0.04	0.04	0.04
Length	(mm)	500	537	586	630	516	644	725	884
Radiation	(h)	2.62	2.59	2.20	1.79	2.39	1.66	1.49	1.47

Table 5.1- Geometrical properties and analysis, variations panel 1-8

the rail curve bends left, see appendix H for radiation analysis. Both on top and bottom of the curve. This means that part of the shaded surface is facing upwards and the other part of the surface faces downwards. The downward facing surface is less favourable due to gravity for the mosses to grow. About 50% of the shaded surface is more optimal for mosses compared to variation 1, where the shaded surfaces are vertical.

[4] Visibility

The panel geometry (variation 1) enables the passer-by to observe the full panel whilst standing in front of it. Less becomes visible on the panel when the panel is perceived from the sides. The zigzagging pattern of the variations decrease visibility on the bryophytes. The pattern blocks the view whilst standing in front of it when the panel is placed above or below eye level. The same decrease in visibility occurs in the zigzagged variation compared to variation 1 when the panel is perceived from the sides. In terms of visibility variation 1 performs best, an increase in curvature of the zigzag pattern decreases visibility on the mosses.

[5] Coverage

Due to the zigzagging pattern there are downward facing surfaces and also more upward facing surfaces. The zigzagging pattern causes some spots to be more favourable for moss coverage and others to be less compared to variation 1. In terms of coverage one of the medium zigzagged patterns are preferred since in these variations the angle of downward facing surfaces are lower.

Optimal panel variation

If all factors influencing bryophytes growth and the panel aesthetics are assessed, panel 6 is presumed to perform best. In terms of moisture the water path is increased with about 15%. Panel 8 would have performed best in terms of moisture but due to coverage and visibility reasons this variation is less favourable. Also in terms of solar radiation panel 7 or 8 would perform best, but panel 6 has minor difference with the best performing variations.

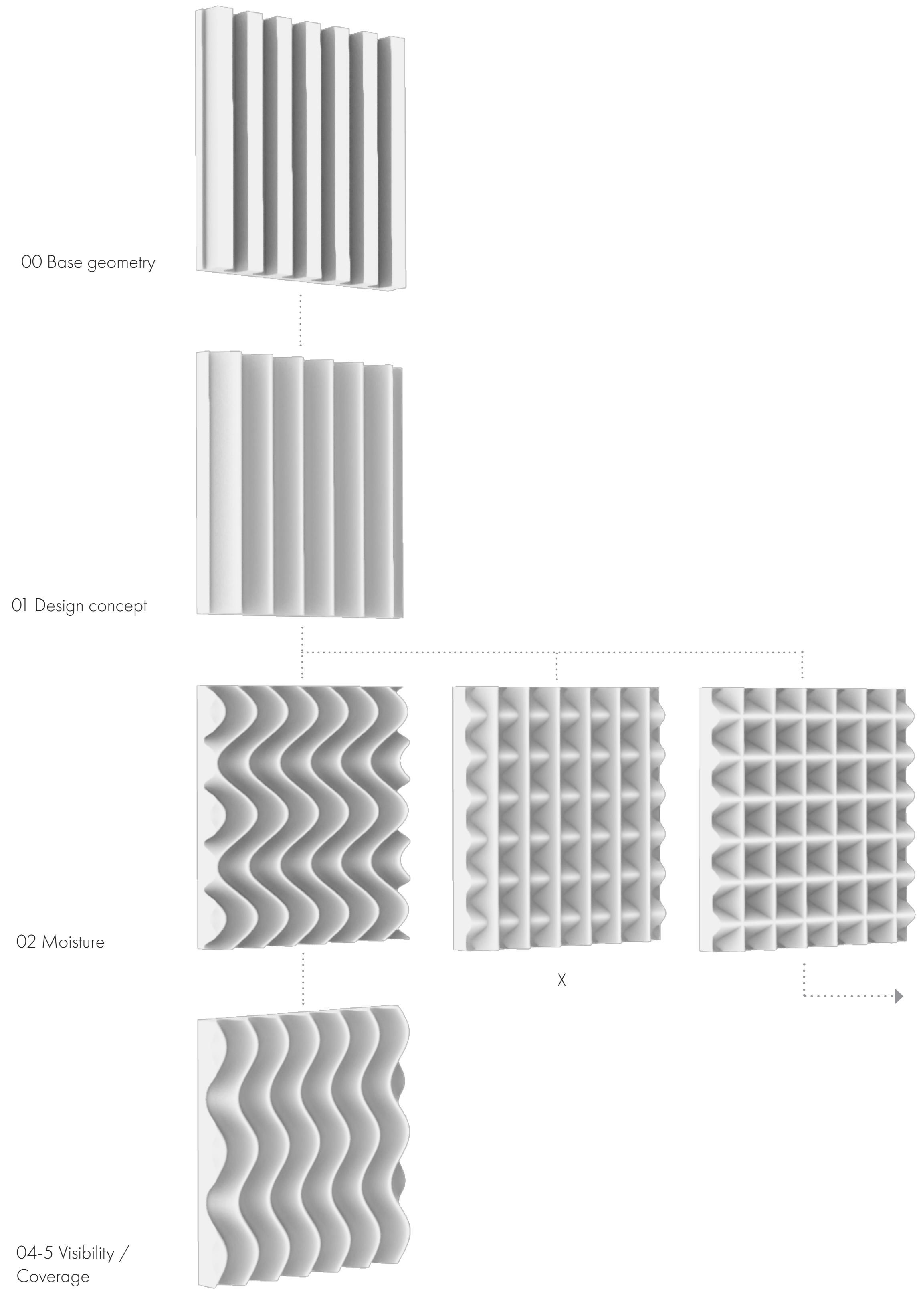


Figure 5.6 - Scheme panel geometry variations

5.3 PANEL 2 VERTICAL CONTINUOUS

[1] Design concept

The shape of this panel is inspired by the field survey observations. In multiple locations moss growth was observed on ledges of stones. One of which is shown in figure 5.7. These ledges are recreated in this panel type, creating shaded areas in the panel simultaneously.
Two different variations for the section of the ledges on this panel are created based on field observations obtained during the field survey. The ledges are described by three dimensions; h, b1 and b2 (see figure 5.8). The patches growing on ledges all have around 2-3 cm thickness, this means h is approximately 2-3 cm. Increasing h more than 3 cm would mean there is more material needed and less visibility, without more possible bryophytes growth on the panel. B1 is preferably kept as small as possible, since this surface area is fully exposed to the sun. However, the ledges can't be too slim; this would make the panel fragile and it makes the horizontal continuous pattern less visible. B2 is preferably around 4 - 5 cm in length since not more vertical growth is observed in the field survey above ledges (figure 5.7). The two panel variations are illustrated in figure 5.8.

Figure 5.7 - Bryophytes on ledges, taken during field survey

Variation 1: h=20 mm, b1= 25 mm, b2=40 mm
Variation 2: h=30 mm, b1=30 mm, b2=50 mm

[2] Moisture

The moisture retention capacity of this shape is performing better in section compared to the 'base geometry' of panel design 1, see figure 4.2 (second section). The shape could be improved by the following figure 4.3. This variation extends certain ledges on the surface to prolong the water path through the panel. Another way of doing this, without altering the panel depth too much is as described in the figure 5.10. In this variation the curvature of the ribs is altered, creating a dripping pattern in plan view of the panel when the water moves sideways. Figure 5.10 depicts the water flow.
The curvature of the ribs is described with a sine curve. The amplitude of the curve possibly influences radiation. Additionally, the ledge height (h) is preferably minimum of 2 cm(in order to support a moss patch), which means the amplitude has per panel variation a maximum. For each of the variations, two different amplitudes are tested on their shading ability. The sine curves of the ledges above each other are inverted; in this way, the shallowest and the widest point are always above each other, see figure 5.12 for variations.

Frequency: 47
Amplitude: variation 1= 5 and 10
variation 2= 10 and 15

[3] Radiation measurements /shading assessment

The dimensions of the 'ledges' determine the amount of sun reaching the surface. In table 5.2, the amount of sun hours on the panel variations are given, see rectangular variation 1 and 2. From the table, it can be concluded that variation 1 is a better self-shading geometry compared to variation 2. The amplitude of the surface curvature has insignificant impact on the average sun hours, solely a minor difference in radiation is measured. In terms of radiation panel variation R.1.1. / R.1.2. shades best.

[4] Visibility

The horizontal ledges block the view on the panel from the bottom (in front or at the sides) whilst the panel is placed above or below eye level. The dimensions of the ledges influence the visibility on the panel, since there is more visibility on the moss growth with a decreased h and increase b2. H and b2 describe the angle in which point A in the section, see figure 5.8, is still visible. This means if this angle is lower the visibility on moss patches is greater. The angle can be calculated with; angle = tan^-1(h/b2).

Variation 1; tan^-1(20/40) = 27°
Variation 2; tan^-1(30/50) = 31°

From this can be concluded there is more visibility on the panel with ledges shaped as in variation 1. The surface curvature of the ledges influences h as well, but due to the sine curve definition of

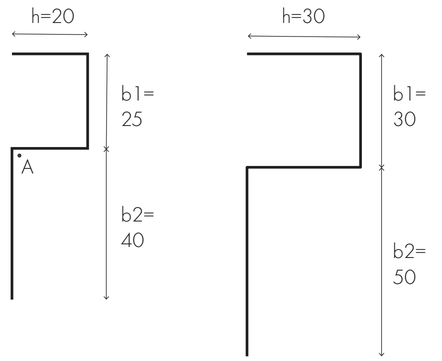


Figure 5.8- Dimensions rectangular section

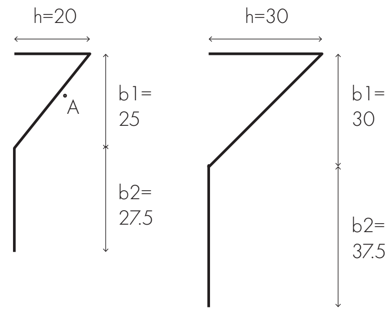


Figure 5.9 - Dimensions triangular section

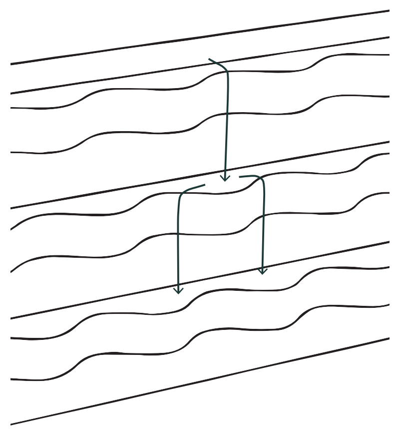


Figure 5.10 - Waterflow on panel (3D)

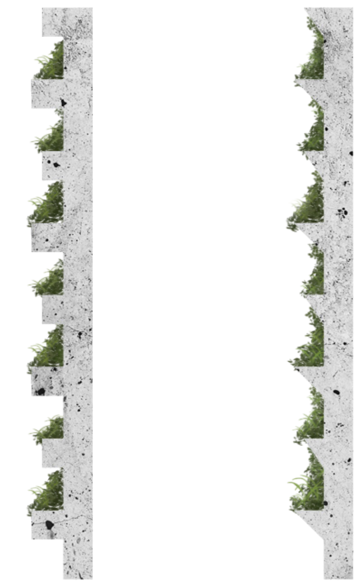


Figure 5.11 - Coverage in section

Nmr.		R.1.1	R.1.2	R.2.1	R.2.2	T.1.1	T.1.2	T.2.1	T.2.2
Section		Rectangular				Triangular			
Variation		1		2		1		2	
Amplitude		5	10	10	15	5	10	10	15
Radiation	(h)	2.10	2.14	2.32	2.33	1.77	1.76	1.90	1.91

Table 5.2 - Geometrical properties and analysis, variations rectangular (R) and triangular (T) section panels

this curvature the visibility reduction and increase equals each other out. Variation 1 is the preferred panel shape in terms of visibility on the moss patches.

[5] Coverage

The coverage on this panel is presumably not performing very well; the vertical surfaces of the ledges are likely to remain uncovered since they are fully exposed and disconnected to the moss patches. A variation of how to improve this is shown in figure 5.11. The section of the ledge has changed from a rectangular shape to a triangular one. In this variation (T) the length of b2 can be decreased simultaneously, since the bryophyte likely will grow higher. In all panel variations the b2 length is decreased by ½ b1. Additionally, in terms of visibility this panel will perform better (despite of the decrease of b2) since the mosses can grow on more surface area. The angle as described previously under 'visibility' is now different since point A will move, see figure 5.9. In table 5.2 the sun hours are measured on this variation T; it performs better as well in terms of solar radiation.

In variation T the probability that the panel will be 100% covered is higher; since the bryophytes easier grow over this section compared to the one of variation R.

Optimal panel variation

The optimal panel 2 variation is T.1.2. Variation 1 for the section dimensions is chosen because of the visibility and radiation performances. The triangular section performs best in terms of solar radiation, coverage and visibility compared to the rectangular one. See table 5.2 for exact values on the radiation analysis. Furthermore, a greater amplitude makes the curvature on the surface more visible.

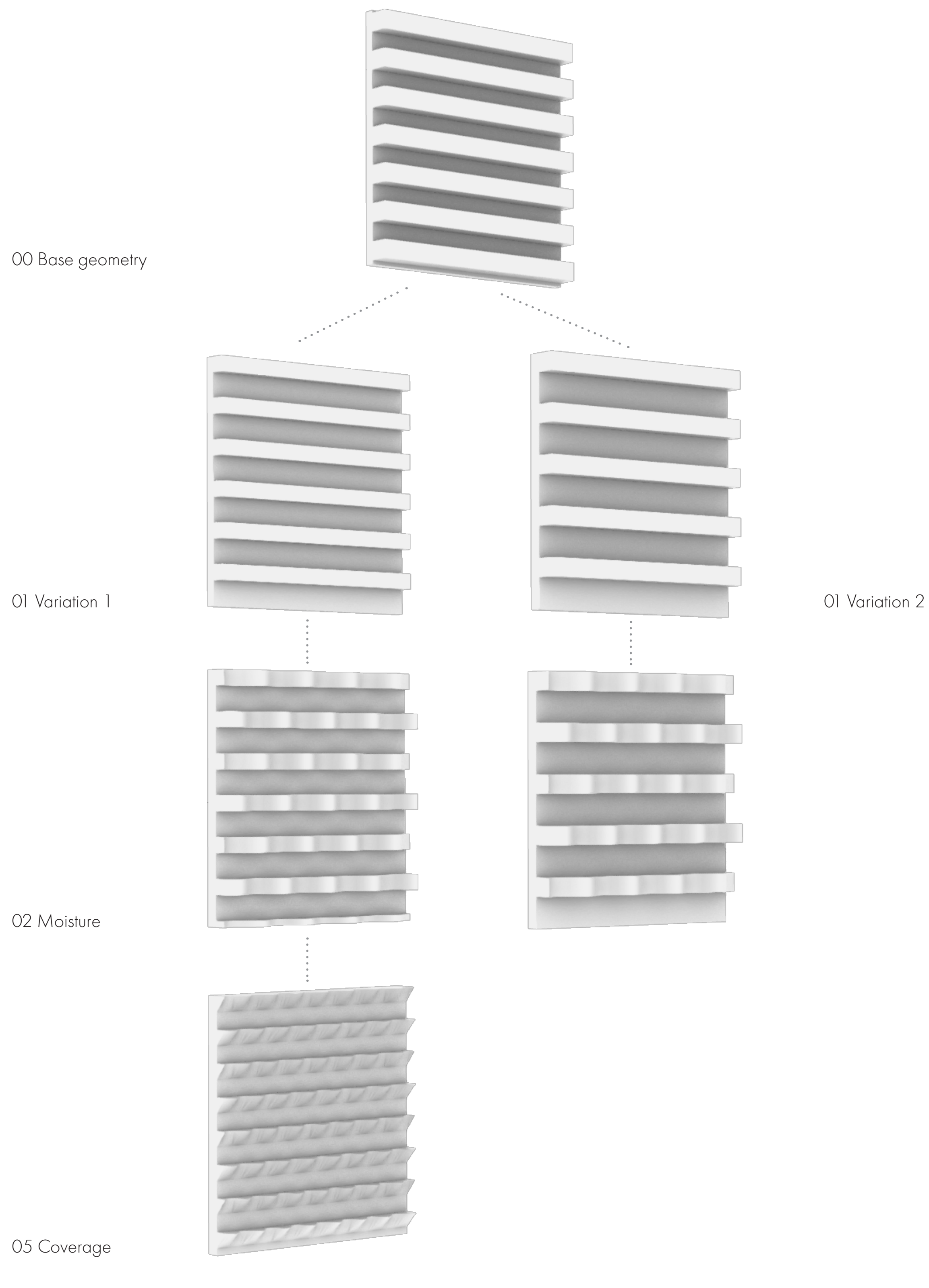


Figure 5.12 - Scheme panel geometry variations

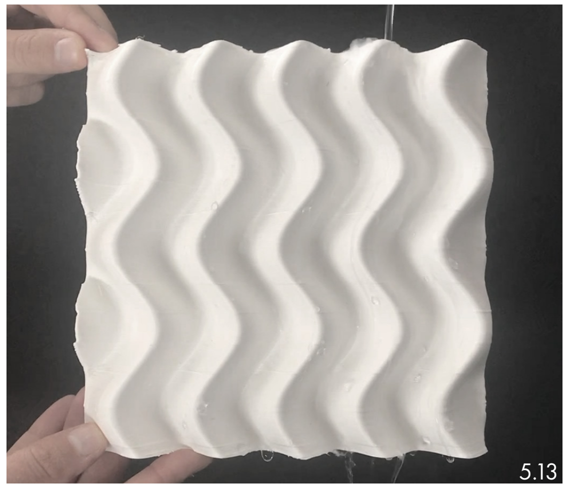
5.4 FINAL PANEL ASSESSMENT

Facade panel designs 1 and 2 are both designed for the same location and following the same design strategy, though the panels differ in initial design concept, creating two different panels. For the facade design and simulations in the next chapter the applicability of the panels will be assessed. As mentioned before the moisture retention, shading ability, surface angle and moss coverage of the panels are important for bryophyte growth on the panels. These aspects of the panels will be further elaborated and compared below.

Moisture

Both panels have an approach to extend the water path on the panel in order to hold the water for a longer time. In figures 5.13-5.19 the water flow on the panels is tested using 3D printed models of the panels. In both panel 1 and 2 the water is not moving vertically down due to the surface geometry. In a real field scenario (on a 1:1 scale) the effect of the water will be altered due to the scale difference, the mosses themselves and climatic factors. These field test do not fit within the time frame of this research though from these observation can be concluded that the geometry does extend the water flow. Especially on panel 2, it is obvious the water flows sideways figure 5.17-5.18. In panel 1 it is best visible looking at the bottom of figure 5.16, where the water is splitted in several streams. Furthermore, the model of panel 2 holds water after the watering of the panel has stopped.

Besides the capacity of the panel to retain water, the humidity levels and precipitation in the area influences the moisture on the panel. Some of these factors will be further elaborated in chapter 7.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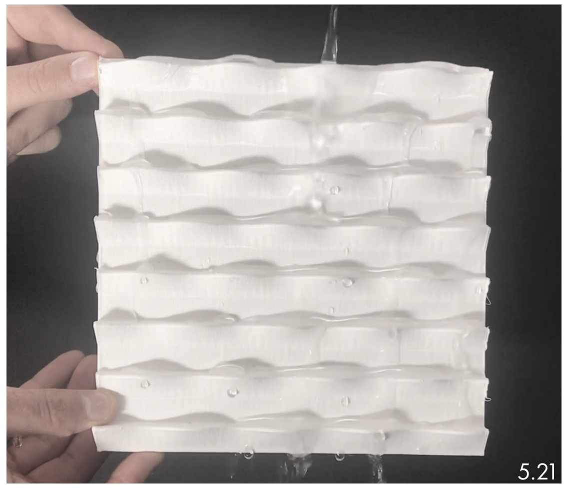
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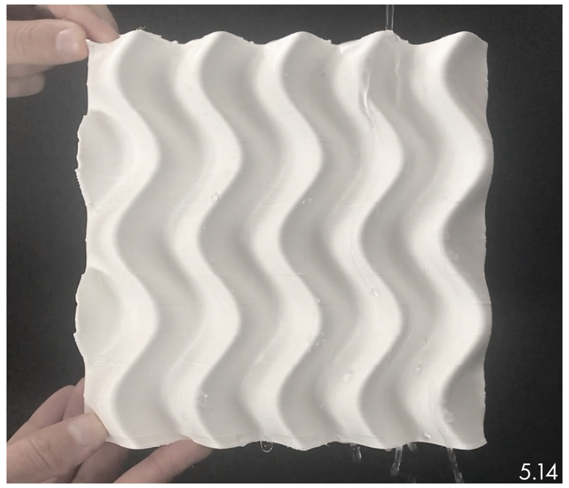
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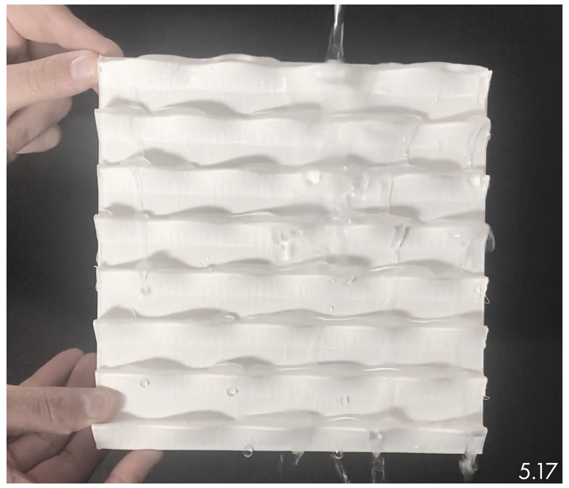
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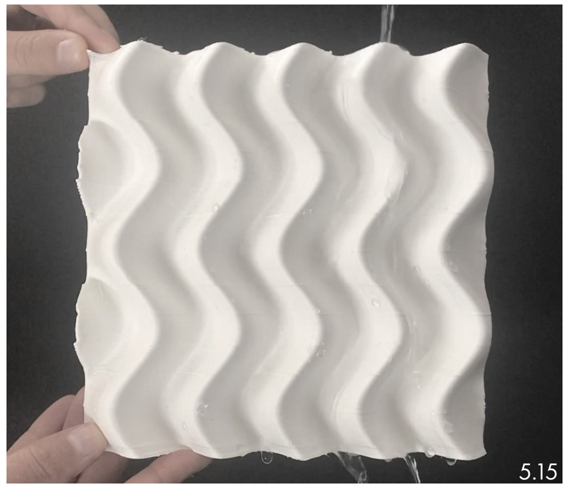
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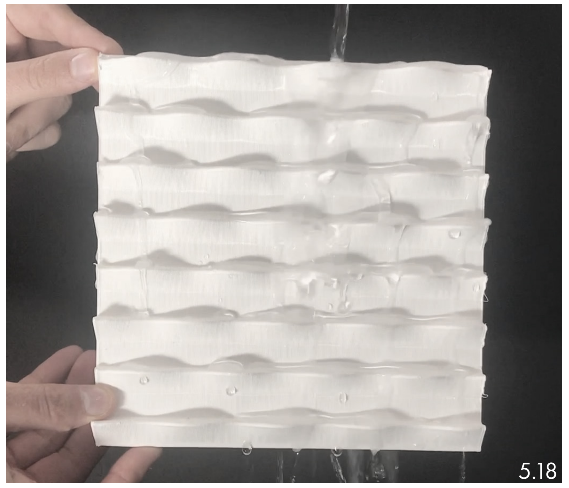
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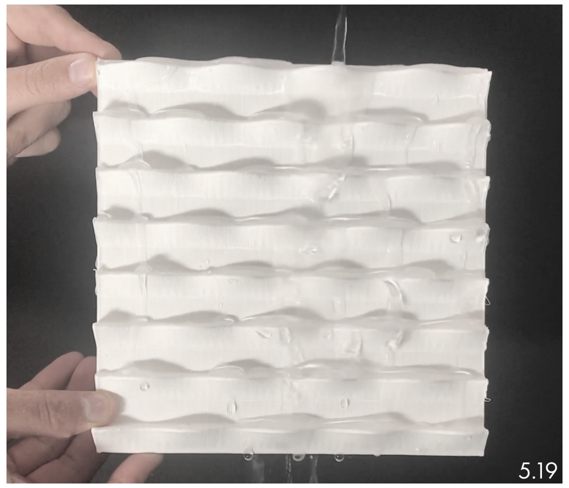
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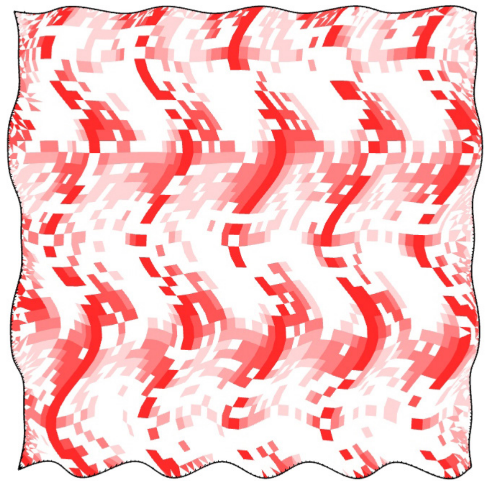


Figure 5.23. - Panel 1 H=5.6

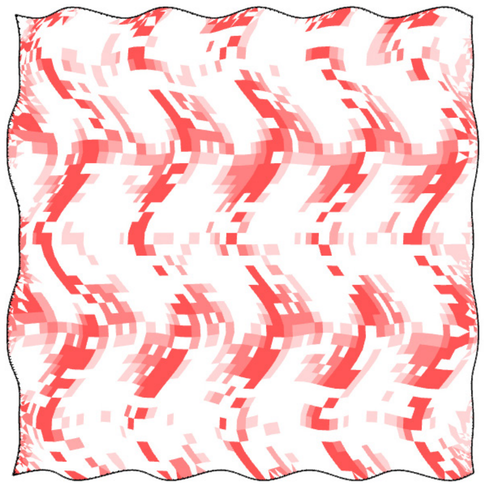


Figure 5.22 - Panel 1 H=4.2

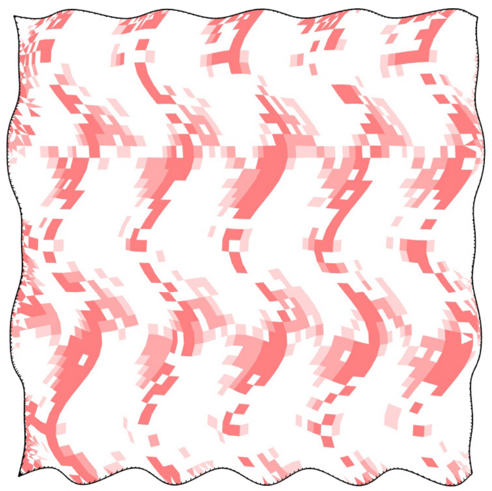


Figure 5.21 - Panel 1 H=2.8

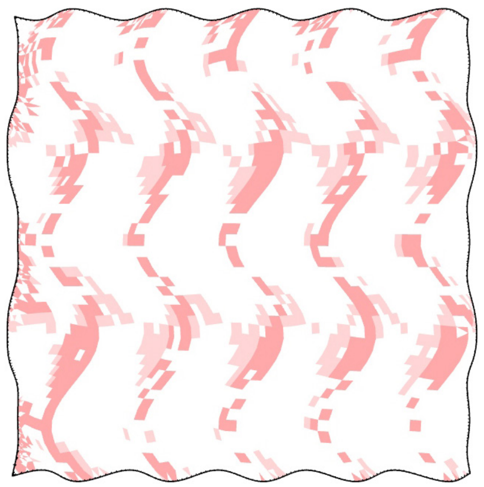


Figure 5.20 - panel 1 H=0

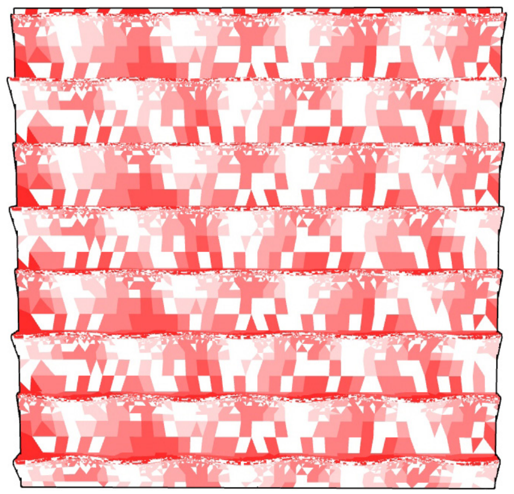


Figure 5.27 - Panel 2 H=5.6

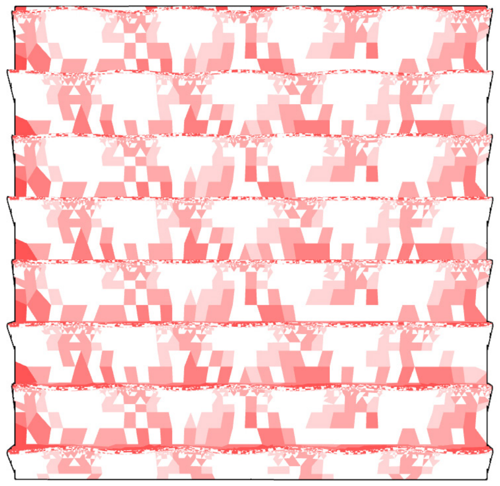


Figure 5.26 - Panel 2 H=4.2

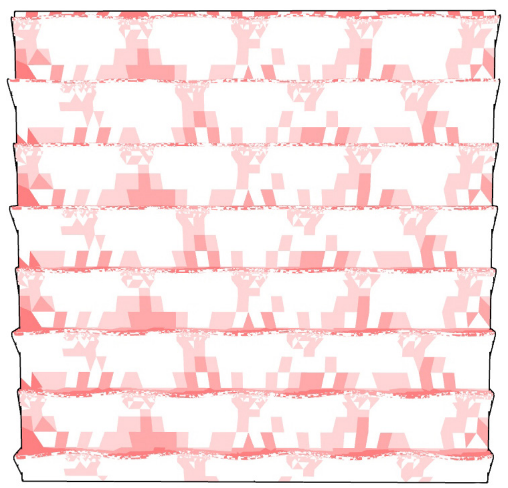


Figure 5.25 - Panel 2 H=2.8

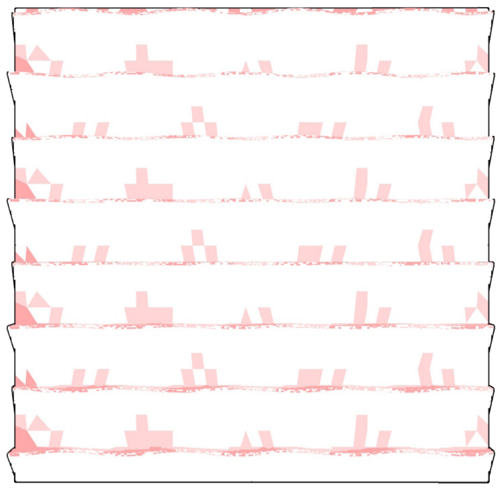
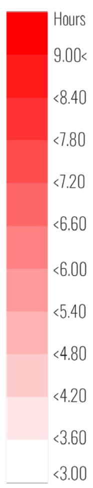


Figure 5.24 - Panel 2 H=0



Radiation

As mentioned in chapter 4, in the design location there is one bryophyte spot observed on which a radiation analysis is performed. The surface receives <4.80 sunhours on a summer day (21st of june). This also matches with the 'few hours of sun' a day as mentioned in chapter 1 for species that are known to be better resistant to sunlight. In the figures 5.20 and 5.24 the panel geometry (panel 1 and 2) at roughly the same height (as the initial observed bryophyte spot) is also measured.

As figure 5.20 shows most of the surface of panel 1 is coloured white. Some spots receive <4.80 hours of sunlight and in some other places it shows <6.00. This means, compared to the existing, this panel performs in some places better (more white coloured surface) and in other places it performs less.

The same analysis is run for panel 2, visible in figure 5.24. This panel shows as well mostly white surface and some spots receive <4.80 hours of sun, this is the same as the existing surface. There are also a few minor spots at the side receiving <6.00 but these are insignificantly small.

Looking at the radiation on the panels of the on site measurements panel 1 performs better compared to panel 2, see images 5.20-5.27 for the radiation analysis of the panels at different heights. In this comparison only the surface color is analysed.

In the table below the average radiation on the panels at several heights on the building are measured(as is shown in appendix F the solar radiation differs on the facade because of the shadowing effect of the context geometry).

Table 5.3- Average sun hours on the panel 1 and 2 at different heights (H).

	Panel 1	Panel 2
Area [m2]	0.29	0.25
H=0	0.45	0.52
H=1.4	0.45	0.52
H=2.8	0.57	0.71
H=4.2	0.69	0.90
H=5.6	0.76	1.10
H=7.0	0.76	1.10

As is shown in table 5.3 the panel 1 performs better (considering average sun hours on the panel) compared to panel 2.

Surface angle

As mentioned in chapter 3 the bryophytes prefer horizontal surfaces over vertical ones. In the table below both panel surfaces are analysed dividing the surface in three groups; upward facing, vertical and downward facing surfaces.

Table 5.4 - Surface area [m2] of panel 1 and 2 of different inclinations

	Panel 1	Panel 2
Total [m2]	0.29	0.25
Upward	0.06	0.06
Vertical	0.17	0.10
Downward	0.06	0.09

In terms of surface angle panel 1 has better results, approximately 80% of the panel will have moss coverage looking at the angle (20% is downward facing). As mentioned before, if this panel is placed in a suitable climate for the mosses, this percentage is likely to be higher.

Coverage

The coverage of the panels is the amount of surface presumed to be covered with bryophyte growth compared to a flat surface. At first the surface area ratio of the panels influence the coverage. The test panels are dimensioned 0.4 m x 0.4 m. The flat surface area would be 0.16 m2. Because of the geometry the surface area of both panels is increased, see table 5.3. Panel 1 has most surface area, approximately 80% more compared to a flat surface.

In determining the presumed coverage of mosses on the panel two aspects are important; radiation at different heights and surface angle. As mentioned under 'surface angle' panel 1 has approximately 80% surface and panel 2 has 60% coverage due to angle. The total coverage of the panel differs on building height, since this influences radiation. This will be further elaborated in chapter 6.

Figure 5.28 - Panel comparison

Comparing the designs

As becomes obvious from the previous, both designs perform better on certain design aspects. Below the performance of the designs on the different aspects are compared. Based on these properties is discussed in which scenarios the designs would be preferred.

The aspects in short;
- Moisture; in terms of moisture panel 2 seems more promising. The panel extends the water flow better than panel 1 and is able to retain water.
- Radiation; panel 1 performs better in terms of average sun hours on the panel. The surface of panel 2 on the other hand reaches lowest maximum radiation on the surface(figures 5.20-5.26).
- The surface area of panel 1 is higher than panel 2, this means the coverage is potentially higher.
- The surface angle of panel 1 is more suiting for bryophytes. This influences the coverage positively. The total coverage of panel 1 is higher compared to panel 2 due to surface angle and surface area.

By comparing these aspects becomes obvious panel 1 performs better in terms of shading ability and coverage due to surface angle and area, and panel 2 in terms of moisture holding capacity. This makes panel 1 the preferred panel for a scenario where the panel is fully exposed to solar radiation compared to panel 2. Panel 2 will perform better on less radiated surfaces, since in terms of moisture this panel seems more promising. As stated in chapter 3 the surface angle is less of influence in places where the growth conditions are more optimum, which will be the case on panel 2 in a less radiated scenario (because in terms of moisture this panel does perform best). This means if placed in the right scenario panel 2 can perform equally to panel 1 in terms of coverage due to the reduced influence of the surface angle.

Furthermore, the surface area of panel 1 is higher compared to panel 2; leaving more area for bryophytes to grow. However, this increase in surface is associated with panel volume and thickness. The surface height in panel 1 has a maximum of 5 cm and panel 1 only 3 cm. The volume of panel 1 is 6.031.857,89 (+/- 0.0025) and panel 2 embodies 4.000.000 mm^3 (+/- 0.001). This makes this panel less effective in terms of material usage compared to panel 2, this accounts for the material usage of the panel itself as well as its supporting structure since panel 1 is much heavier. This aspect also needs to be taken into consideration when the designs are compared.

Preferably, the designs would be further optimized to increase their effectivity (in terms of radiation) and material use. In this research multiple variations are assessed of each panel shape and this could be further optimized also in terms of surface angle (coverage) and moisture to increase the effectivity of the shapes. This optimization should be performed along with field observations, which can lead to more specific design guidelines and restrictions for the relation of the moss coverage and surface properties. The panels would be better comparable in their shading ability with the same thickness, though if the panels would be optimized in their material use and shading ability the thickness will in all probability differ.

From these observations can be concluded that on north facing facade surfaces panel 2 will be the most suitable design since solar radiation isn't of influence; the moisture performance is better, the moss coverage is less affected by the surface angle and the material usage is minimized. Of other orientations such conclusions can not be drawn, since the radiation amount is most of the part influenced by context geometry in an urban environment.

FACADE DESIGN

Chapter 6

FACADE DESIGN

In the previous chapter two bioreceptive facade panel variations have been designed. In this chapter will be zoomed out to the level of facade design and implementation. Furthermore, the facade properties are calculated which will be necessary for simulating the facade performance.

6.1 FACADE SYSTEM

The casted concrete facade panels will be part of a facade system for residential areas in The Netherlands. The designed facade panels are applicable in different settings for a 'worst case scenario' in a representative neighborhood in The Netherlands which makes the system applicable in multiple scenarios in The Netherlands. As stated before there are different architectural typologies present in the selected neighborhood, see figures 2.6-2.10 chapter 2. The different typologies have an impact on the facade coverage. Figures 6.2-6.3 show the implementation of the facade panels on different architectural typologies if the current openings of the facades remain and the panels have one type of fixed dimensions.

The panels can be used for retrofitting or new constructed housing. Whether the facade typology is implemented in the initial facade design and the design ideas for the facade influences the coverage of the panels on the facade. The facade typology consists of a secondary steel structure onto which the panels are attached. The secondary steel structure is connected to the main load bearing structure via a facade bracket system. Figure 6.1 shows in detail such facade system. The panels will have fixed dimensions and shapes available which can be selected according to the architects preference. The available panels can be mixed and matched on the facade. The panels are part of a demountable facade system which

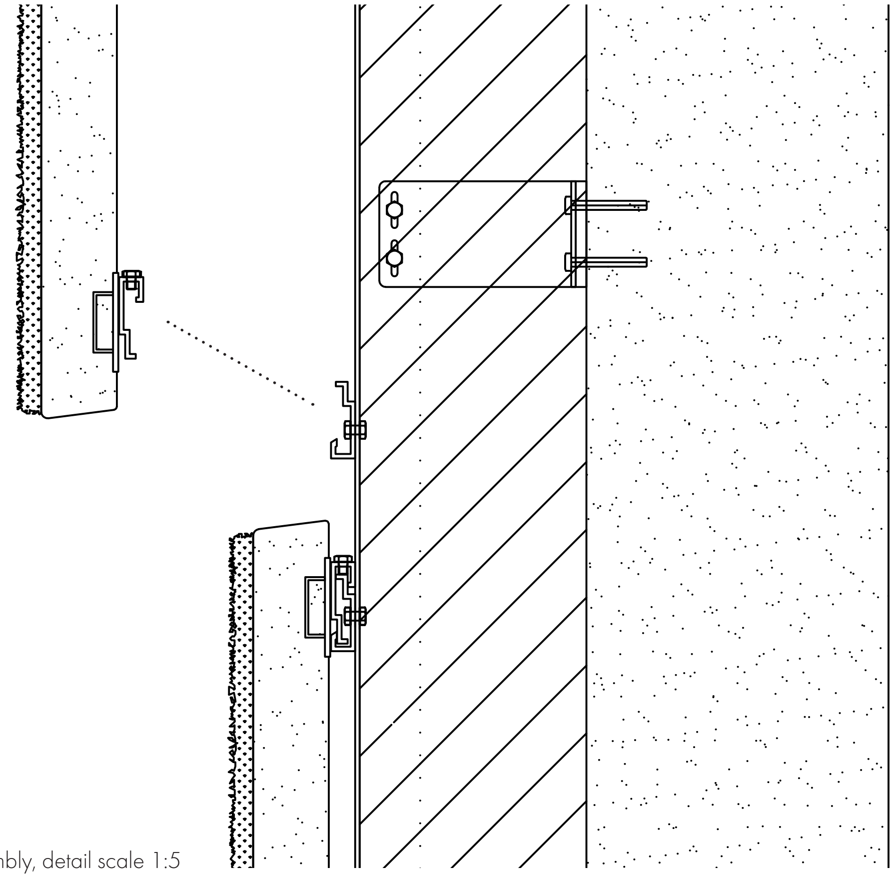


Figure 6.1 - Facade assembly, detail scale 1:5

Figure 6.2 - Facade paneling on architectural typology in LCZ 5

Figure 6.3 - Facade paneling on architectural typology in LCZ 3

allows them to potentially be reused.
For the panels universal dimensions should be developed, making the panels widely applicable and increasing the coverage on the facades.
The exact definition of these sizes are beyond the scope of this research, since such definition will acquire a thorough research of different architectural (material) typologies and their dimensions in The Netherlands.

6.2 FACADE COVERAGE

The coverage of moss on the facade influences the impact on the outdoor climate, which will be assessed in chapter 7. The moss coverage in the street profile is dependant on at first, the coverage of the panel design which is presumed to be covered by mosses, and secondly, the surface of bioreceptive panels on the facade. In this section the surface area covered by mosses in the street profile of the design location will be calculated.

Panel coverage

At first the coverage of the panel is calculated, using the following formula;

Coverage ratio panel=
surface area ratio panel * moss coverage panel

In the previous chapter the two different facade panel designs have been assessed on their application in different scenarios. For the design location panel 1 will be suitable, this panel design is applicable in the whole street canyon, creating one type of facade pattern in the street. The calculations relating to the coverage ratio of the panel will be based on the properties of panel 1.

Surface area panel

Due to the surface geometry, the surface area of the designs is increased compared to a flat surface. As mentioned in chapter 5, for panel 1 the ratio surface area panel : flat surface = 0.16 : 0.25 = 1.8.

Moss coverage panel

In chapter 5 the panel is assessed on moss coverage, which is described by two things; radiation (height dependant) and surface angle. Both factors are described below.

Surface angle
As mentioned in chapter 5, the coverage decrease due to the surface angle is calculated by subtracting the downward facing surface area from the total surface area. The surface area of panel 1 numbers 0.25 m2 of which 0.07 m2 faces downward. Panel 1 has 0.8 ratio suitable surface for growth in terms of surface angle.

Radiation
The facade in the design location has four different 'zones' in terms of sun hours, see appendix F.
The average sun hours on these four zones is as follows; zone 1 <3.60 h, zone 2 <6.60 h, zone 3 <7.80 h and zone 4 numbers <9.00 sun hours.
The different amount of sun reaching the panel influences the coverage. The coverage of panel in zone 1 isn't influenced by radiation since the sunhours are <3.60, see figure 5.20. On the other panels part of the surface is irradiated more, leaving approximately 76% suitable for growth(this amount is measured using Rhino surface analysis of the colored mesh).

Zone 1 = 1
Zone 2-4: 0.76

Zone 1 covers approximately 25% of the building surface. The mean value for the growth ratio due to radiation is calculated as follows; 1 * ¼ + 0.76 * ¾ = 0.82.

Unfortunately, the parts of the surface that are unsuitable due to the solar radiation are the suitable growth spots in terms of surface angle. This means the ratio for angle and radiation need to be multiplied to calculate the moss coverage of the panel.

Coverage ratio panel=
surface area ratio panel * moss coverage panel =
1.8 * 0.8 * 0.82 = 1.18

The panel coverage ratio of 1.18 means the total surface area covered with mosses is 18% more compared to a fully covered flat surface.

Facade coverage

Now the moss coverage of the facade panel is calculated, this can be used to calculate the surface ratio on the facade covered with moss. As previously mentioned the percentage of the facade covered with bioreceptive panels is dependant on the architectural typology of the facade and design aspects, which makes it difficult to calculate. Therefore two scenarios are developed in order to measure the impact on the outdoor climate, which will be assessed in chapter 7. The first scenario is the 'optimum' scenario where besides the facade openings all closed surfaces consist of bioreceptive panels. The second scenario is the amount of facade that at least can be covered with bioreceptive panels. The coverage is derived from the architectural typologies in the design area, assuming the dimensions of the facade aren't aligned with the facade panel dimensions.

Optimum scenario
The window to wall ratio defines the facade coverage since the facade openings will not be covered with greening. The window to wall ratio differs per architectural typology and configuration of the buildings. In this case a common ratio for residential buildings is taken in order to draw conclusions representative for The Netherlands. As mentioned in other studies in The Netherlands a window to wall ratio of 0.3 is representative (Taleghani et al., 2013; Taleghani et al., 2014).

Altogether the facade coverage is calculated as follows;
Coverage ratio = 1.8 * 0.8 * 0.82 * 0.7 = 0.83

Applied scenario
The coverage of the second scenario is derived from the architectural typologies in the design area, assuming the dimensions of the facade aren't aligned with the facade panel dimensions. The configuration and dimensions of the selected housing (representative for their neighborhood) are shown in line drawings, see figures 6.2 and 6.3 and more elaborate in appendix K. The sizes of the panels have the same ratio in all schemes(length:height) but different sizes. As visible from figures 6.2-6.3 and appendix K, the coverage of the houses is at least 40%. This means the coverage on these facades is 1.8 * 0.8 * 0.82 * 0.4 = 0.47, or 47% coverage.

For the simulations both the optimum scenario will be measured (83% coverage) and the applied scenario where the coverage is 47%. The 47% coverage also resembles the scenario where approximately half of the houses in the street has 83% coverage, this is further elaborated in chapter 7.

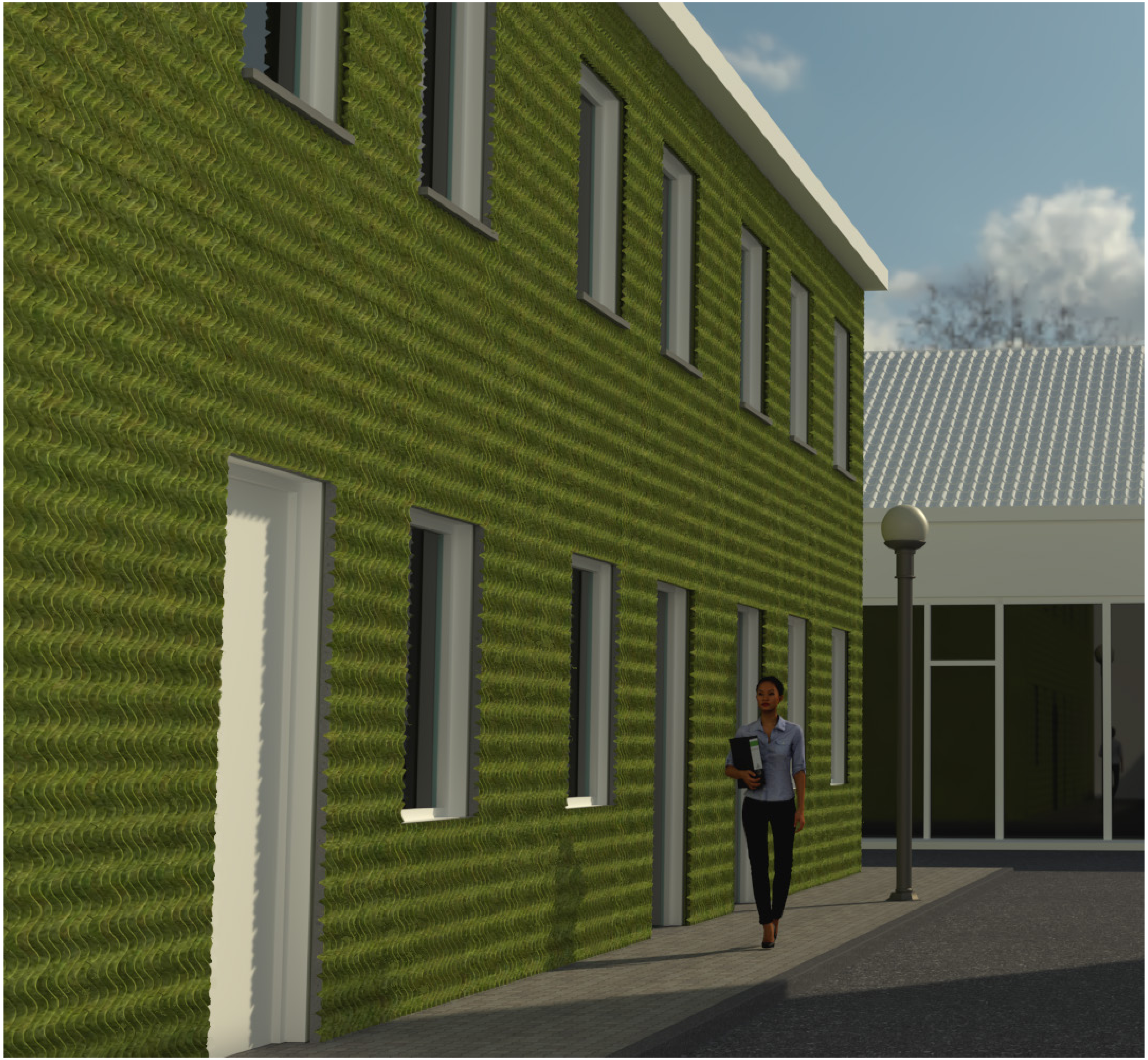


Figure 6.4 - Impression of the facade system in an urban context. Geometry of panel type 1 is rendered.

SIMULATE

Chapter 7

SIMULATE

In this chapter the bioreceptive facade performance will be simulated for the case study area as described in previous chapters. At first, the context model, simulation input and the facade greening properties will be described. Furthermore, the simulation results are described and discussed.

7.1 SIMULATION

The simulation has as goal to measure the impact of the bryophyte panels on the outdoor climate at canopy layer in the given urban configuration. As mentioned in the introduction bryophytes have multiple benefits on the environment; air quality (purification), air temperature, water retainment and aesthetical benefits. The simulations in this chapter will focus on the direct factors; air quality and air temperature influences of bryophytes in a city environment. As previously mentioned the bryophytes are affected by these factors and also contribute themselves in improving these for their own existance. As mentioned in chapter 2 the two primary causes for the UHI effect are difference in materials (thermal admittance) and structure (street geometry). The location as explained in chapter 4 is used as city structure in order to measure the impact of difference in materials. The properties of the urban structure are stated in chapter 2 table 2.1, page 36.

Software

The effect of the bioreceptive green wall system can be measured using ENVI-met microclimate modelling software. This software can be controlled by Grasshopper plugin Dragonfly and Ladybug in order to use Rhinoceros geometry as an input and set the simulation variables. The Dragonfly software is currently in development, limiting the options available. The ENVI-met program Leonardo, Grasshopper and Excel are used to visualize the simulation data.

7.2 DEFINITION SIMULATION

Simulation input

The input for the simulation is shown as Grasshopper script in appendix L. The main settings are explained below. For the simulation the simple forcing method is used which is a simplified method for simulating with ENVI-MET compared to full forcing in ENVI-MET. This method is used due to simulation time and resource restrictions. The simulation is run for 24 h on a midsummer day (21th of June) in The Netherlands in order to simulate heating during the day and cooling during nighttime. For the simulation input an EPW (Energy Plus weather) file is used for the climate data, in this case an epw file for Rotterdam/The Hague Airport is used.

Simulation duration

As mentioned above the simulation is run for 24 h on the 21th of June (start date). As is shown in appendix L the simulation starts and ends at 4:00, because the sun rises that day at 4:22(also visible in the script).

Climatic input

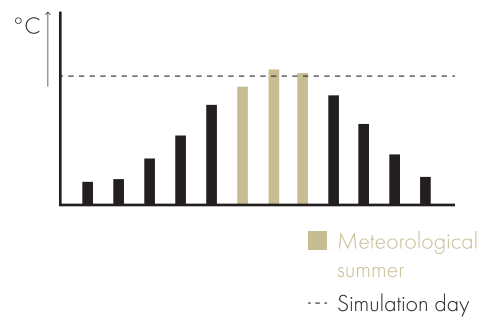
The values for wind speed, wind direction, initial temperature and relative humidity are extracted from the epw file at the time the simulation starts (4:00). See below for specific values for these factors. The specific humidity is calculated using the initial temperature and relative humidity, as just mentioned, using a calculation tool(Hygrotemp, n.d.). At last the effective terrain roughness length z0 is set at very rough, this value is a geometrical property for LZC 3 and is visible in appendix B (Stewart & Oke, 2012).

Wind speed: 4 m/s
Wind direction: 210 (if N=0)
Initial temperature: 15.5 °C
Relative humidity(RH): 92%
Specific humidity: 10.11 g water/kg air
Roughness length: 0.5 (very rough)

The average air temperature during simulation numbers 17,4 °C(extracted from epw file). The highest input temperature is 21 °C and lowest 14.9 °C. According the dutch meteorological institute, KNMI, the monthly averages in summer; June - 15,6 °C, July - 17.9 °C, August - 17.5 °C and september 14.5 °C. (KNMI, n.d.). The simulation temperatures are high compared to the average in June, but more similar to the averages in July/August. The temperatures during simulation can be described as average for Dutch summer weather.

The average RH input for the simulation is 71.9 %, with a minimum of 53% and a maximum of 92%.

Table 7.1 - Temperature simulation day compared to monthly averages in The Netherlands. Data from KNMI, n.d.



As can be concluded from the previous paragraph the humidity levels on the simulation day are >50% and the maximum temperature doesn't exceed 25 °C, to be certain to measure a summer day on which the bryophytes are likely active.

7.3 DEFINITION CONTEXT MODEL

Context model

The model needs to be simplified in order to reduce calculation time. The location for this simulation is the same street as described in chapter 4. In appendix L the script to generate an ENVI-met context model is depicted. The model consists of three elements; the surrounding surface, the building blocks and the street surface. The latitude and longitude of Rotterdam are set and the orientation of the street 22.5 (if N=0).
The road is simplified into one surface element with concrete pavement applied to it. The two rows of houses at the sides are both simplified in one solid with a red brick wall outer layer - albedo 0.2-0.3, (Santamouris, 2013) - and grey roof tiles. See appendix L for additional values of the applied materials.

The grid size remains the default value of 3 m for x,y and z direction. The number of grids in z direction is set at 17. A decrease in grid size unnecessarily extends simulation time; the output changes insignificantly. These settings are used to create an ENVI-met spaces model which will be used for simulation.

Testing variations

As previously mentioned the context model needs to be simplified to reduce simulation time. Different variations of the street and its context are tested.

Street length
The street of the design location is shorter compared to the ones next to it. In order to measure if the street canyon length influences the maximum temperatures in the urban canyon, several models are tested. In figure 7.1 the initial situation (variation 1.1) and the tested options (variation 1.2-1.3) are shown.
Variation 1.1 is the existing design situation, variation 1.2 is 130% street length compared to variation 1.1 and variation 1.3 is 160% street length. As mentioned before, the the impact on the outdoor climate at street level in a given urban canyon is measured. This means the data is compared 1.5 meter above ground level in the middle of the street canyon. In Appendix M, a section can be found of the urban canyon where becomes visible that the maximum temperatures of the street canyon are also found at 1,5 m height.

The three street variations are tested with ENVI-met using the input as described in section 7.2. The simulations are compared looking at air temperature in the middle of the urban canyon at 1.5 m height. In appendix M the graphs are illustrating the temperatures in the urban canyon. The maximum temperatures for the urban canyon are equal in all three cases. A slight difference in temperature appears at night; due to the length of the canyon variation 1.3 shows a slight temperature increase. This difference seems insignificant and for further simulations the first variation will be used.

Multiple canyons
At last will be tested if adding canyons beside the test canyon, will affect the measurements. Since LCZ 3 consists of an area with three streets in same orientation next to each other, see figure 3.1 chapter 3, this area will be used as simulation model. Additionally this area is simplified as visible in figure 7.2. In this variation 2.1(V-2.1) the gardens are simplified into a grass surface, so the trees, plants and paved surface area in the gardens are neglected in order to simplify the simulation. The middle street will be used to compare with variation 1.1 since the influence of the surroundings should be present in this street canyon. In appendix M, the graphs of the air temperature and humidity are given for a point in the middle of the street canyon, for both variation 1.1 and variation 2.1. From the graphs can be concluded that the model with increased surrounding area does influence simulation results in terms of RH levels and temperature. The maximum temperature difference

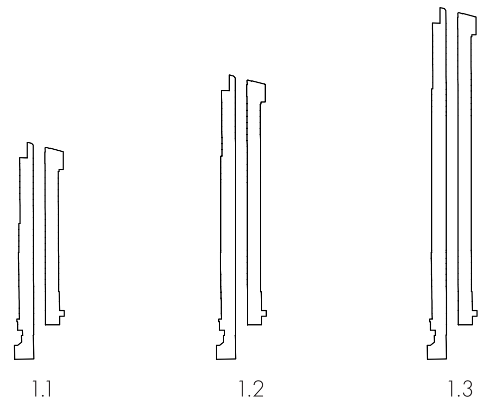


Figure 7.1 - Length variations 1.1-1.3 of context model

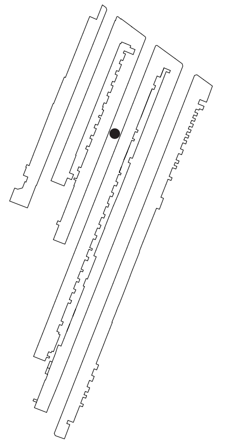


Figure 7.2 - Multiple canyons and receptor location, V-2.1

numbers 0.49 °C (increase in variation 2.1) and the RH 2%. The RH levels are slightly higher during simulation, besides between 15:00 and 19:00 variation 1.1 is higher.
Furthermore the temperatures of the third canyon are increased at nighttime, see appendix M, this can be caused by the context geometry, street length and/or the increased canyon in this street. In the next paragraph the canyon ratio is further elaborated.

Canyon ratio
An additional simulation is run to test the relation between the temperature reduction of the bioreceptive facades and the canyon ratio. As mentioned before, the initial simulation is run for LCZ 3, compact lowrise, with an aspect ratio of 1. The second simulation will be run for the same street (e.g. orientation, length, materiality) but for LCZ 2, compact midrise, where the aspect ratio is usually 0.75 - 2. The other typical properties of LCZ 2 and 3 are in the same magnitude; building plan fraction, impervious plan fraction, sky view factor and roughness length. LCZ 2 can be found in Rotterdam in the south and in/around the centre(Theeuwes et al., 2014). An example of a street canyon with aspect ratio 1.5 can be found in Rotterdam south, Wieldrechtstraat, which has

an height of 15 and width of 10. This example is used as H:W ratio for the model for variation 3. Additionally, variation 4 is tested with a canyon ratio of 2, which is LCZ 1, also using the same input as for the other variations. This can be found in the city centre of Rotterdam, see figure 2.12 section 2.4. The H:W ratio is this street is +/- 40:20.

Appendix M shows slight difference in temperature between variation 3/4 and variation 1.1. In variation 1.1 the maximum temperature during the day is 21.69 °C where in variation 3 the maximum temperature is only 21.30 °C. The maximum temperature reduces even further in street canyon variation 4 to 21.15 °C. The night temperature at (3:00) is only an 0.1 °C increase in the variation with the highest aspect ratio, variation 4, compared to variation 1.1.

In Appendix M the difference of temperature and humidity of variation 3 and 4 are shown in the cases with and without bioreceptive facades (100% moss coverage on facades). From the tables becomes obvious the impact of the panels decreases at street level despite of the increased surface area that the mosses are covering. The maximum temperature difference in variation 3 is 0.45 °C and in variation 4 the difference is reduced to 0.26 °C. For further simulations the aspect ratio will not be a variable in the simulations.

Conclusion context model
As visible in appendix M the increased context model does impact the temperature en RH levels in the simulation. Unfortunately the model also increases simulation runtime with 300%. For further input analysis the small model (variation 1.1) will be used in order to reduce simulation time. For the final simulations variation 2.1 will be used.

7.4 DEFINITION GREEN WALL

In the simulation model is tried to mimic bryophytes for the facade surface. The input is limited by available data about bryophytes and input parameters in ENVI-met. In ENVI-met two types of green systems exist; with or without an air gap (cavity) between the substrate and the wall material, as default the only greening facades are without cavity. Looking at the facade greenings present in the ENVI-met database there are three predefined options; Fern, Ivy and Funkia (Hosta). For the moss facade a new plant type is created, which is described in the following.

Greening parameters
Greening parameters. In the following the plant variables are discussed. An overview of the parameters and their sources is shown in appendix N.

Plant layer thickness [m] = 3 cm. This value is observed in field survey and used as input for panel design. Additionally, the value is used as default thickness in reference moss simulation study(K., Katoh, Katsurayama, Koganei, & Mizunuma, 2018).

Define greening as with/without substrate, without in this case; bryophytes grow directly on concrete without a substrate layer present.

LAI [m2/m2] = leaf surface area index = 10.
Leaf area index in bryophytes is generally difficult to obtain. Measurements of LAI for bryophytes range from 6 to 140 which is much greater compared to vascular plants which range from 1 to 20(Glime, 2017). Hanson & Rice mention in 2017 LAI values between 4 and 129 for different bryophytes species. Furthermore they discuss the LAI in bryophytes, see table Appendix N. It is mentioned that the extreme values by the author Simon have not been confirmed by others and only small patches are measured which questions the representivity of this value. The other LAI values range from 4.1 - 22.5(Hanson & Rice, 2013). However, in other studies the LAI seems much lower ranging from approximately 0.5 to 6.7(Bond-Lamberty & Gower, 2006). In a more recent study by Niinemets and Tobias in 2019 eleven widespread moss types are selected and their LAI measured, showing more resemblance to the LAI described by Hanson & Rice. The LAI values found range from 2.9 to 26.1 with an average of 15.7, and they found a correlation (positive) between LAI and light demand and a negative one between LAI and moisture demand. If all studies are taken into account a lower value of approximately 10 m2/m2 seems average.
The LAI is a dominant factor in the plant variables since it influences the greening amount. Therefore it would be interesting to simulate an LAI at the high end of the range in the same simulation conditions to measure the impact of this factor.

Leaf angle distribution = angle of leaves compared to wall = 0.5. In study about the desert moss, *Syntrichia caninervis*, a leaf angle distribution of 0.3 is measured (Wu et al., 2013). In another study several moss types are measured where the angle differed from 0.35 to 0.87 degrees at a low LAI (high light intensity on the bryophytes) site. Since the leaf angle changes throughout the day the average is considered(of bryophyte species in high light intensity environments); 55 degrees(Falster & Westoby, 2003).

CO2 fixation type = C3. Most of the plants have C3 fixation type(ENVI-met, n.d.). There is no clear evidence that bryophytes have C4 fixation(Hanson & Rice, 2013).

Leaf type (Grass/deciduous(=leaves fall off when mature)/conifer(=needle type)). Given the dense, needle-like, leaves of bryophytes 'conifer' presents a more appropriate model to describe bryophytes(Hanson & Rice, 2013).

Albedo, leaf albedo to shortwave radiation. The shortwave albedo of the plant leaves is normally set to 0.2 (ENVI-met, n.d.) also in other studies grasses and forest have an albedo of +/- 0.2 (Houldcroft, 2009). In a reference moss study the albedo is calculated for dry and moist Sunagoke moss. Dry moss 0.08-0.09 and moist moss 0.05-0.06(K., Katoh, Katsurayama, Koganei, & Mizunuma, 2018). Another study also suggest that the albedo of mosses are lower, the species *Tortula Ruralis* ranges from approximately 0.13 to 0.19(Wood & Oliver, 2004). Species can adapt their albedo to different environmental conditions (Porada et al., 2013) and moisture plays a role in albedo(K., Katoh, Katsurayama, Koganei, & Mizunuma, 2018). Concluding that for this simulation the albedo is kept at 0.2 since the bryophytes will grow in an environment with high light intensities. In another study where ENVI-met simulations are performed the albedo for the plants are kept at 0.2 (Declet-Barreto et al., 2012).

Table 7.2 - Input greening variables moss type 1

Variables	Type 1
Thickness	0.03
With/without substrate	no
LAI	10
Leaf angle	0.5
CO2 fixation	C3
Leaf type	conifer
Albedo	0.2
Transmittance	0.3
Height	0.25
Root zone	0.5
LAD	0.15
RAD	0.1
Season	1

Transmittance = 0.3, the factor of leaves for shortwave radiation. Transmittance for predefined plant types Ivy/Fern/Funkia/Grass is all set to 0.3. No specific transmittance value found for mosses.

Plant height, height of the plants. Kept at default value.

Root zone depth, depth of plant root zone. Kept at default value.

Leaf area profile, vertical LAD profile. Initially the LAD is kept at a default value of 0.15.

Root area profile, vertical RAD profile. Kept at default value.

Season profile, dynamic growing factor of LAD. Seems to be unimplemented yet in ENVI-met. Default value is kept.

Moss type 1

The parameters of the moss created, are listed in table 7.1. For further simulations this moss type is used.

Evaporation mosses as bare soil
Voortman describes in his study the evaporation rate of mosses and compares it with the evaporation of bare wet soil in dunes in The Netherlands(Voortman, 2018). Also in other studies this resemblance is described(Dighton & White, 2017). This could be an interesting comparison to validify the greening properties of the moss as described above. Unfortunately, ENVI-met calculates transpiration and evaporation with physical plant parametres (e.g. photosynthetic rate) which makes such simulation incomparable.

Moss facade coverage
The impact in the street canyon is measured for 50% and 100% moss coverage. The left street side faces south-east and the right side is facing north-west. Two simulations are run with each one facade side covered with moss type 1 and one simulation with 100% coverage (both sides). In appendix O the results are shown for the left side, right side, 0% coverage and 100% coverage in the street canyon for both temperature and RH. The left side is radiated by the sun until about 14:00 when the sun is shining direct into the canyon. Afterwards the north-west facades face the sun. In terms of temperature reduction the left side coverage (sun facing) performs better compared to the right side - performance comparable with full coverage - until 14:00. The maximum temperature reduction measured is approximately 0.42 °C. Afterwards 100% coverage performs best and the right side (radiated in the afternoon) reduces slightly more than left. These results show that covering the sun facing facades is more efficient in terms of temperature reduction.

In appendix O the RH levels are also shown for the four different cases. The graph shows the right side is more efficient in inducing the RH levels from approximately 11:00 onward compared to the left side, which is only performing slightly better compared to the 0% coverage. The maximum RH difference measured is 6.98%, measured at 13:00. Afterwards the difference slowly decreases, when the right side is radiated. These results show the facade panels are more efficient in terms of RH increase if placed on the most shaded facades.

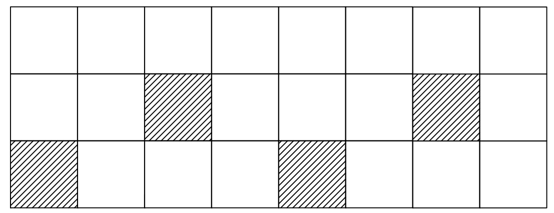
For further simulations the facade panels will not be placed adjacent to each other but facing each other, since, for the simulations run in this chapter, both temperature and RH levels are important.
In previous simulations the coverage on the facades itself haven't been considered yet. In the final simulations the two scenario's as described in chapter 6 will be simulated.

7.5 FINAL SIMULATIONS

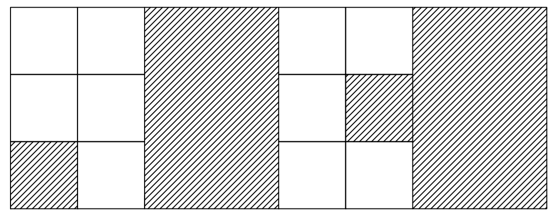
Model and Coverage
The context model variation 2.1 is used for simulation, see figure 7.2. As mentioned previously the facade coverage on the facades is mirrored in the street. In the first scenario the facades itself have a coverage of 83%. As mentioned before the model is simplified with an 3x3 m grid, the facade coverage is simplified as shown in figure 7.3 resulting in a coverage of 83,33%. For the applied scenario this means the facade panels are implemented on 40% of the facades (the applied scenario), the surface coverage in the grid is 42%.

Figure 7.3- Configuration moss facades in grid

Scenario 1 - Optimum scenario



Scenario 2 - Applied scenario



Greening
The developed moss type 1 as mentioned in the previous is used, see table 7.2. This greening type will be compared with Ivy, where the predefined plant settings of ENVI-met are used. The layer thickness of the Ivy facade is set to 20 cm. See appendix O for specific variables Ivy greening.

Input and receptor
Simulation input following description section 7.2. Script shown in appendix L. The receptor is added in the model, see figure 7.2, in the middle of the street canyon. The receptor measures as default every 10 min during simulating at every grid height.

Simulation datalog
1; Situation 0 (baseline simulation), brick facades (0% of the houses bioreceptive)
2; Situation 1 - Applied scenario; 40% Moss surface coverage (50% of the houses bioreceptive)
3; Situation 2 - Optimum scenario; 80%

Moss surface coverage (100% of the houses bioreceptive)
4: Situation 3; 80% Ivy surface coverage (100% of the houses bioreceptive)

7.6 RESULTS

Description simulation day

The simulation starts at 04:00. In the first hour the sun rises (04:22) and the minimum temperature, 15.83 °C, is a bit more than the initial temperature of 15.5 °C. The maximum temperatures are found in the most right street. Around 07:00 the maximum temperatures are noted at the most right building surface; where the sun starts reaching the building facade. The minimum temperatures in the model are found in the garden canyons. From 10:00 onward, it becomes obvious the south-east facades are heated up by the solar radiation, heating up the street canyons. Around 14:00 the sun shines into the urban canyon, there is no shadowing effect of the buildings, and the highest temperatures are reached. From 16:00 onwards the north-west facades are heated up, leaving the highest temperatures at the left side of the model. Around 21:00 it becomes obvious at the upper right corner most of the heat is trapped. This effect is present throughout the night but the temperature difference in the model keeps decreasing until the lowest maximum temperature of 15.81 °C in the model is found.

During the 24 h simulation the wind speed has a minimum of 2.94 m/s, maximum of 3.41 m/s. The average temperature of the baseline simulation is 18.20 °C and the relative humidity 75.47 %. These values extracted from receptor output in the middle of street canyon.

Moss simulations

In appendix P the temperature and RH levels are illustrated to compare the different measurements. At first becomes obvious the panels influence more the RH levels in the street canyon than temperature. Temperature and humidity will be further elaborated below. The difference in average temperature during simulation time is 0.17 °C and the difference in average humidity levels is 3.8% (comparing the baseline situation with 80% moss coverage). In table 7.5 the minimum and maximum values are shown of each simulation and what time these extremes are measured.

Temperature

In appendix P the graphs are shown for every simulation compared with situation 0, the baseline measurement. The values are extracted from the receptor output. The temperatures are measured in the middle of the street canyon halfway the street, see figure 7.2. At first the variation with 80% moss coverage in the street canyon shows highest temperature difference compared to the baseline. Also the temperature difference is graphed, see table 7.3. The simulation representing 80% coverage is the most effective measure in the canyon in terms of temperature reduction, with a maximum temperature reduction of +/- 0.55 °C reached at 16:20 during simulation, see table 7.2 (reduction is stated in positive values). From approximately 14:00 the temperature reduction starts to be significant (>0.2 °C) until about 20:20.

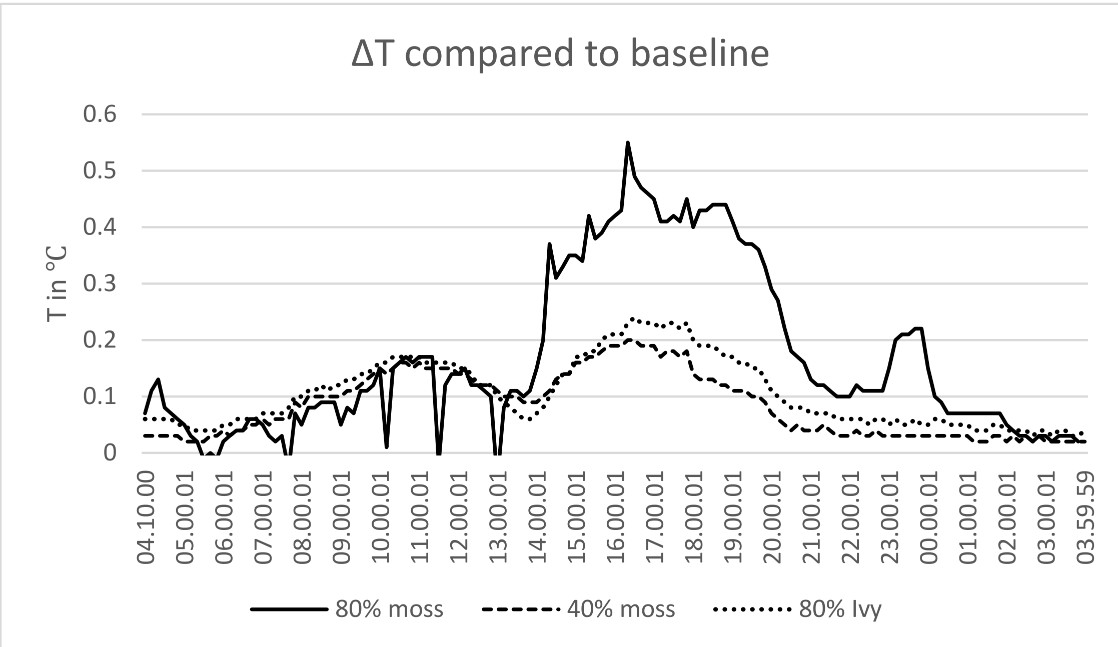


Table 7.3 - Temperature difference for different facade greening types compared to baseline simulation.

Both the 40% moss coverage and the Ivy facade perform less in terms of temperature reduction in this specific street canyon. The Ivy facade reduces slightly more (+/- 0.05 °C) from around 16:30 till 19:50. Around midnight (00:00) all the facade types start to perform equally, also the temperatures of the baseline situation stabilize.

Appendix P shows a section through the model at 1.5 m height in plan view. The temperature difference is shown between the baseline model and the 80% coverage model. Image 1 shows the peak at 11:00. The highest air temperatures are found at the south-east facing facade, which is irradiated around this time. At 14:00 the sun shines in the street canyon and the maximum temperatures are found throughout the street profile. The third image shows the air temperatures around 16:00, the maximum temperatures are found at the north-east facing facades, which is irradiated around this time. The air temperature differences from the images differ slightly from the receptor output since the receptor measurements are more precise and the images regard the section plane through the full model where the receptor measures at one specific point in the model.

Relative humidity

In appendix P the graphs are shown for every simulation compared with situation 0, the baseline measurement. The values are extracted from the receptor output. Comparing the graphs it becomes obvious the 80% moss coverage has most impact on the increase of RH levels compared to the baseline measurements. This difference is also shown in table 7.4. The highest humidity difference is measured around 13:00-14:00, which is 10.21%. The increase is most significant during 09:00 and 19:00 (>4%), which is during the warmest temperatures during measurement.

The difference of 40% moss facades is approximately half of the 80%. The Ivy facade greening performs very poorly; the maximum RH difference is 2.24%, reached around 16:20 during simulation.

Around 21:30 the difference of all situations nearly equals zero (besides a slight peak). From 00:00 onward the RH levels of the baseline situation also become steady.

Appendix P shows a section through the model at 1.5 m height in plan view. The temperature difference is shown between the baseline model and the 80% coverage model. The image shows the levels at 12:00. The highest RH levels are found at the left side (south-east facing) facades. These values differ slightly from the tables since the graphs show the difference at one point (middle canyon, 1.5 height) where the images show difference in the entire section plane.

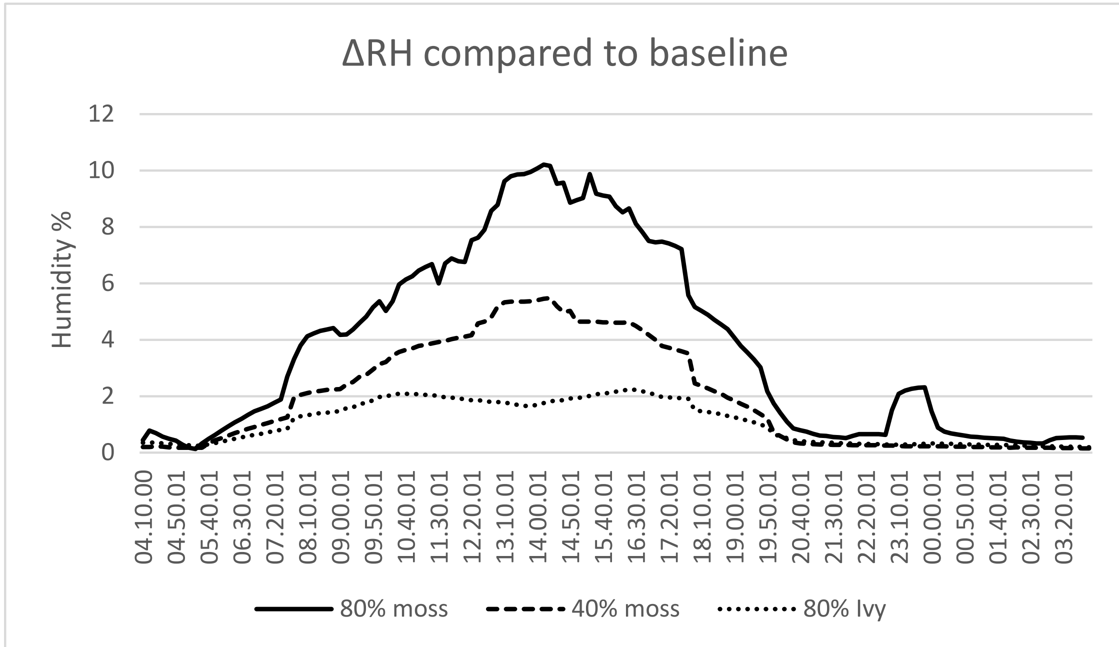


Table 7.4 - RH level difference of different facade greening types compared to baseline simulation.

7.7 CONCLUSION

Input analysis results

Canyon ratio

In the given urban configuration the aspect ratio reduces the impact of bryophyte panels on the outdoor climate at street level, 1.5 m height. The simulations showed the maximum day temperatures are reduced when the aspect ratio increases. Furthermore, the temperature reduction of the facade greening decreases - when aspect ratio increases - despite of the increased total surface area in the increased street canyons. The context model for these simulations consists of a single street. An increase of context area might affect the day temperatures and the impact of the facade greening on the surroundings. Further simulation testing would be necessary to substantiate this observation.

Orientation facades

In the given urban configuration the facades in the street are oriented south-west or north-east. Simulations show that the sun facing facades, in this case the south-west facing surfaces, perform better in temperature reduction compared to the north-east faced facade surfaces. The opposite effect is visible if the RH levels are considered. The north-east faced surfaces perform better in inducing the humidity levels compared to the south-west facing surfaces. This effect can be explained by the induced evaporation by the sun or the reduced thermal admittance.
This means the facade greening can be placed strategically whether the impact on temperature or humidity levels of the facade greening is desired. For further research other orientations should be considered to validate this effect. In addition, the context model for these simulations consists of a single street. An increase of context area affects day temperatures/RH levels and presumably the impact of the facade greening on the surroundings. Further simulation testing would be necessary.

Results final simulations

As table 7.3 depicts best, 80% coverage is the most effective measure in the urban configuration in terms of temperature reduction, with a maximum temperature reduction of +/- 0.55 °C reached at 16:20 during simulation. The temperature reduction is significant (>0.2 °C) from 14:00 until about 20:20. The 40% moss coverage and the 80% Ivy coverage facade greenings perform equal in terms of temperature reduction. Around midnight (00:00) all the facade types start to perform equally, simultaneously the temperatures of the baseline situation stabilize.

The 80% moss coverage has most impact on the increase of RH levels compared to the baseline measurements. The highest humidity difference is measured around 13:00-14:00, which is 10.21%. The increase is most significant during 09:00 and 19:00 (>4 %), which is during the highest temperatures during measurement. The difference of 40% moss facades is approximately half of the 80%. The Ivy facade greening performs very poorly; the maximum difference is 2.24%, reached around 16:20 during simulation.

Profiles

In the baseline measurement the min RH levels and the highest temperatures measured take place at the same time in simulation. At both the 40% and 80% moss coverage the RH level profile changes and the min RH levels are measured later during simulation. The RH level profile of the Ivy facade remains unchanged compared to the baseline measurement.

The images and the graphs of the min/max temperatures and RH levels measured show the maxima are found beside the facades thus not measured throughout the street profile. The maximum temperature reduction measure in the whole profile is 0.2 °C and for the RH levels below 8.73%(in the 80% coverage simulation).

	0	40% Moss	80% Moss	80% Ivy
Min. temp	15.53 (02:00)	15.50 (02:10)	15.48 (01:50)	15.49 (02:00)
Max. temp	21.92 (14:10)	21.82 (14:10)	21.74 (14:00)	21.84 (14:10)
Min. RH	58.20 (14:20)	63.44 (15:00)	68.54 (17:00)	60.02 (14:20)
Max. RH	89.97 (04:00)	90.12 (04:00)	90.26 (04:00)	90.16 (04:00)

Table 7.5 - Temperature / RH measurements and measurement time for different facade greening types

7.8 DISCUSSION

In order to run the simulation as described in chapter 7 several assumptions have been made. In the following these assumptions are discussed in order to draw valid conclusions from the simulated results.

Case selection

The case study neighborhood is selected on its representivity in The Netherlands. The neighborhood is classified as LCZ 3 which is a representative neighborhood typology of which its physical properties are known to influence the UHI effect up to a certain degree. However, of the representivity of the climatic conditions in Rotterdam for the Netherlands is unknown. Here must be stated that the size of The Netherlands is relatively small and so are the climatic differences.

Coverage

At first the moss coverage on the facade panels and the coverage of the facade panels on the facade have been measured. As described in chapter 4 t/m 7 the moss coverage on the facade panels is dependent on the surface area, surface angle and radiation on the panels, where the radiation is measured at 21st of June, the day usually with the highest amount of sunhours. The coverage reduction due to surface angle might be lower in a real life scenario; the surfaces which are rotated more than vertical are defined as 'uncovered' where in nature bryophytes on for example trees also grow on downward inclined surfaces. However, during the field observation bryophyte growth on downward inclined stoney surfaces isn't observed. The moss coverage reduction due to radiation is calculated using literature and an analysis of a real life scenario, which has lead to the restriction of 3.60 h sun maximum, higher values of radiation are defined as 'uncovered' surface. This value can differ per bryophyte species and moisture content of the moss stand, and therefore the maximum radiation will be part of a range of values. Because of the use of the field observation to determine this value, it validates that this (unknown) bryophyte species is able to 'at least' survive these radiation amounts. Therefore, this bryophyte species(or others) might be able to survive more radiation than the maximum which is used here. This will influence the coverage positively. Field tests on moss coverage of the panel designs can shed light into the exact restrictions for the facade panel properties.
As visible in the field survey the bryophyte stands don't always form a uniform covered layer on the surface. External factors, besides climatic factors, can have an impact on the moss coverage (birds, humans) which is not accounted for in the coverage calculation. Altogether, the calculated coverage is a realistic assessment of the possible coverage on the panels.

The coverage on the facade is calculated in chapter 6. For the facade coverage two scenarios are developed which are both simulated in chapter 7. The first scenario is an optimum scenario where all facade surface - besides the facade openings - is cladded with bioreceptive panels. This is only possible in a facade design where all dimensions are aligned with the bioreceptive facade panel dimensions. In the current building industry the dimensions of materials aren't adjusted and this would be difficult to achieve. Secondly, the vision of the designer is of influence on the panel coverage; 100% facade surface covered with bioreceptive panels might not be the prefered aesthetics of the facade design. This facade coverage calculation is an exceptional case.
In the second scenario the coverage is calculated using the housing typologies present in the area to calculate possible coverage. At first must be noted that this neighborhood is selected on its representivity of the urban configuration and not its architectural typology, which means this value is not representative for housing in the Netherlands. Of the different architectural typologies present, one single facade is used for analysis. The exact facade dimensions were unavailable for this research and these are extracted using Google Maps images. The facade panels used for this analysis have the same L:H ratio but different dimensions in each of the analysed facades. The minimum coverage found in the analysis is used for simulation. Therefore, the combination of these two scenarios can be seen as a range, the minimum and maximum coverage possible in a street. From this range the maximum is more representative for The Netherlands than the minimum value.

Because of the current configuration of the mosses in the street these scenarios would only be possible in large scale building retrofitting or neighborhood plans.

Simulation model

Reduction context

In order to reduce the simulation time the model is simplified. The impact of the model size is addressed in section 7.2. The model with an increased area showed higher temperatures in the street canyon, since the air leaving a street canyon is heated up. A further increase of the context model possibly would have led to an increase in the temperatures in the model. The impact of such temperature increase on the effectivity of the temperature reduction of the facade greening is more difficult to state. Additional simulations should prove if there is a correlation between outdoor temperature and temperature reduction of the facade greening. In terms of bryophyte activity this range is known, the upper boundary is 25°C and the minimum often around -10 °C. It would be interesting to measure bryophyte behaviour within this temperature range. Additionally, in chapter 1 was stated the temperature of bryophytes isn't necessarily the temperature of their surroundings in a natural environment (they can act as an insulating layer), this substantiates that laboratory or field test should be performed to research the relation of bryophyte temperature and out- and indoor temperature on a facade element in an urban environment.

Grid

For the simulation model several simplifications of the design location took place. As previously mentioned the model is simplified by a 3 x 3 m grid. For the housing blocks this means most of the buildings have a height of 9 m (where in the actual scenario the houses are approximately 8 m +/- 1 m), this value is still representative for its LCZ classification. Additionally, the street width is simplified to a constant 9 m (where in the existent scenario this width approximately numbers 9.8 m). This means the aspect ratio of 1 is still valid for the simplified model.

Simplification materials

At first, is noted that the measured temperature difference, or the temperature reduction performance of the facade panels, is dependant on initial material (albedo). In the scenario where a darker facade finishing is chosen as initial facade material, the temperature reduction of the moss facade compared to the baseline simulation increases. This should be kept in mind for further facade material selection for simulations. In this case a red brick facade is chosen which albedo is comparable to that of the moss facade and it is a representative material for neighborhoods in The Netherlands.

By setting the material properties for the context model the windows in the street have been neglected. In the proposed grid of 3 by 3 m this would have rendered an unrealistic scenario. The presence of the windows will influence outdoor temperature (dependant on the difference in indoor and exterior temperature) due to the reduced insulation properties. During summer this temperature difference will likely be minimal. Furthermore, it will have slight influence because of the comparison of the same scenarios in this research.

The gardens in the model are simplified to a grass surface element, which means the paved garden surface and plants (trees) are neglected. It will have slight influence on the temperature because of the comparison of the same scenarios in this research. The presence of trees might increase the humidity which can lead to less humidity increase due bryophyte presence. This will likely have only a slight influence since the trees are present behind the measured street canyon.

Climatic data and ENVI-met

Due to resource restrictions only one day is measured for the simulation (24 h), since the impact of the facade greening minimizes at night and the temperatures are representative for a summer day in The Netherlands. This simulation runtime gives a representative indication of the impact of the facade greening on a summer day, but to measure bryophyte impact for example in summer, longer simulation runtime would be needed (simulating different day temperatures).

For the climatic data an EPW file of Rotterdam/ The Hague is used for input. This file is the nearest measuring station for an EPW found. EPW files are commonly used for energy and weather simulations.
The simple forcing method in ENVI-met is used to reduce simulation time. This means only the hourly temperature and humidity data is assimilated to define the lateral boundary conditions for the context model (ENVI-met consists of a one dimensional boundary model), where the full forcing method can also calculate radiation or cloud cover, wind speed and direction, air temperature and humidity in a diurnal profile. The simple forcing method is sufficient for a realistic simulation, although the full forcing method would make it more accurate.

Bryophytes

In section 7.4 the physical plant properties are discussed. Extensive literature research is performed to develop the plant properties according to the case scenario. Only little is known about the influence of the individual parameters and what it's used to calculate for. The LAI and

leaf angle distribution seem dominant factors since they influence the surface area of the leaves. Additional simulations should indicate the influence different properties and reveal the dominant ones. For further research using bryophyte simulation it would be recommended to validate the bryophyte properties by checking the evaporation from the greening as calculated by ENVI-met. For this research this data was not suitable yet to process.

Comparative studies

In the study of Djedjig et al. in 2017 the temperature reduction of their vertical green wall system are in the same magnitude of the moss facade measurements in this research. In these field experiments 100% coverage (one side) of a downscaled street canyon, canyon ratio of 1.2 and facing east and west, is measured. Maximum temperature reduction measured across the street canyon is approximately 0.8°C. From this can be concluded the results from the simulation are in a realistic order of magnitude although their measured performance is higher. Moreover, the influence of the green wall system on the interior heat gain is generally much higher compared to the outdoor temperature reduction(Djedjig et al., 2017, Safikhani et al., 2014).
The time profile of temperature reduction due to the presence of greening is additionally comparable with the results in this study. The temperature reduction performance is highest during the day from approximately mid day till late afternoon, about 20:00. Outdoor temperature reduction during nighttime is insignificant(Djedjig et al., 2017, Safikhani et al., 2014).

In this research a difference is measured between the outdoor temperature reduction of moss and Ivy facade greening. For the Ivy plant the default plant properties are used from ENVI-met. As previously mentioned the LAI of plants might be a dominant factor in their impact on the climate, which might explain the difference in temperature reduction since the LAI value of Ivy is much lower compared to moss. In a study where the impact of Ivy greening on the local microclimate is measured using a series of experiments for several days during summer, the vegetated facade was measured to reduce the outdoor air temperature next to the greening with an average of 0.8 - 2.1 °C lower (depending on orientation) and the relative humidity was 2-4% higher(Susorova et al., 2014). The relative humidity differences are similar to the results in this research. Measurements are taken approximately 5 cm from the wall in the study of Susorova which might explain the air temperature difference, since ENVI-met has a more coarse measuring grid, also other climatic variables are of influence (f.e. wind velocity and direction, surroundings, radiation intensity, different bare surface material) which might have led to different outcomes.

The UHI in a street canyon is influenced by wind direction and street orientation; if moss effectivity is dependant on the temperature (between 25°C and -10°C), additional simulations necessary to state a general conclusion about moss presence and UHI mitigation. Moreover, the behaviour of mosses under different circumstances need to be analysed (wind speed and direction, temperature, radiation, humidity, different seasons) since there variables influence the photosynthesis or evaporation rate in plants.

Generally, more knowledge is necessary about the behaviour of bryophytes in different climatic conditions, in different urban configurations and with different physical plant properties. To start the response bryophytes to temperature within their activity range 25 °C and the minimum around -10 °C. There is a range of variables (probably) influencing its effectivity, climatic factors such as wind speed and direction, temperature, radiation, humidity, radiation and different seasons and urban geometrical properties such as orientation, facade material and the influence of different physical plant properties on its effectivity. The results as proposed in the research are an indication of its performance on temperature reduction in an urban canyon in one specific climatic condition and more research is necessary to draw an general conclusion about the moss performance in the urban climate of the Netherlands.

CONCLUSIONS

Chapter 8

CONCLUSIONS

At last, the research question, '*Are bioreceptive facade panels an effective measure to improve the city climates in The Netherlands?*' as stated in the introduction, can be answered. Where the '*effectiveness*' of bioreceptivity is described by the following factors; air temperature, air quality, water retainment, aesthetical benefits. In this research is focussed on the reduction of outdoor temperature in cities by bioreceptive facade greening. As mentioned in the introduction the bryophytes growing on the facades are affected by the city climate, which will be addressed first. Secondly, the impact of the bioreceptive facade is assessed and compared with competitive facade greening systems.

Limits of the city climate

The effectivity of mosses in the urban environment is dependant on the habitat conditions. If the conditions for bryophytes aren't reached in their habitat, they can be damaged (or die) and go dormant. Dormant bryophytes can lose their aesthetic value (dormant mosses turn brown), their ability to reduce air temperature (evaporation) and partially their ability to improve air quality(photosynthesis, purify air). Their ability to improve air quality is only partially dependant on their activity, since research has shown uptake of major and trace elements also takes place passively. The three main factors inducing dormancy or damages in bryophytes (thus limiting their growth and effectivity) in an urban environment are moisture(drought), high temperatures and solar radiation.

Moisture

Because of the poikilohydric character of bryophytes, water availability is the limiting factor in their habitat(precipitation and humidity). Research shows the optimal water content for respiration and photosynthesis as measured for several bryophyte species is around 87% to 305% of their own dry weight. This means bryophytes are effective in water retainment.
From this can be concluded, on a facade surface additional irrigation is necessary to optimise the effectivity of the panels. Additionally, on an irrigated facade panel the moisture won't be the limiting growth factor for bryophytes. Humidity levels play a role as well, relative humidity levels below approximately 50% can damage even desiccation tolerant species(without irrigation). Additionally, high humidity levels reduce the amount of irrigation needed.

Temperature

Bryophytes seldom have a net gain at temperatures above 25°C, making temperature an important factor in the effectiveness of bryophytes in the urban environment. In the case study area Rotterdam this means 21 days a year the moss facade panels will be inactive and this number will increase in the future.

Solar radiation

Generally, bryophytes are adapted to low light conditions relatively to other plants. Even in dehydration state too much sunlight can damage the bryophytes. Generally, bryophytes are better resistant against solar radiation damage whilst being moist. Some sun adapted species are known to handle several hours of sunlight. By the geometrical design of the facade panels the self shading ability is an important design factor to enhance the bryophyte coverage on the facade panels.

The impact of bryophytes

The impact of the designed bioreceptive facade in this research is measured used ENVI-met climate modelling software. Besides outdoor temperature the humidity levels are measured, which is an important direct factor in the habitat of bryophytes.

Temperature

The simulations show the maximum outdoor temperature reduction during an average summer day in an urban canyon at screen height of a representative urban configuration in The Netherlands ranges between +/- 0.2°C and +/- 0.55°C. These temperature differences are relatively low for the impact of facade greening on the outdoor temperature.

Furthermore, the impact on indoor temperature reduction disregarded, research has shown this impact is usually higher compared to the influence on outdoor temperature. The impact of this type of facade greening on the indoor conditions is necessary to compare this system to other facade greening typologies.

Humidity levels

The simulations show the maximum outdoor relative humidity increase during an average summer day in an urban canyon at screen height of a representative urban configuration in The Netherlands ranges between +/- 5.48 and +/- 10.21 %. This increase will contribute against the drought in cities, which makes the bryophytes more effective and is positive for other plant growth in cities.

Profile

Due to the presence of bryophytes in the street canyon the lowest RH levels and highest temperatures do not occur at the same time during the day, this contributes to reducing the chances of dehydration of the bryophytes.

Ivy facade greening

In terms of temperature and humidity levels the facade greening performance is compared with the performance of Ivy greening facade in the same climatic conditions, context and simulation input. The simulations show the maximum outdoor relative humidity increase during an average summer day in an urban canyon at screen height of a representative urban configuration in The Netherlands is +/- 2.24% and a maximum outdoor temperature reduction of +/- 0.24°C. In these simulations the coverage is equal to the optimum scenario of the moss simulations.

The results are an indication for moss facade in one single climatic condition and orientation, additional research is necessary to state a general conclusion about moss facade panel effectivity in the urban climate of The Netherlands. There are still multiple variables of the climatic conditions and urban structure which influence the conditions and the effect of these different conditions on the effectivity of bryophytes remains unknown. Especially, the variables as orientation, wind speed and direction and different seasons on the effectivity of bryophytes need to be measured in order to draw a comprehensive conclusion. In the measured conditions the effectivity of bryophytes on the outdoor temperature is relatively small and its impact on relative humidity levels seems promising. Furthermore, the performance of the Ivy facade in the measured conditions is much less, especially compared to other research on this facade greening type. Besides to influence of climatic factors, which also affect the performance of bryophytes, this difference can be explained by the plant properties used for simulation.

Bioreceptivity

At last, the findings in this research are used to compare the bioreceptive facade to the existing green wall systems. As mentioned in the introduction, there are roughly two types of green wall systems; the green facade (among others the Ivy greening) and the living wall system, see figure 1. The bioreceptive facade greening is a new type of green wall for buildings.

An important benefit of bryophytes, as extensively discussed in this research, is the ability of bryophytes to go dormant and be able to resume activity when conditions allow for it. On one hand, this reduces the effectivity of the panels to contribute to the climate but on the other hand, it makes the system more resilient and lower in maintenance compared to especially the living wall systems. Also must be noted that some benefits such as air purification of bryophytes also (partially) take place passively.

Bryophytes are characterized by their high water retention ability and their uptake of major and trace elements compared to other vascular plants, which both benefits the city climate.

The simulation results assume the bioreceptive facade performs better in terms of outdoor temperature reduction in the given conditions compared to the Ivy greening. This will benefit the bioreceptive facade over the Ivy greening.

The material usage of bioreceptive facades is less compared to the living wall systems where an additional structure is added on top of the exterior facade layer. As described in chapter 6, the concrete facade panels as used for bioreceptivity do need a secondary support structure which means for bioreceptivity as well more material would be needed compared to a self supporting brick facade layer (on which Ivy grows!). The disadvantage of the green facade is the fact that the plants either need pots to grow in or ground surface.

Besides material usage the facade layer thickness of bioreceptive facade is also reduced. As visible in figure 1 both the green facade and living wall system use more space since the plant roots need area to grow. This makes the bioreceptive facade especially beneficial in urban areas where there is pressure for space.

Altogether can be stated that bioreceptive facades as proposed in this research is a promising new system that has multiple benefits over its competitive green wall systems. Further research is necessary into the bryophyte behaviour under different climatic conditions to state a general conclusion about the effectivity of bryophyte facade panels in cities.

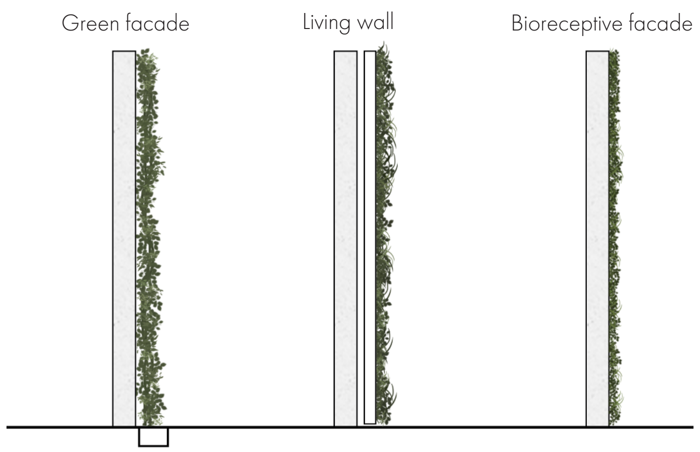


Figure 1 - Green wall systems.

EVALUATION

Bryophytes

For further research it would be interesting to elaborate further on different bryophytes species and the selection of them on their physical properties. As can be subtracted from this research, the type of bryophytes are more effective (in some cases affecting the coverage) if they are desiccation tolerant, high light intensity tolerant, metabolically active until high temperatures, aesthetic when dormant and low in albedo. More research into their physical properties and species can lead to selection of bryophytes on their preferred impact on the climate or specific habitat. Additionally, in this research bryophytes are only measured during summer, their behaviour in other seasons have been disregarded.

Also bryophytes can behave as an insulating layer (the temperature of the bryophytes not necessarily of the ambient) between substrate and ambient temperature. Further field testing necessary to measure behaviour on a stoney surface in urban climate and how this influences the ambient and indoor temperatures. Generally can be stated that the specific climatic variables influencing the bryophyte behaviour in urban climates would be a next chapter in the bioreceptive research.

Architectural design

In this research a design tool has been developed and two panels have been designed accordingly. Due to time restrictions these designs aren't optimized in performance and material use, and they have not been tested in field conditions. The performance of field tests gives feedback on the relation of the moss coverage and the surface properties. Furthermore, field tests lead to more specific guidelines (f.e. maximum radiation endurance or surface angle) which can be implemented in the design tool. The field observations can substantiate the geometrical restrictions in the design tool, increasing its credibility. These restrictions can be implemented in the design to further optimise its effectivity in terms of moss growth and material usage. Additionally, there are still numerous different geometrical possibilities in terms of shape which can be elaborated on and might lead to a more effective shape than the two proposed designs.

Durability and reusability aspects of the facade panels have briefly been addressed in this research. In terms of size, production and applicability in different architectural typologies (also besides residential use) there is still much more to be elaborated on. Additionally, has been mentioned the habitat and substrate diversity in urban environments turn out to be the influential parameters on species richness and distribution. In the panel design different habitat typologies can be created; difference in materials and shapes. These different habitat typologies can be matched with different preferred bryophytes species as mentioned in section bryophytes. Besides facades, other urban surfaces can play a role in this strategy as well.

Urban design

In this research the relation of the physical structure of the city and distinct urban climates have been explained. An important property for bryophyte conditions is the vegetal fraction, since vegetation in known to induce humidity levels in cities. Therefore vegetation fraction influences the effectivity of bryophyte panels in an urban climate.

The relation of orientation (radiation) of bryophyte facade panels with temperature and humidity has been described. The facade system is more effective in terms of temperature reduction once placed on the sun facing surfaces and on the shaded surfaces the panels perform better in humidity induction. These observations can be used in strategically implementing the facade greening in an urban environment. In this research this has only been measured in one street which north-east and south-west facing facade surfaces. This effect also needs to be measured in other directions. On a smaller scale the configuration of bryophytes at different heights on the facade can be an interesting measurement, affecting the facade design.

In the specific configuration increasing the aspect ratio seemed to reduce the effectivity of bioreceptive facade panels despite the induced facade surface amount, suggesting street width has more relation to the facade performance than street height.

REFLECTION

The idea of bioreceptivity appealed to me because of the simplicity in concept and the hands-on focus of research. From the beginning onwards, the question triggered me whether mosses actually grow in urban environments and if bioreceptivity is something feasible if a lot of measures have to be taken in achieving it. Especially, since the simplicity of the concept - the facade acting as a mediating layer - is the strength of the concept. The idea of mosses being affected and contributing to the urban climate has been the initial incentive for this research, which lead me to a broader view on the topic including many different fields such as (urban) climatology and bryology.

The focus on climate is interesting but it proved difficult to grasp the complex systems of the climate and find ways to systematize or add focus to it such that it makes sense. After the P2 retake the focus switched from a hands-on approach towards simulations which suited the (broad) focus of the research and it's time frame better. The combination of literature review validated by field observations (the field survey) contributed to substantiate the conclusions and choices, and in the end bridge the relationship between the research and design in this research. The relationship between the research and design is established in a stepwise manner; the field observations laid the foundations for the design tool and the tool has been used to create two different panel designs. Unfortunately, the validation of (or feedback on) the design tool is missing in this research due to time restrictions. This would have been an interesting contribution to this research.

For the selection of different urban zones in case study area Rotterdam the Local Climate Zone classification method proved to be very useful to select different urban configurations influencing the urban climate. This classification contributed to make substantiated statements about representativity of neighborhoods in The Netherlands. As well as the typical physical urban properties of the different climate zones, which have been used in setting simulation input.

The research is carried out on a lot of different scales; the literature review starts on a global scale and it narrows down to facade details, ending with a more general conclusion. Because of these different scales it touches upon wider scientific fields (urbanism and architecture) as can be noted in the 'elaboration' section of this research. This broad view on the topic of bioreceptivity has made this research eminently one where more questions are raised during research than answers given.

An ethical issue constraint to this research is the use of photographs of existing streets/houses without permission of the owners. However, no persons are present in the images to ensure it is not in conflict with the law. At last can be said that the Covid-19 circumstances influenced this research. Besides the challenges involving trying to work at home, the use of ENVI-met has been limited due to simulation time and licence restrictions which has negatively affected this research.

CONTRIBUTORS

The research in this thesis is carried out as graduation project at the Technische Universiteit Delft, track Building Technology.

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Software:
Adobe Illustrator, Photoshop, Indesign,
Premiere Pro
Microsoft Excel/Word
AutoCAD 2019
ENVI-met 4.4.4.
Rhinoceros 6 with plug-ins Grasshopper, Ladybug,
Dragonfly (beta version)
V-Ray for Rhino

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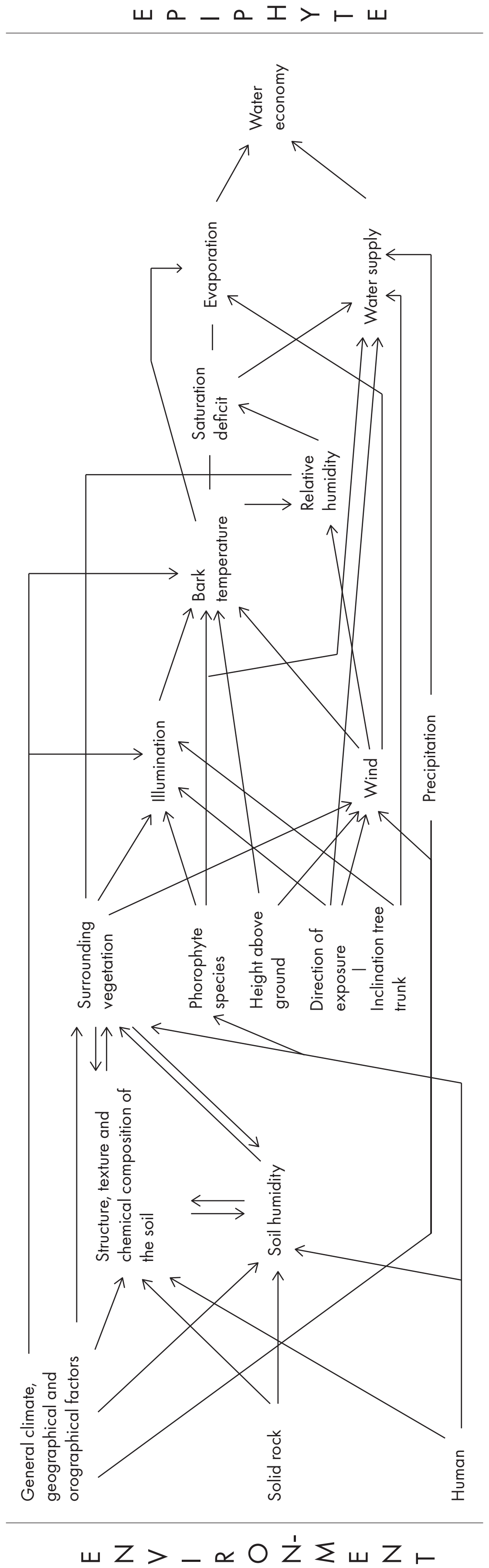
APPENDIX

A



Scheme reproduced from Barkman, 1958

B

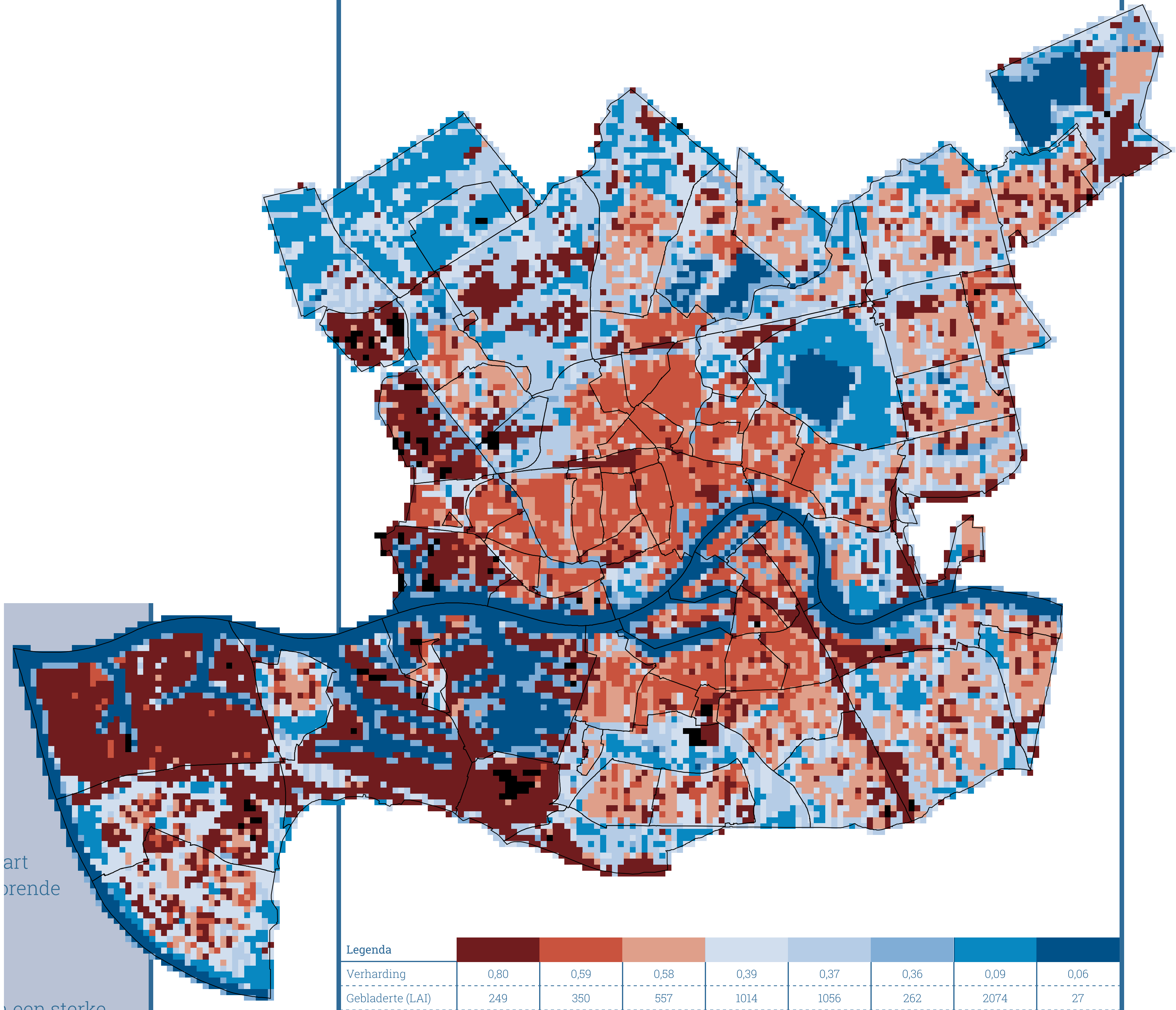
Table 2.2 Typical properties found in the Built Zone series of the Local Climate Zone (LCZ) classes illustrated in Figure 2.9. A detailed tabulation of all LCZ classes including additional properties can be found in Stewart and Oke (2012).

Local Climate Zone	Building plan fraction[1], λ_b (%)	Impervious plan fraction[2], λ_i (%)	Canyon aspect ratio[3], $\lambda_s = H/W$	Sky view factor, ψ_{sky}	Mean height of roughness elements, z_H (m)	Thermal admittance[4] of system, μ (J m^{-2} s$^{-1/2}$ K^{-1})	Anthropogenic heat flux density[5], Q_F (W m^{-2})
LCZ 1 Compact high-rise	40–60	40–60	> 2	0.2–0.4	> 25	1,500–1,800	50–300
LCZ 2 Compact midrise	40–70	30–50	0.75–2	0.3–0.6	10–25	1,500–2,200	< 75
LCZ 3 Compact lowrise	40–70	20–50	0.75–1.5	0.2–0.6	3–10	1,200–1,800	< 75
LCZ 4 Open high-rise	20–40	30–40	0.75–1.25	0.5–0.7	> 25	1,400–1,800	< 50
LCZ 5 Open midrise	20–40	30–50	0.3–0.75	0.5–0.8	10–25	1,400–2,000	< 25
LCZ 6 Open lowrise	20–40	20–50	0.3–0.75	0.6–0.9	3–10	1,200–1,800	< 25
LCZ 7 Lightweight lowrise	60–90	< 20	1–2	0.2–0.5	2–4	800–1,500	< 35
LCZ 8 Large lowrise	30–50	40–50	0.1–0.3	> 0.7	3–10	1,200–1,800	< 50
LCZ 9 Sparsely built	10–20	< 20	0.1–0.25	> 0.8	3–10	1,000–1,800	< 10
LCZ 10 Heavy industry	20–30	20–40	0.2–0.5	0.6–0.9	5–15	1,000–2,500	> 300

(1) Plan area fraction of ground covered by buildings.
(2) Plan area fraction of ground covered by impervious surfaces.
(3) Ratio of mean height of buildings to mean street width (LCZ 1–7) or distance between houses and trees (LCZ 8–10).
(4) Thermal property governing ease with which a body accepts or releases heat at its surface. Values are typical range for surfaces in each LCZ (e.g., buildings, roads, soils). Varies with soil wetness and density of materials (see Section 6.3).
(5) Heat released per area as a result of human activities, e.g. due to combustion of fuels. Mean annual values at local, not building, scale. Varies with heating/cooling degree days and season (see Section 6.2).

Table copied from Oke, Mills, Christen, & Voogt, 2017

C

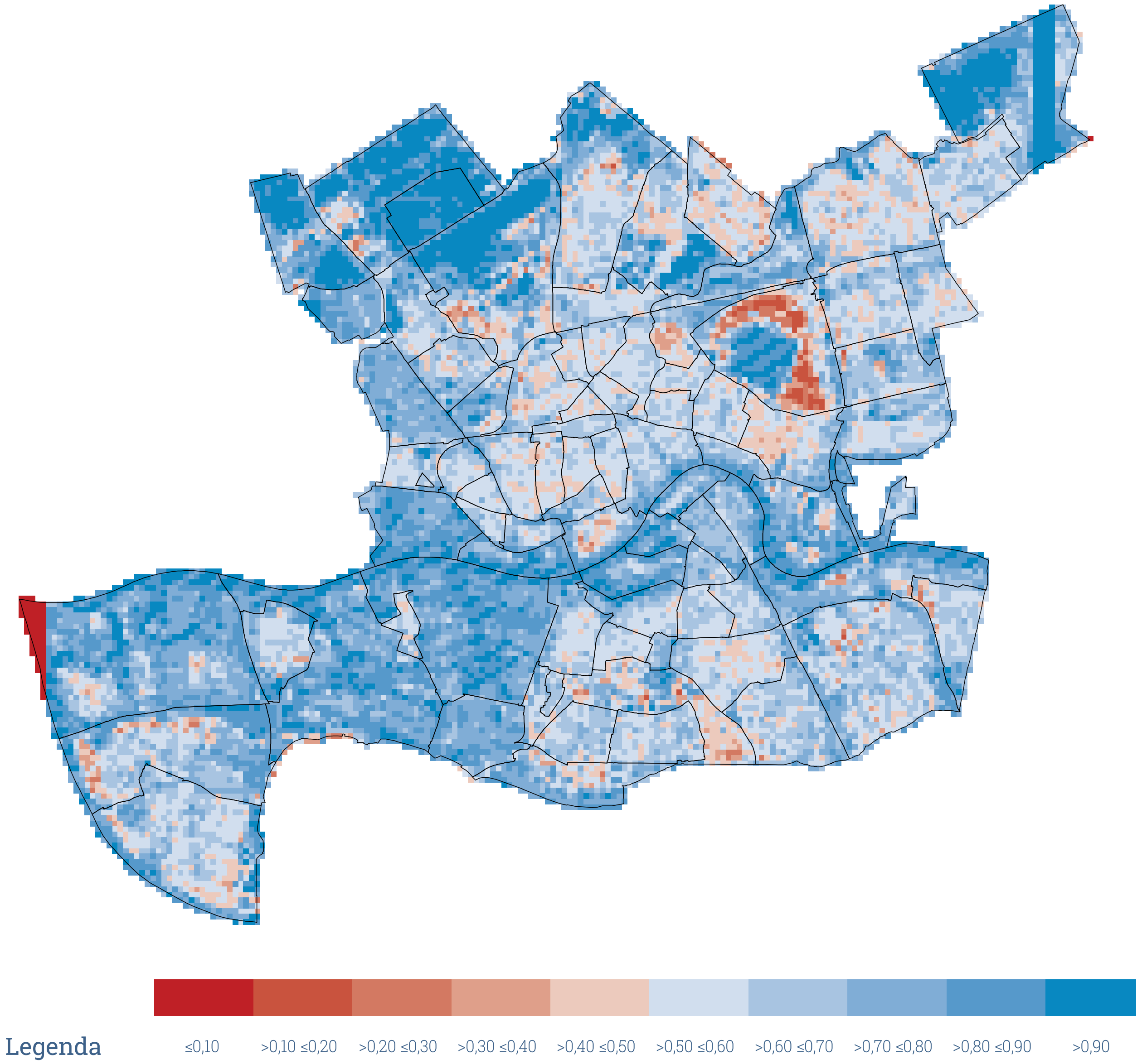


Legenda								
Verharding	0,80	0,59	0,58	0,39	0,37	0,36	0,09	0,06
Gebladerte (LAI)	249	350	557	1014	1056	262	2074	27
Gebouwschil	1261 m^2/ha	8136 m^2/ha	4269 m^2/ha	1139 m^2/ha	663 m^2/ha	732 m^2/ha	136 m^2/ha	23 m^2/ha
Oppervlaktewater	3%	2%	4%	7%	8%	54%	8%	96%
Schaduw	2,4	2,8	3,9	1,4	4,5	2,9	2,8	2,5
QH + QS	456 W/m^2	406 W/m^2	375 W/m^2	324 W/m^2	316 W/m^2	311 W/m^2	242 W/m^2	119 W/m^2

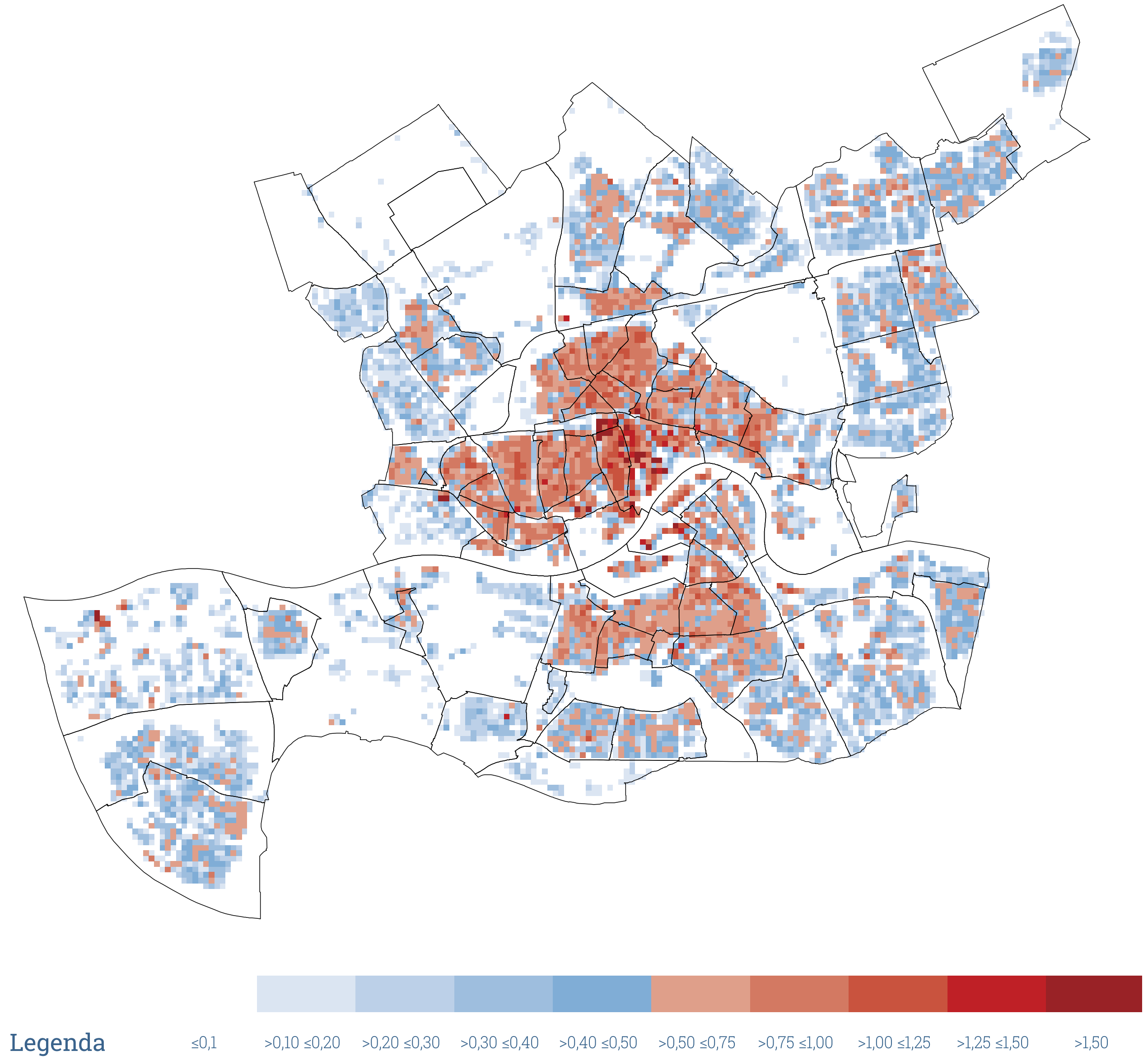
Resultaten clusteranalyse Warmtekaart Fysiek.

Warmtekaar

Maps copied from (Van der Hoeven & Wandl, 2015)



SVF index in Rotterdam, map copied from (Van der Hoeven & Wandl, 2015)



Building surface in Rotterdam, map copied from (Van der Hoeven & Wandl, 2015)

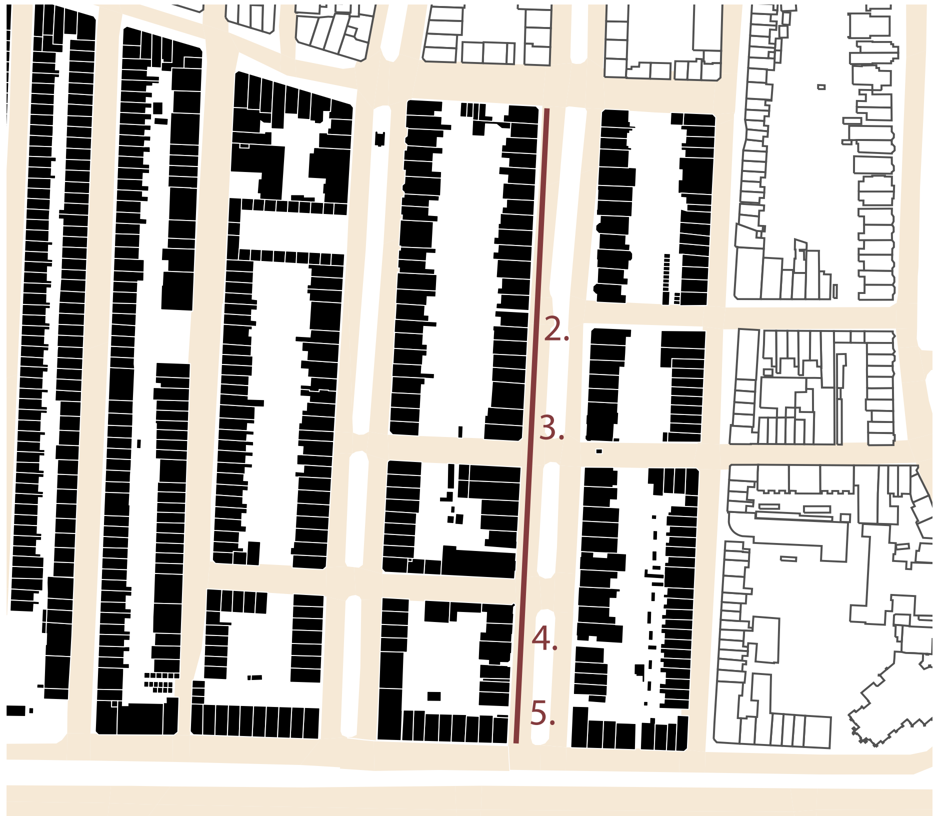
D

FIELD SURVEY

LCZ 5 - Open Midrise
(1) Housing facing north-west

LCZ 5 - Open Midrise
(1) Central reservation

LCZ 5 - Open Midrise
(1) Housing facing south-east



LCZ 5 - Open Midrise
(2) Housing facing north-west

LCZ 5 - Open Midrise
(2) Central reservation

LCZ 5 - Open Midrise
(2) Housing facing south-east

LCZ 3 - Compact lowrise
(1) Housing facing north-west

LCZ 3 - Compact lowrise
(1) Housing facing south-east

LCZ 3 - Compact lowrise
(2) Housing facing south-east

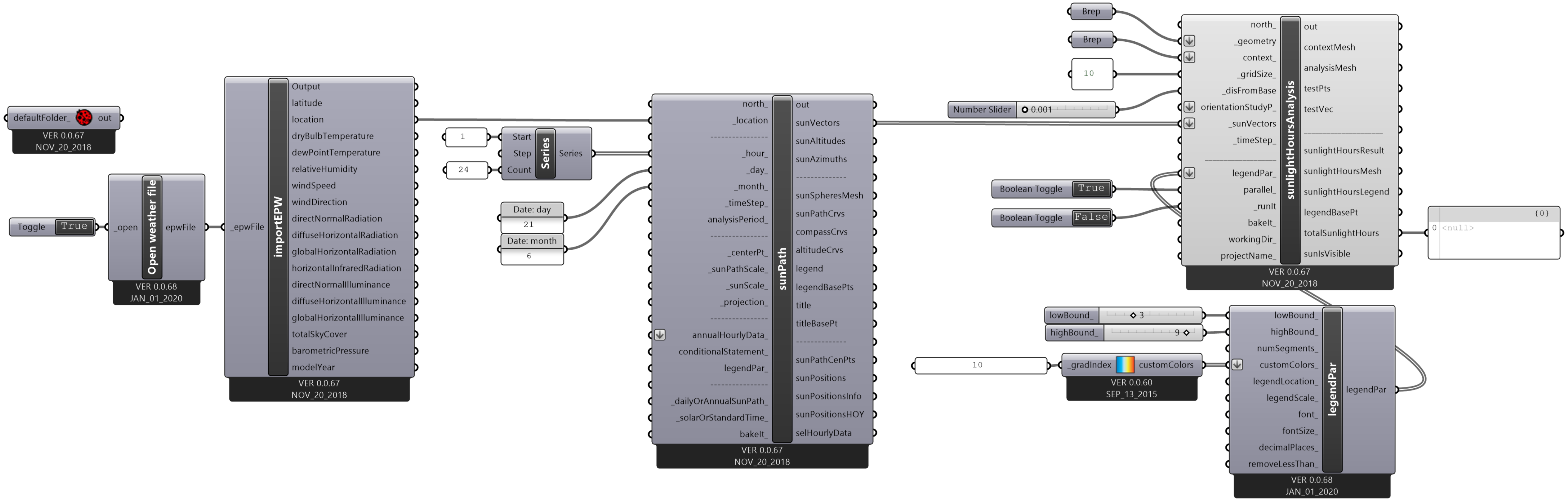
LCZ 3 - Compact lowrise
(2) Housing facing north-west

LCZ 3 - Compact lowrise
(3) Housing facing south-east

LCZ 3 - Compact lowrise
(3) Housing facing north-west

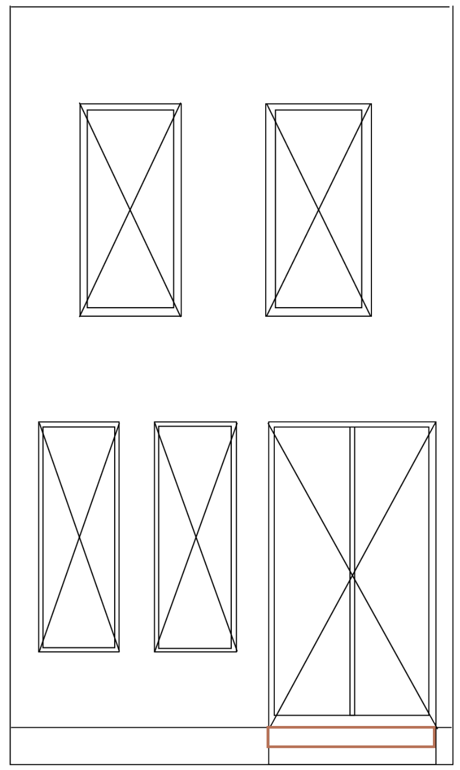
E

RADIATION ANALYSIS INPUT

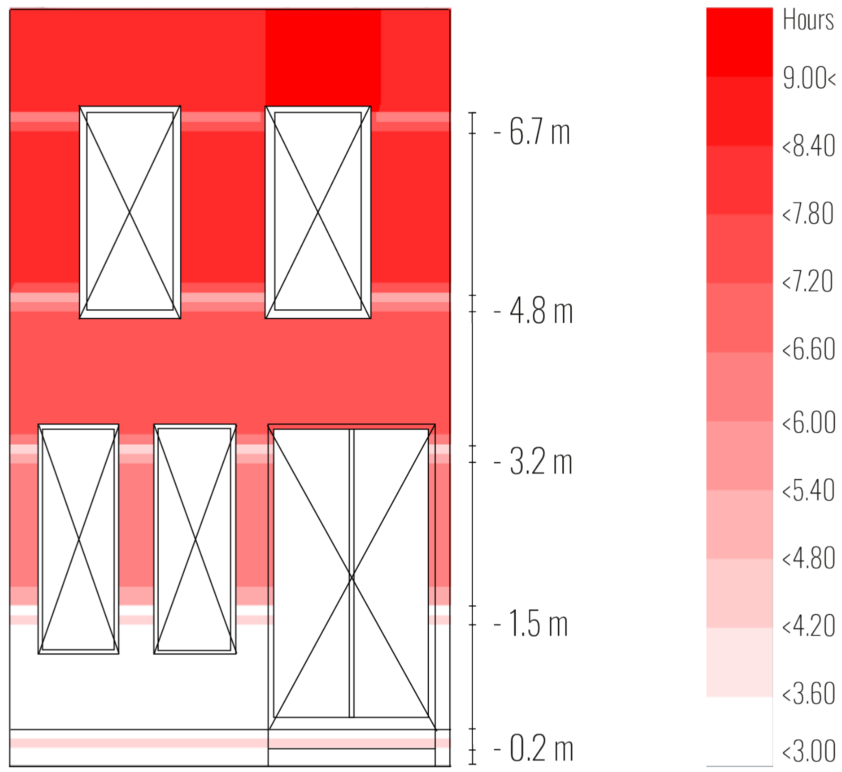


F

RADIATION ANALYSIS FACADE



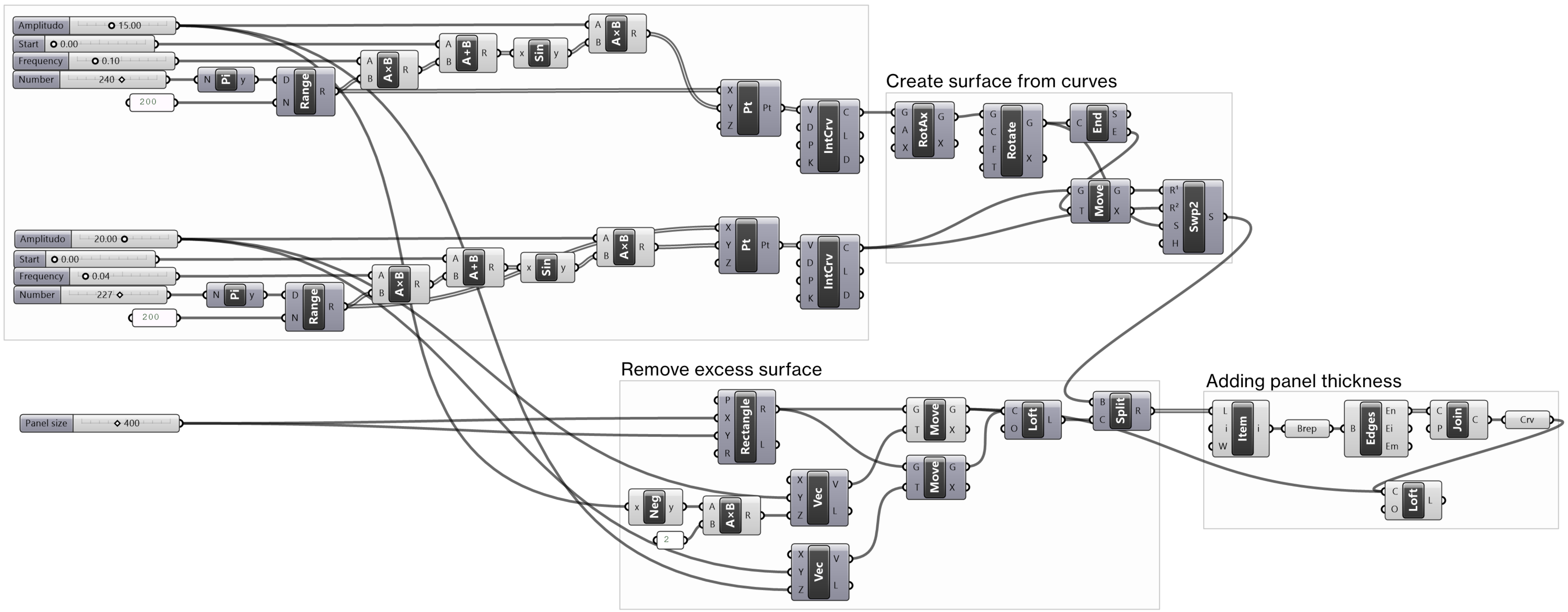
Location observed vertical bryophyte growth



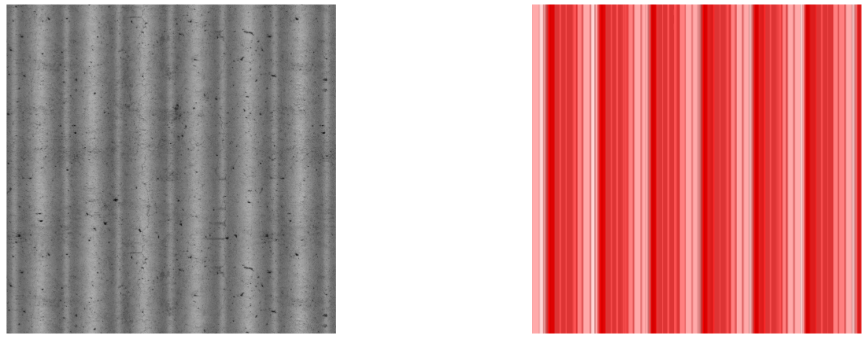
Radiation analysis of shaded surface on different heights (0.2/1.5/3.2/4.8/6.7)

G

GEOMETRY PANEL 1



H
RADIATION
ANALYSIS
PANEL 1



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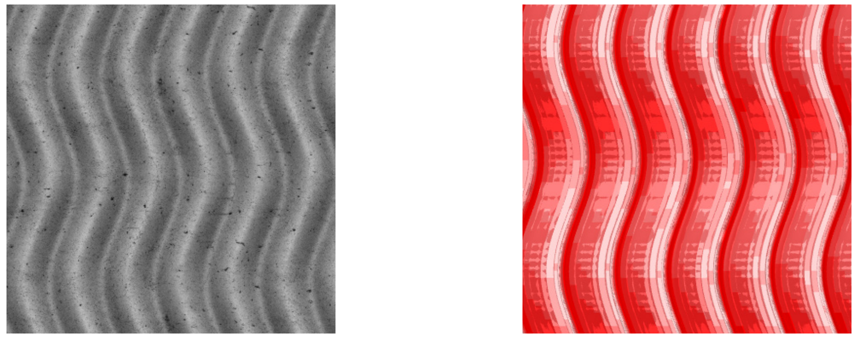

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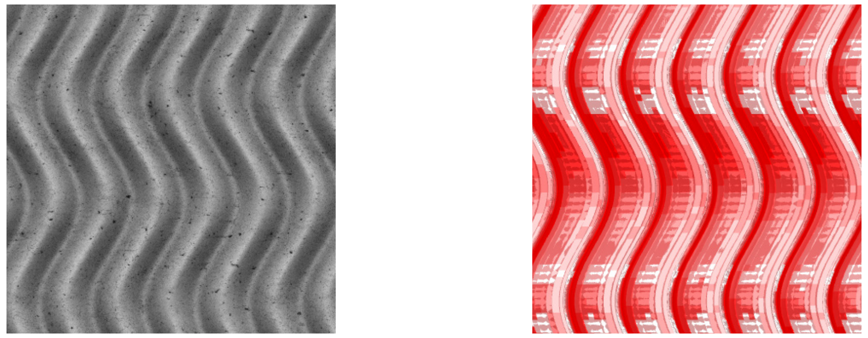

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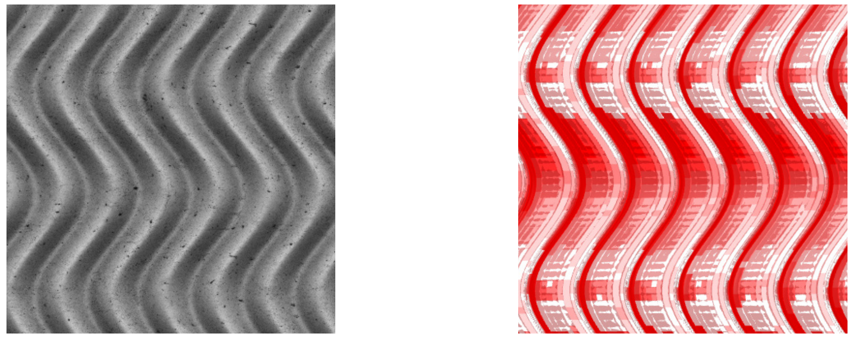

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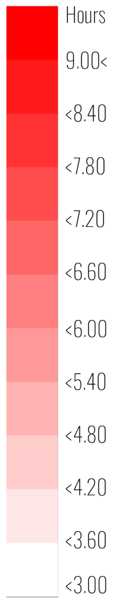

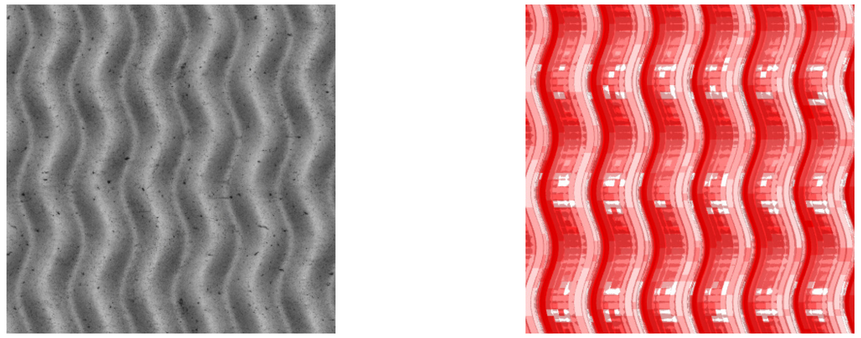

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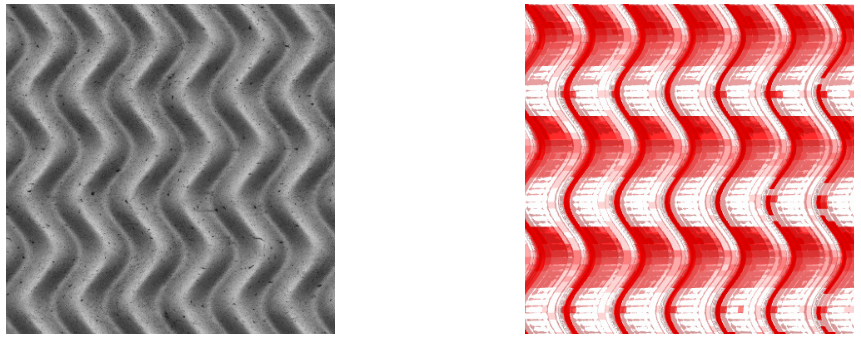

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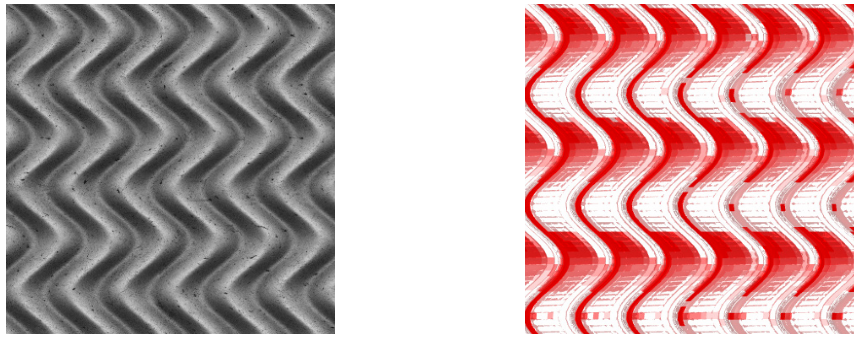

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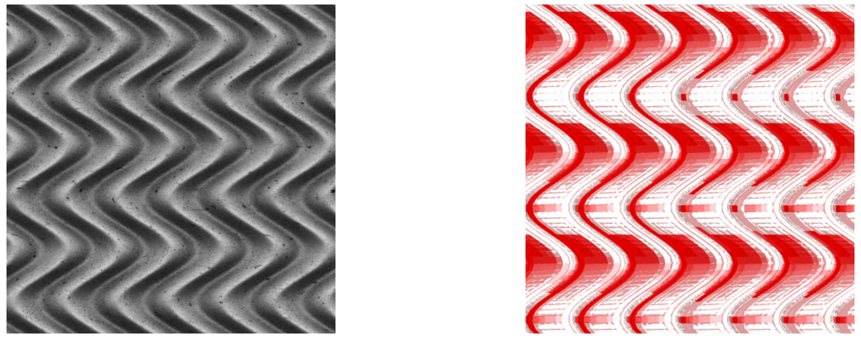

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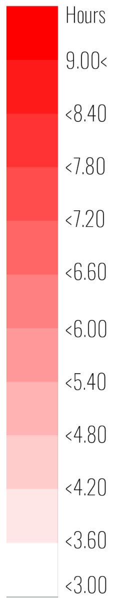
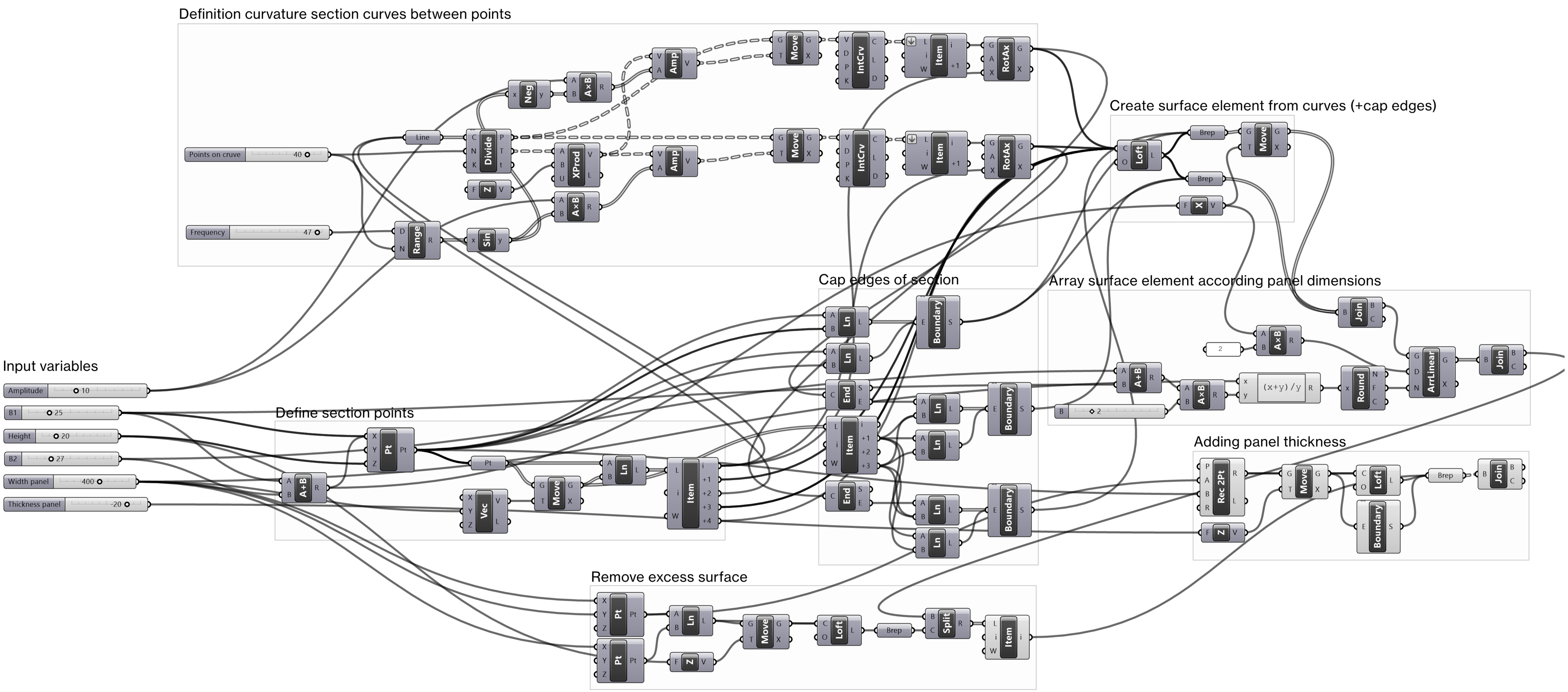
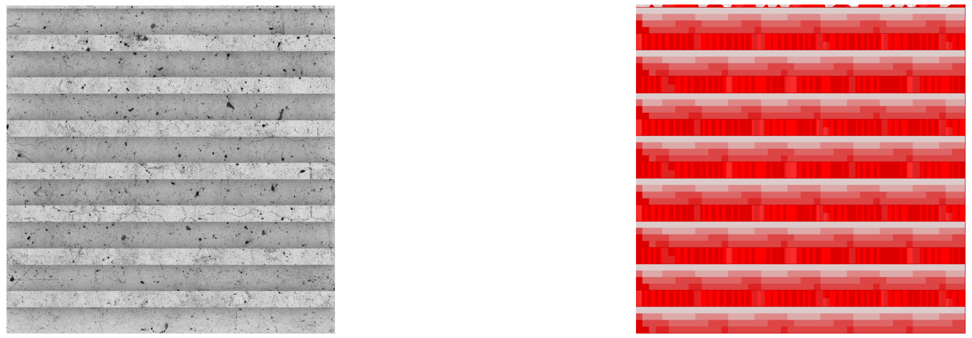


SCRIPT GEOMETRY PANEL 2 FINAL DESIGN (T.2.1)



J
RADIATION ANALYSIS PANEL 2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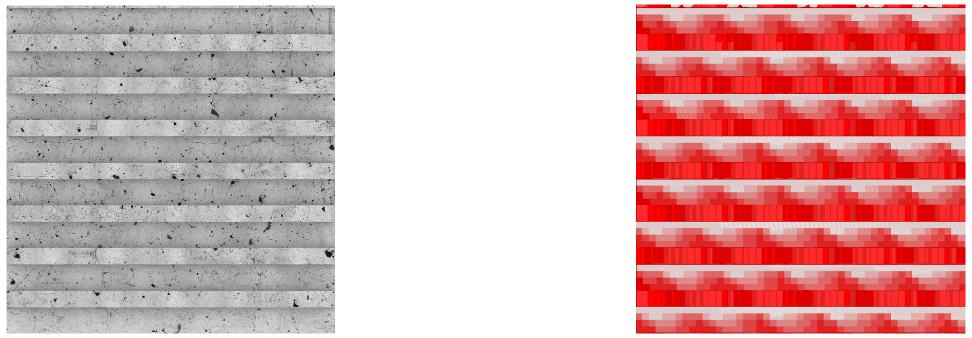
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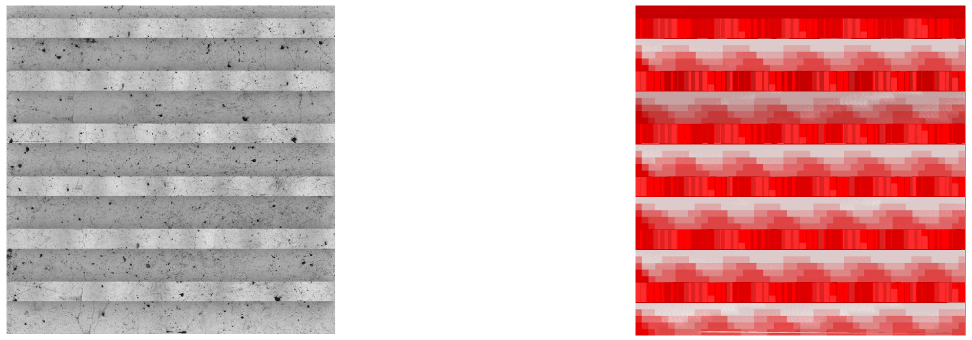
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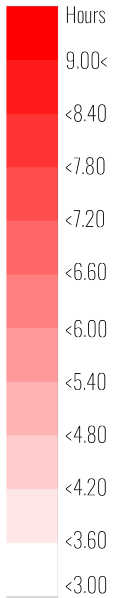

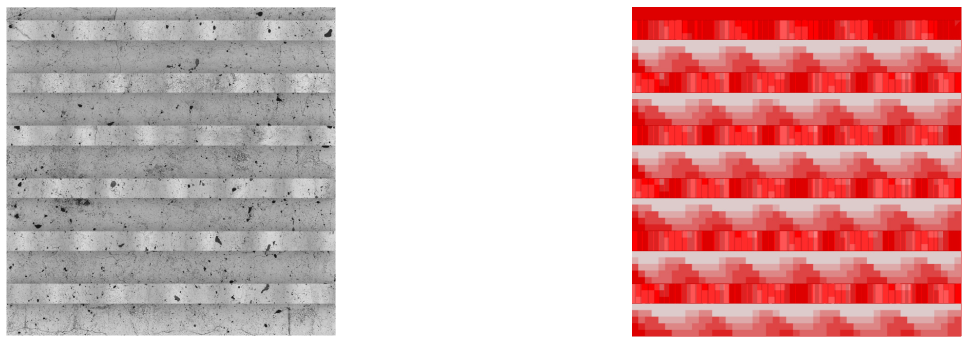
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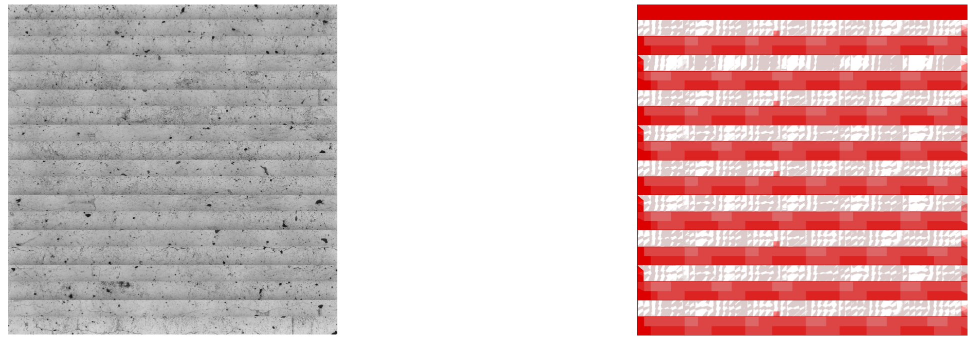
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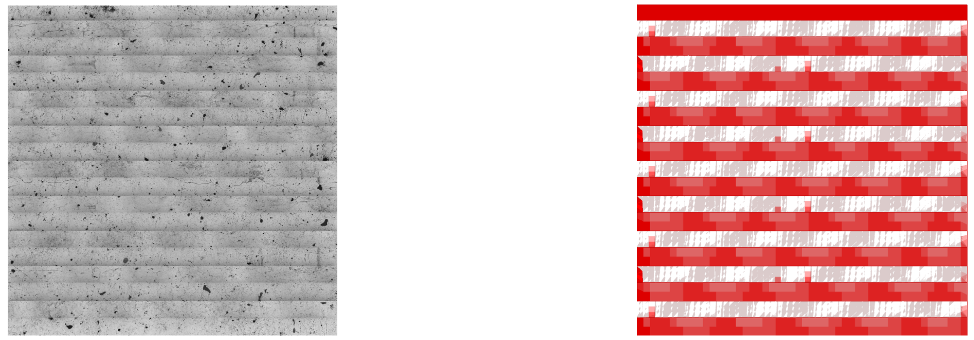
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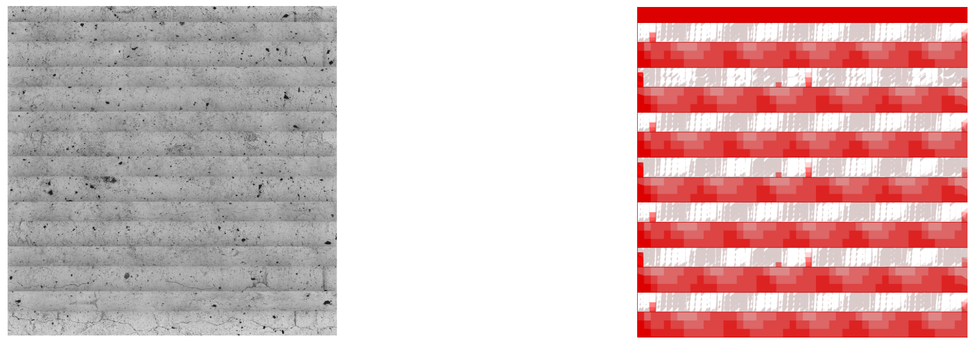
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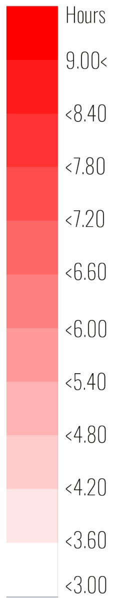
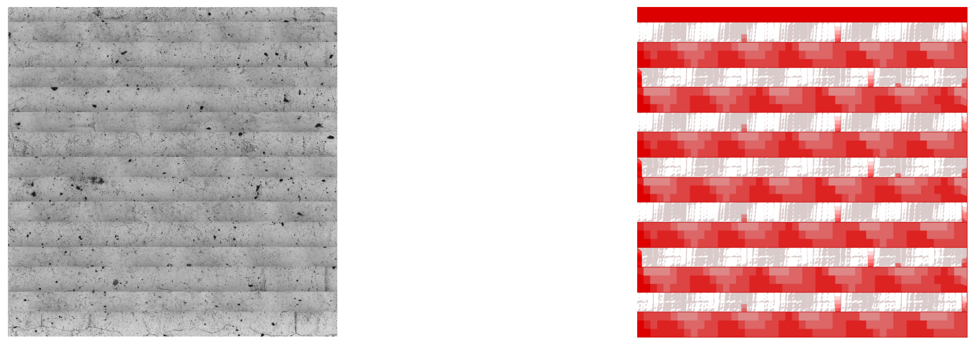
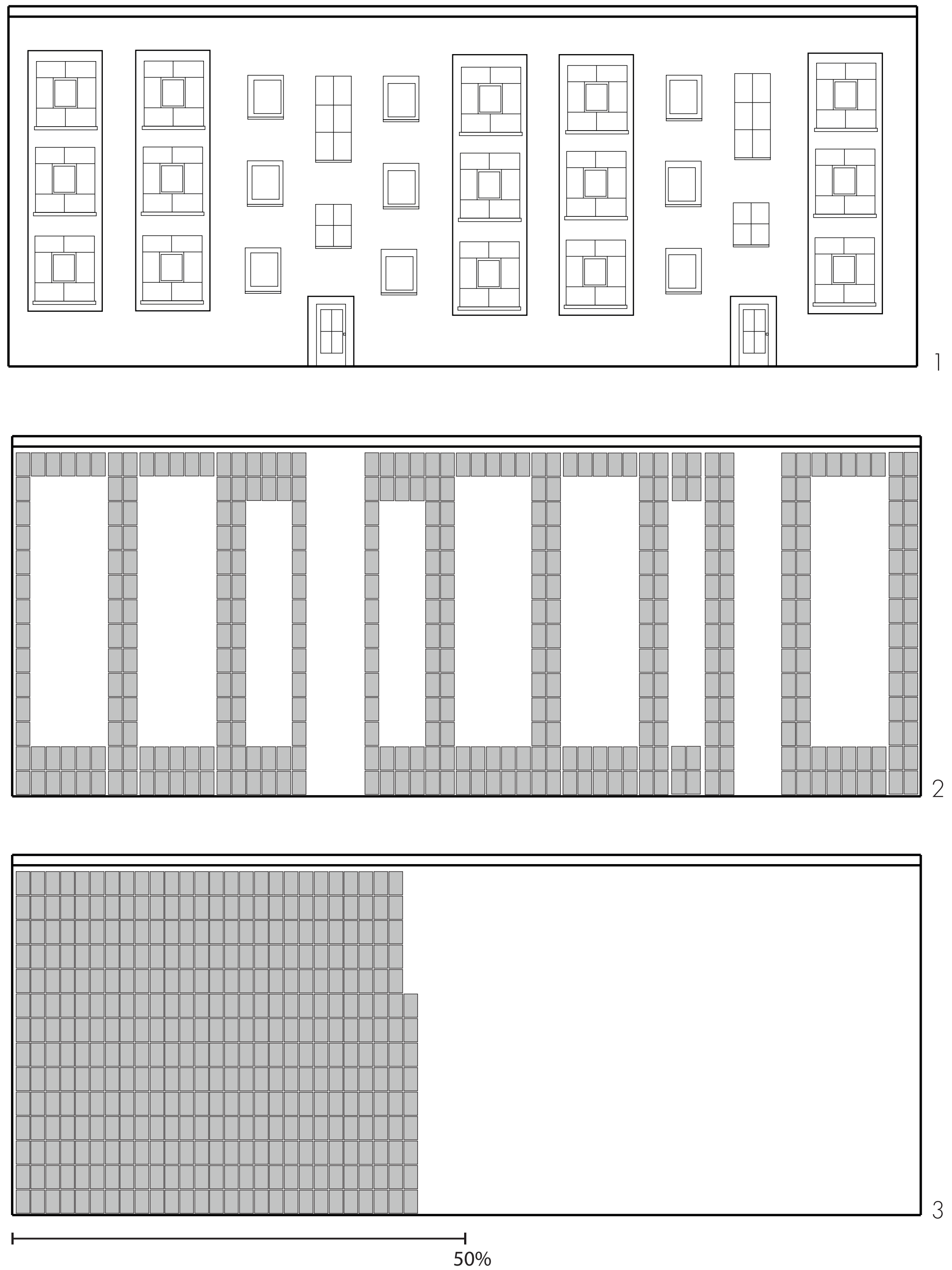
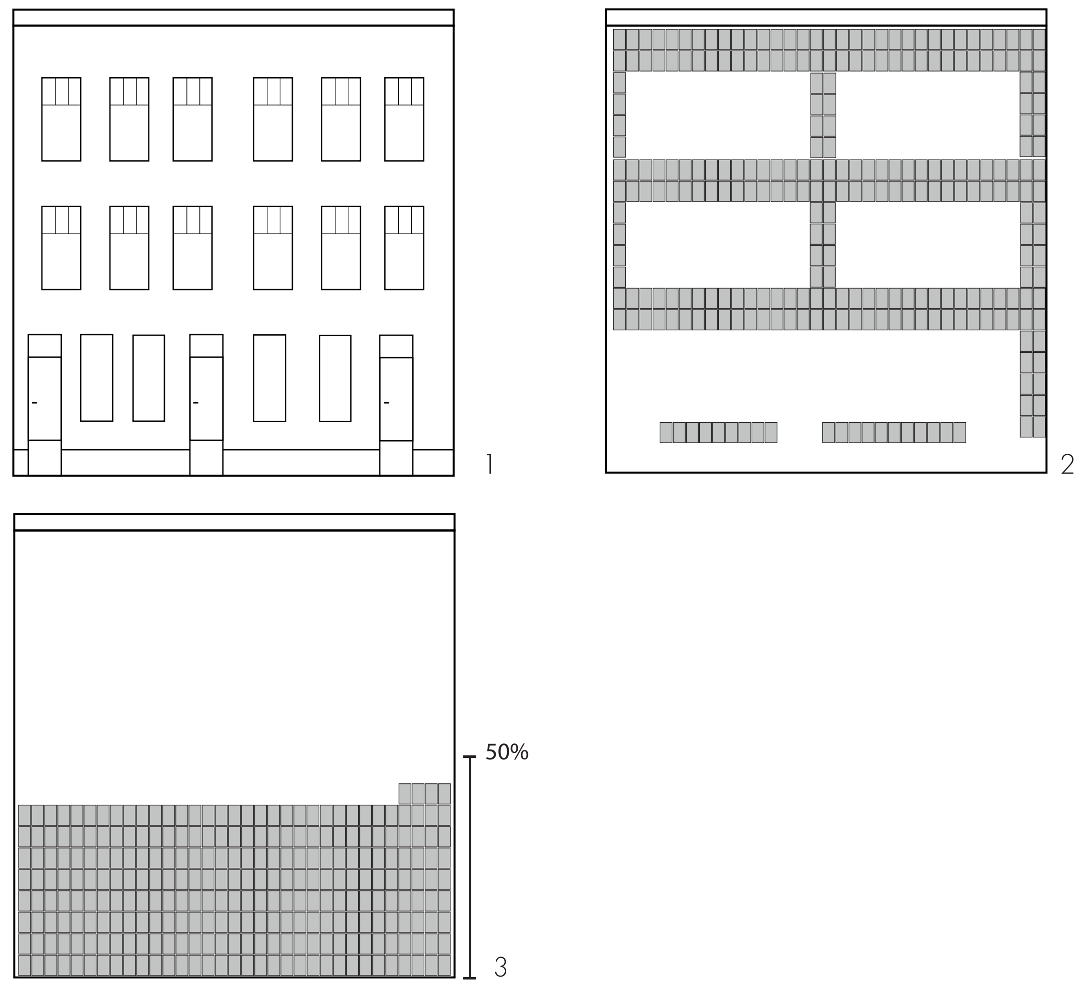



T.2.2

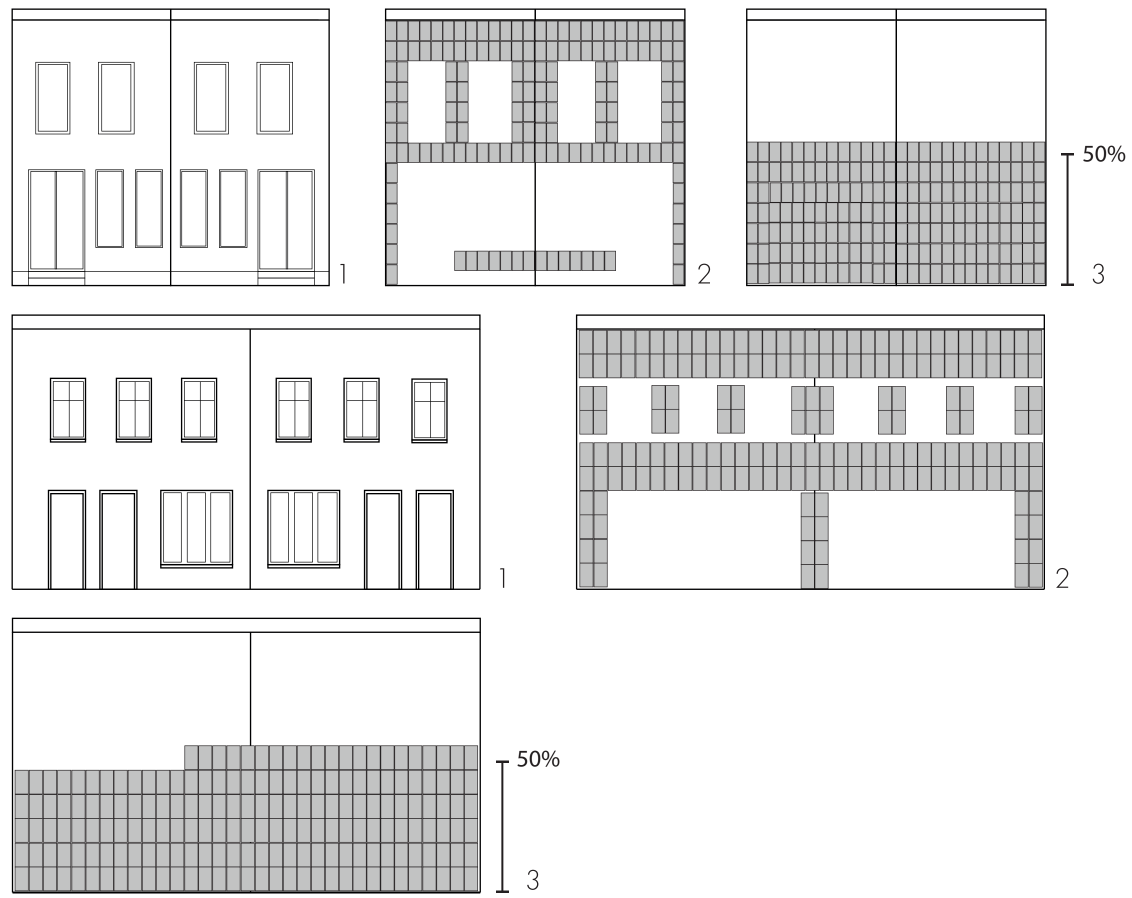
K FACADE COVERAGE SCHEMES

LCZ 5 - Schemes of coverage percentage, (1) original facade (2) facade with panels (3) coverage



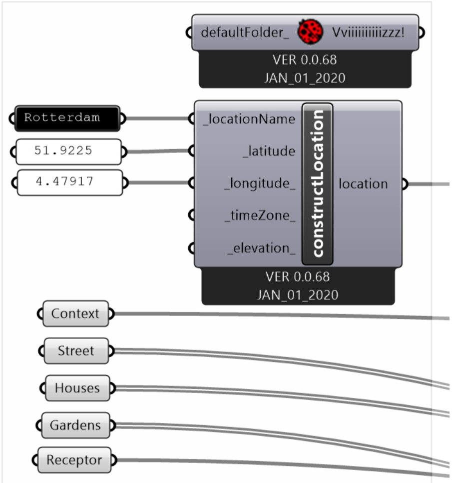


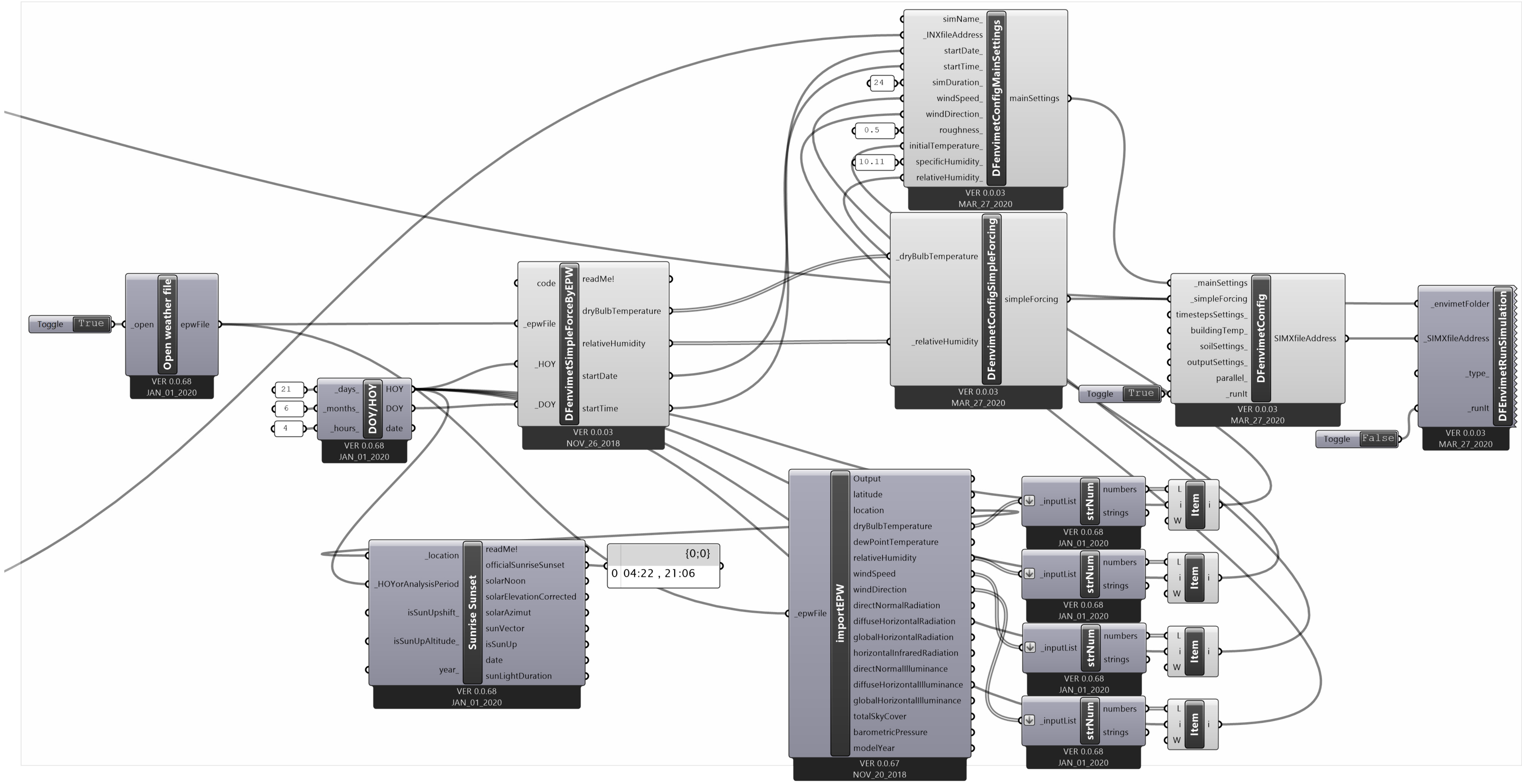
LCZ 3 - Schemes of coverage percentage, (1) original facade (2) facade with panels (3) coverage



L

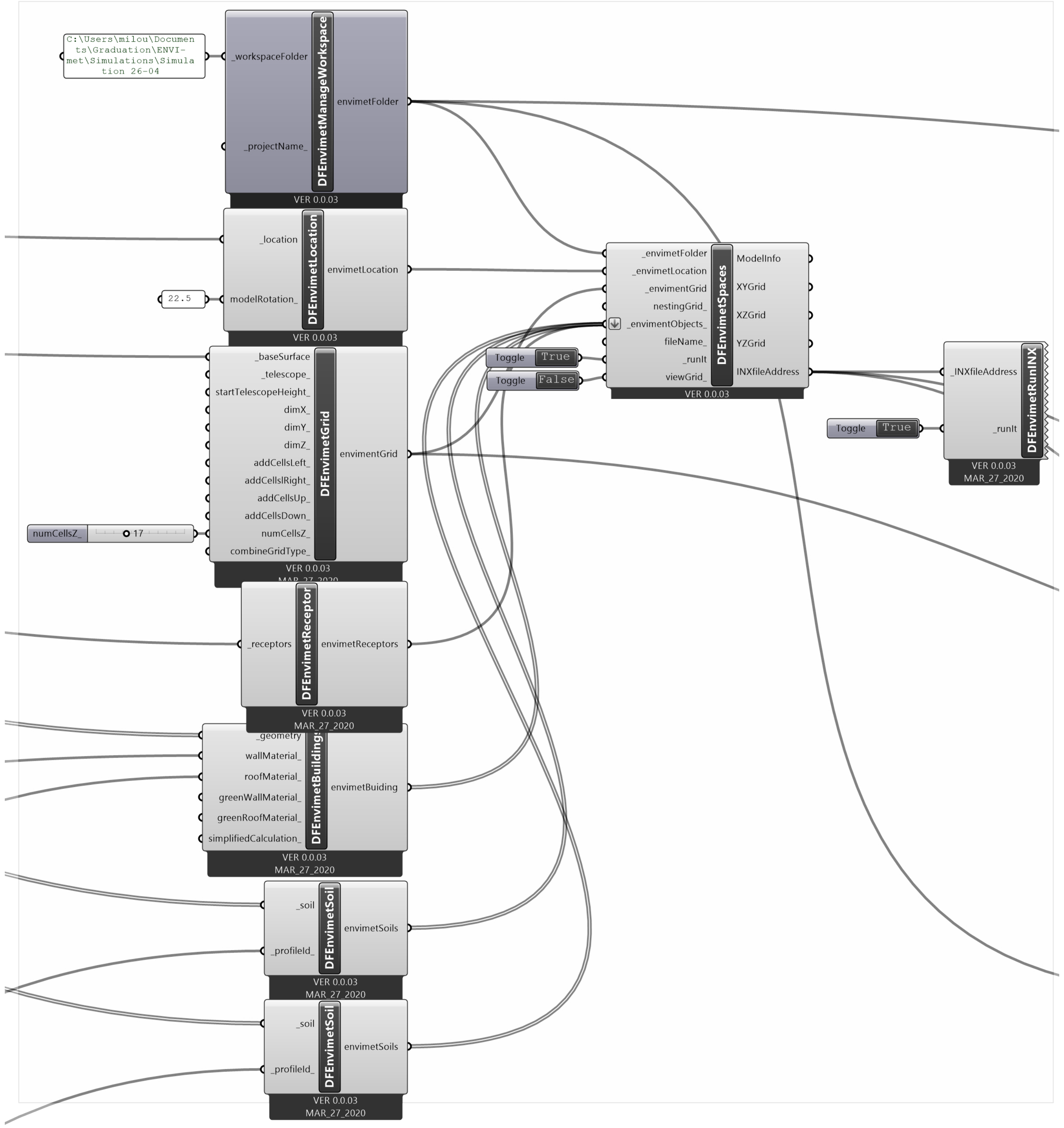
DEFINITION SIMULATION INPUT

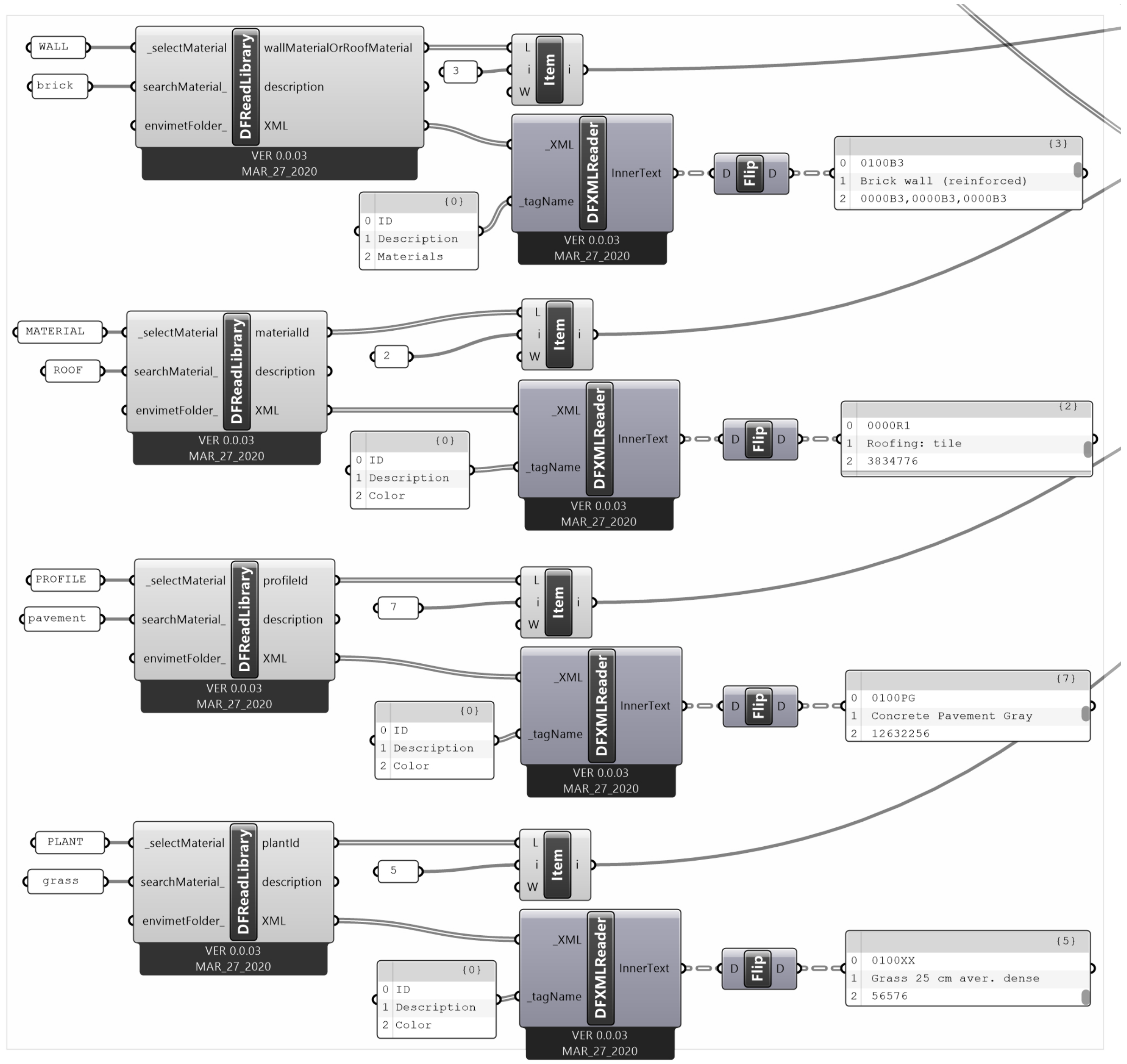


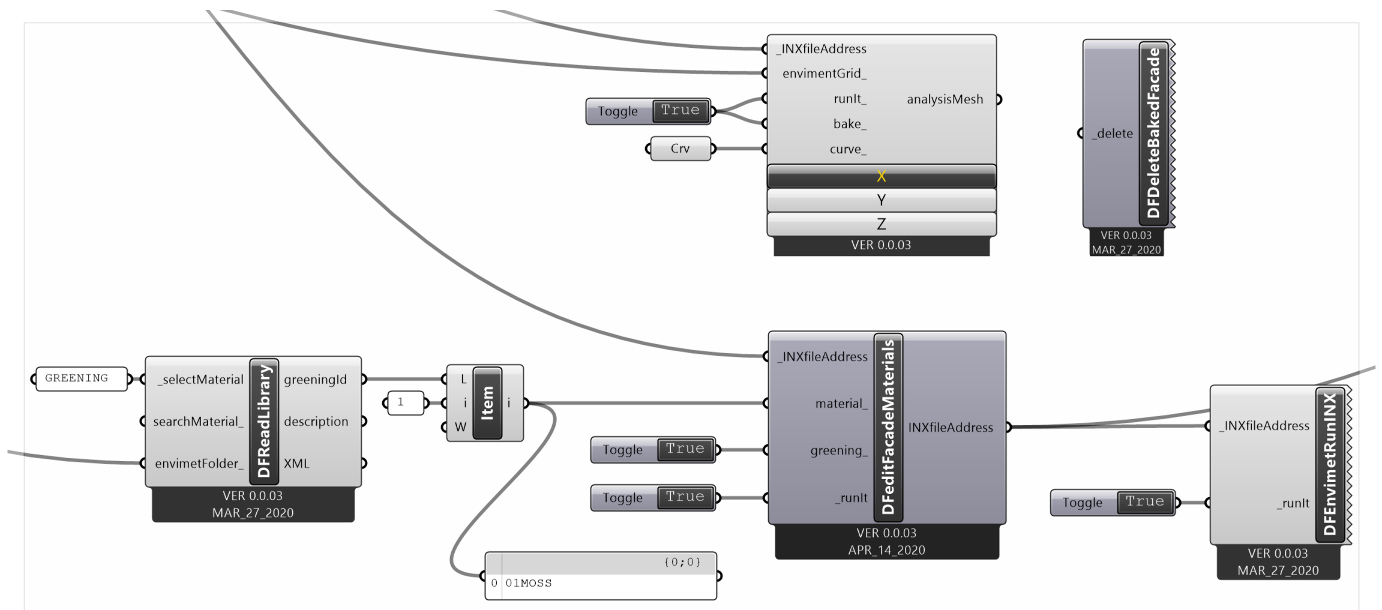


L

DEFINITION CONTEXT MODEL







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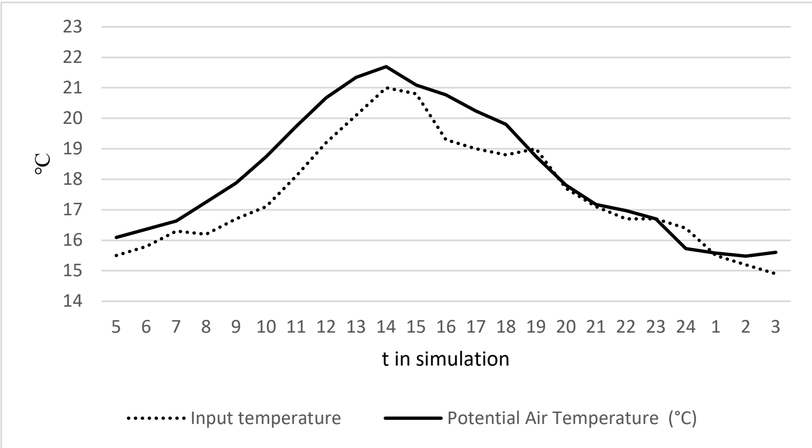
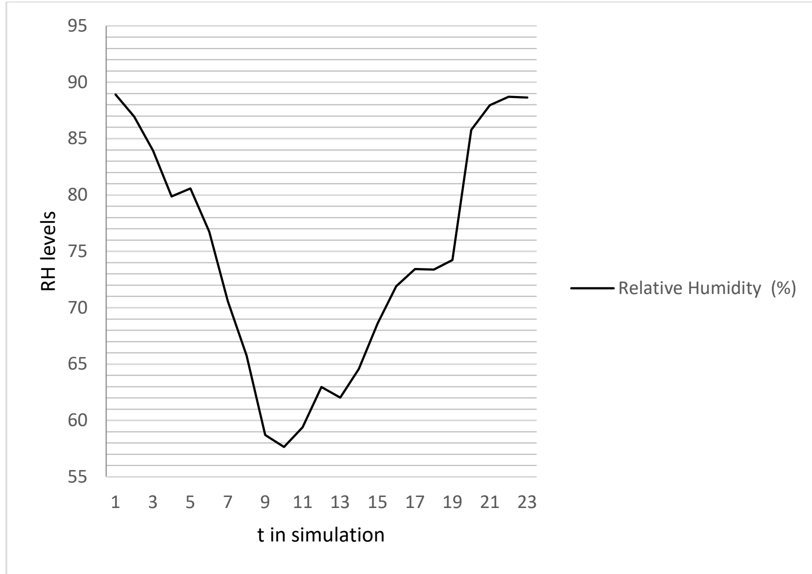
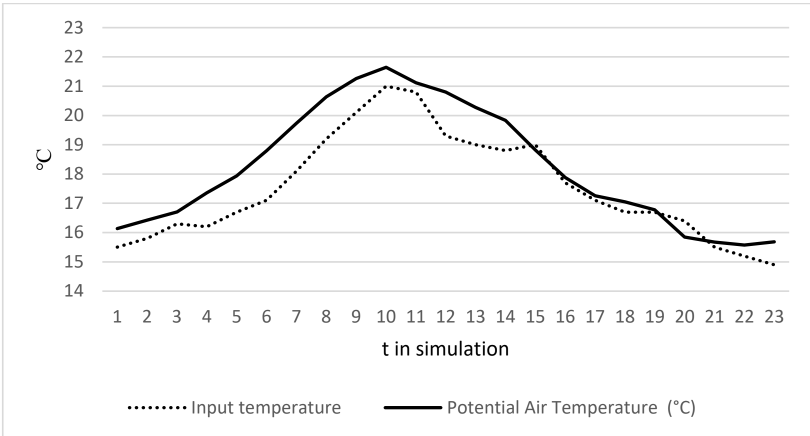


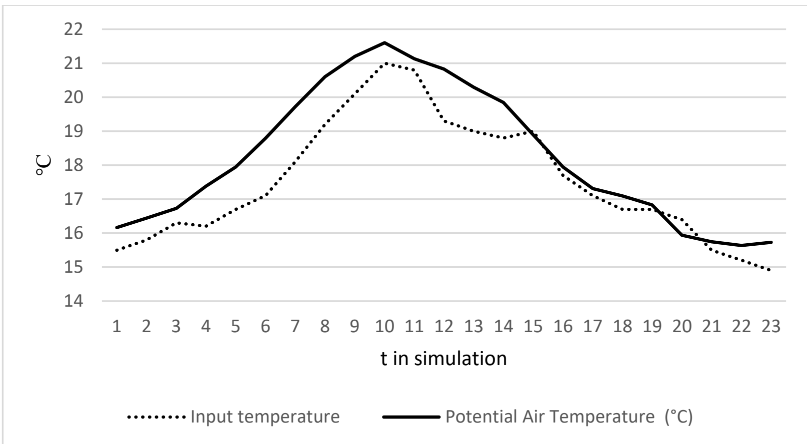
VARIATION 1.1
TEMP. MIDDLE CANYON



VARIATION 1.1
RH MIDDLE CANYON

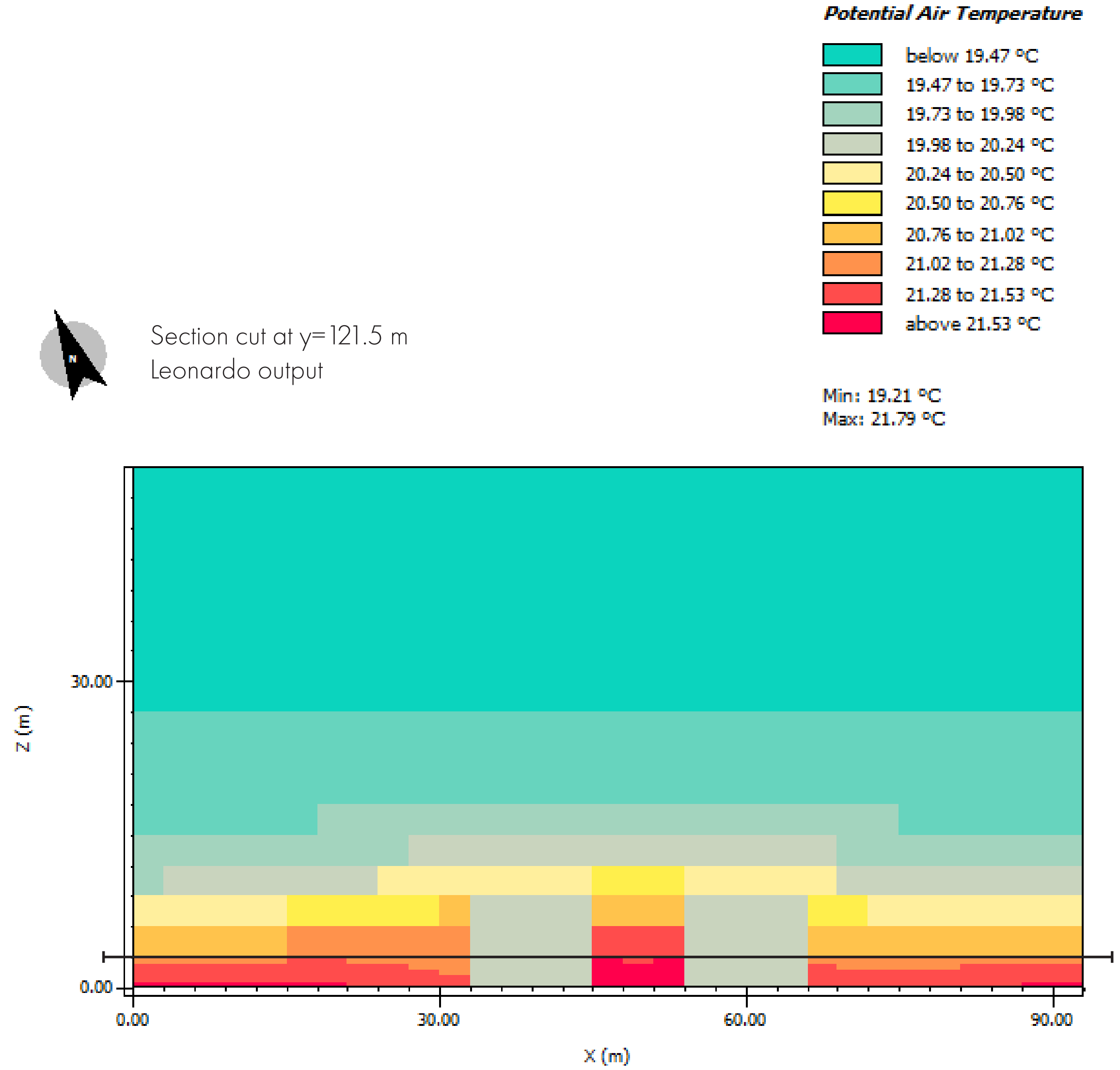


VARIATION 1.2
TEMP. MIDDLE CANYON

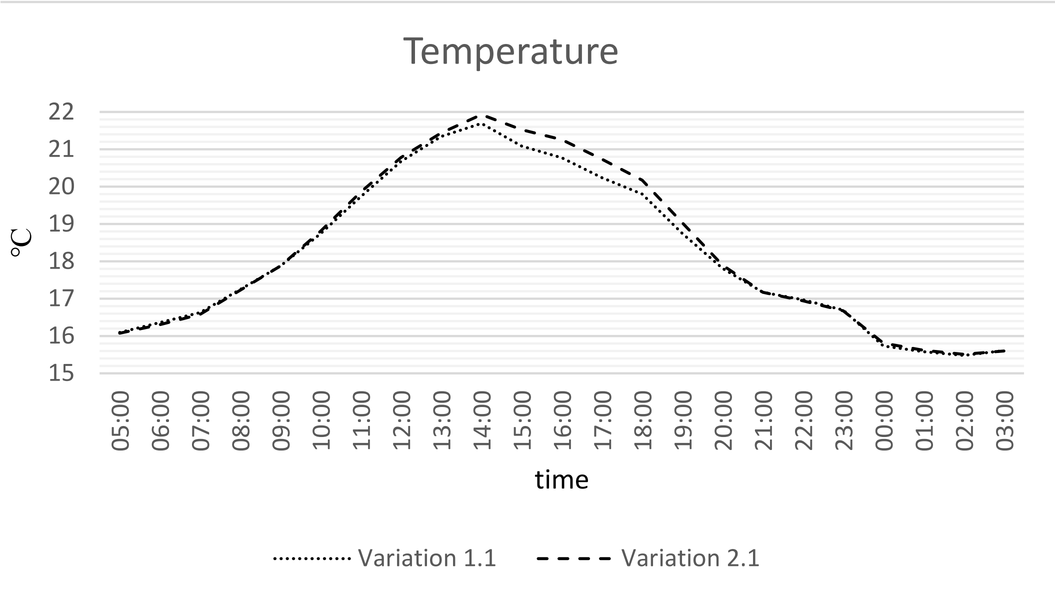


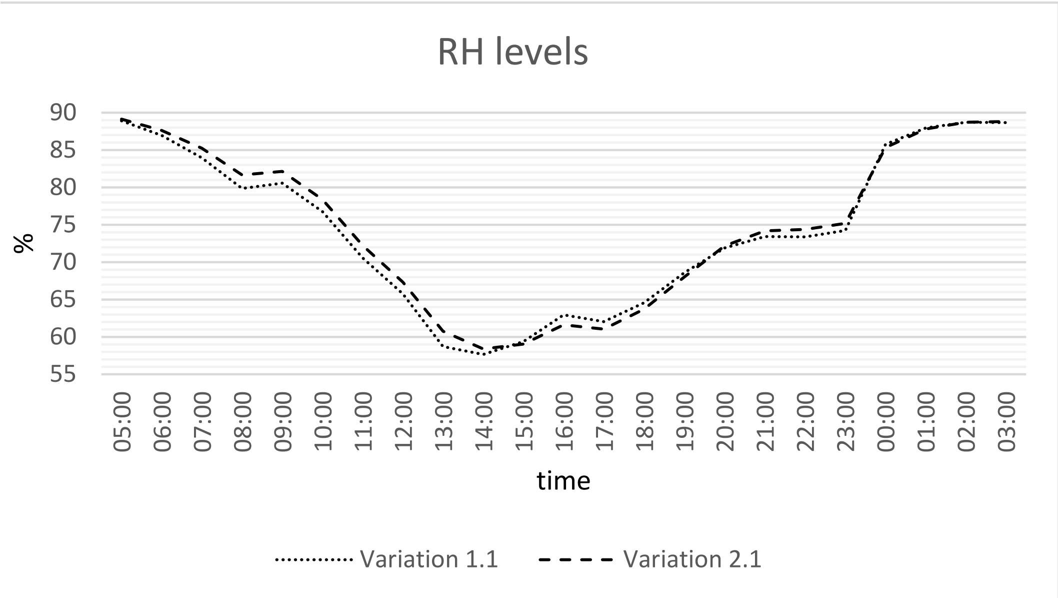
VARIATION 1.3
TEMP. MIDDLE CANYON

VERTICAL SECTION

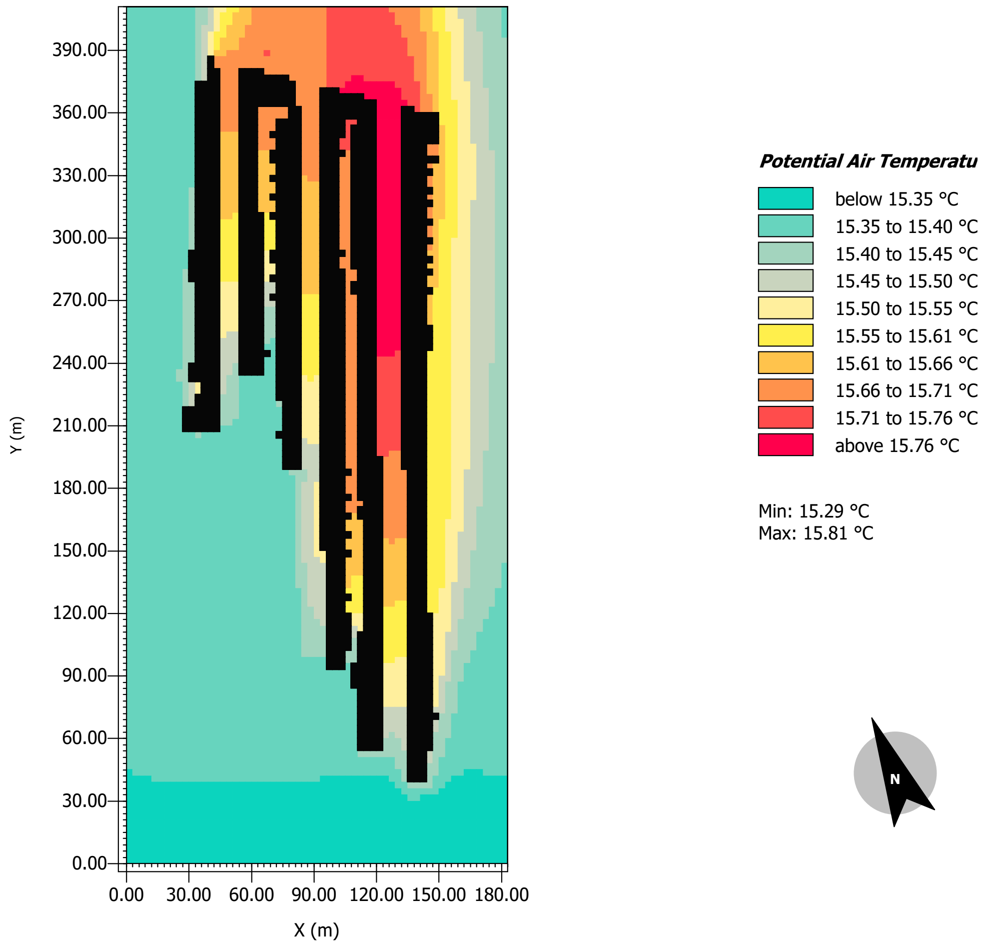


VARIATION 2.1



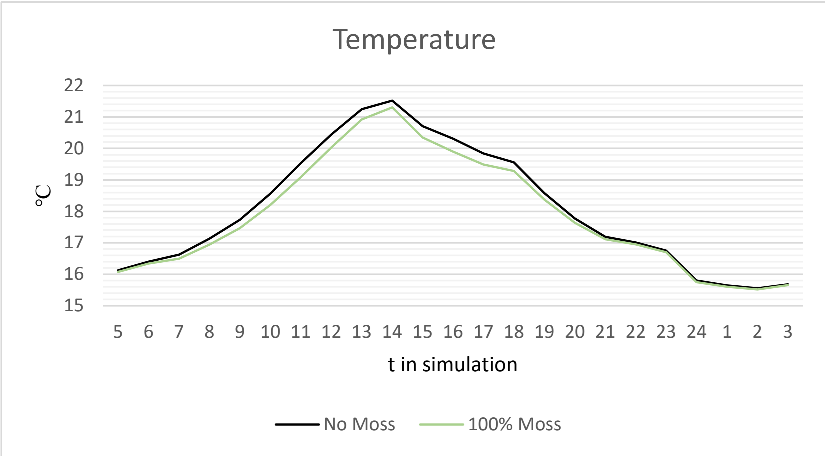


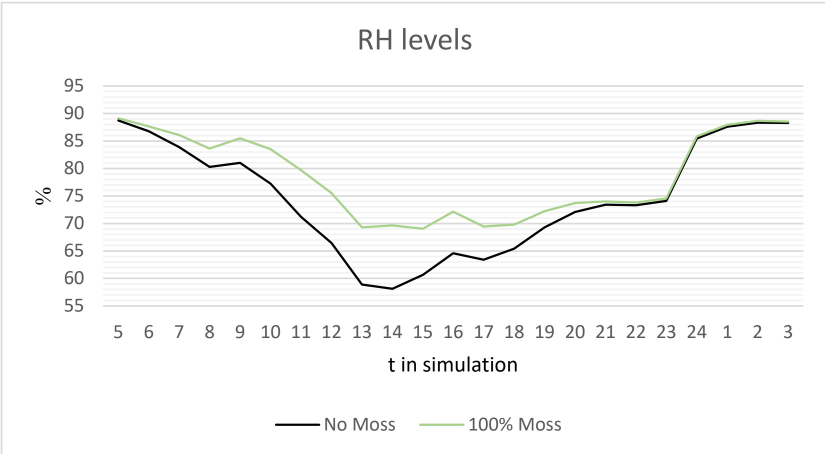
VARIATION 2.1 NIGHT TEMPERATURES



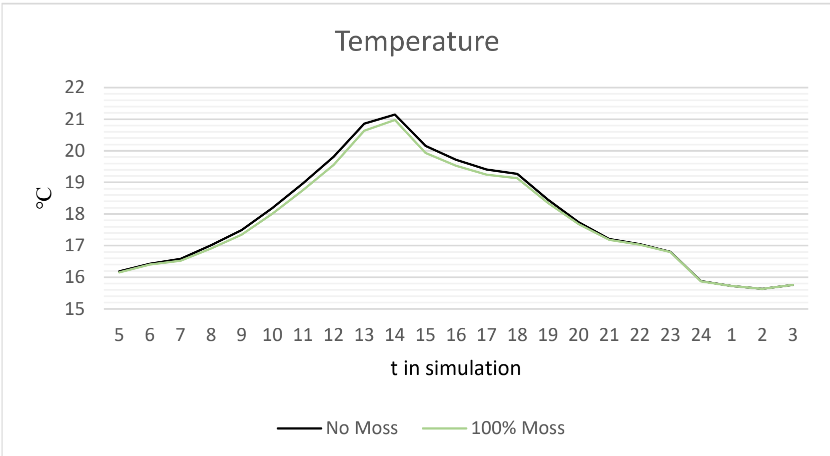
Section cut at 1.5 m height (03:00)
Leonardo output

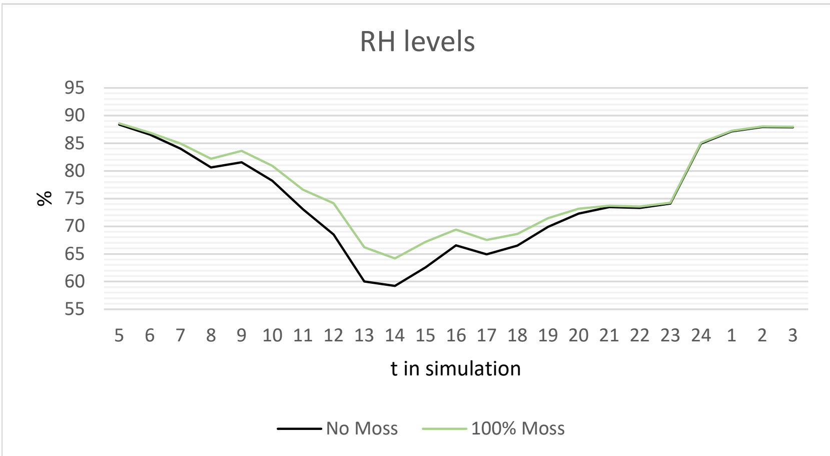
VARIATION 3





VARIATION 4





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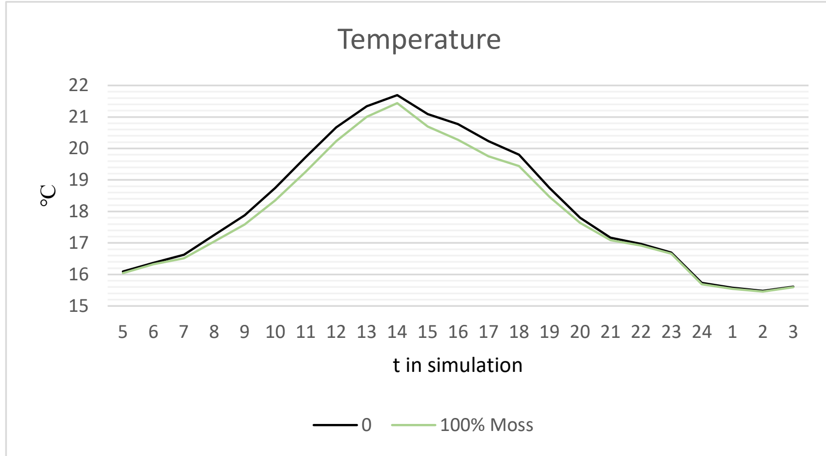
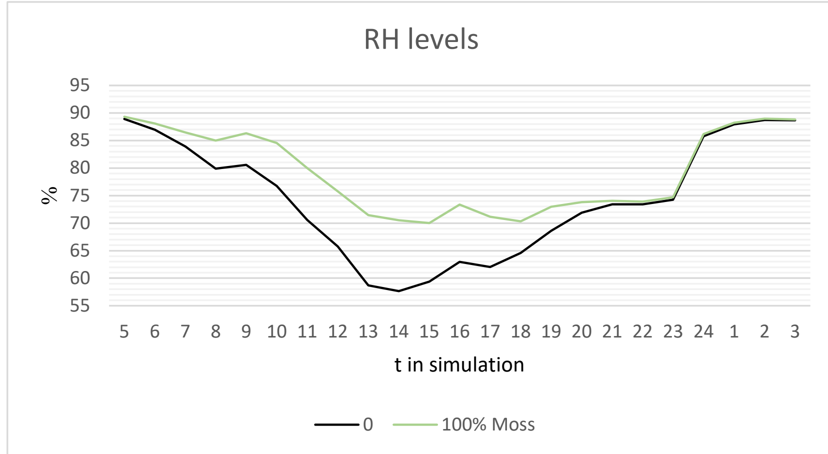




N

Greening variable	Value(s)	Reference
Plant layer thickness	2-3 cm 3 cm	Field observations (chapter … section …) K., Katoh, Katsurayama, Koganei, & Mizunuma, 2018
With/without substrate	Without	Design factor
LAI	6 to 140 4 to 22.5 0.5 to 6.7 2.9 to 26.1	Glime, 2017 Hanson & Rice, 2013 Bond-Lamberty & Gower, 2006 Niinemets & Tobias, 2019
Leaf angle	0.3 0.35 to 0.87	Wu et al., 2013 Falster & Westoby, 2003
CO2 fixation (C3/C4 fixation)	C3 No measured C4	ENVI-met, n.d. Hanson & Rice, 2013
Leaf type Grass/deciduous/conifer	Conifer	Hanson & Rice, 2013
Albedo	0.2 0.2 0.08-0.09 / 0.05-0.06 0.13 to 0.19 0.2	ENVI-met, n.d. Houldcroft, 2009 K., Katoh, Katsurayama, Koganei, & Mizunuma, 2018 Wood & Oliver, 2004 Declet-Barreto et al., 2012
Transmittance	0.3	ENVI-met, n.d.
Plant height	0.25	Default
Root zone depth	0.5	Default
Leaf area profile	0.15	Default
Root area profile	0.1	Default
Season profile	1	ENVI-met, n.d. (Not implemented yet)

Bryophyte variables and references

Species[a]	Life form[b]	L (m² m⁻²)	S (m² m⁻²)	Reference
Acroporium fuscoflavum	Large cushion	11.2		Waite and Sack (2010)
Calliergonella cuspidata	Tall turf/weft		11.9–23.6	van der Hoeven et al. (1993)
Campylopus hawaiicus	Large cushion	14.4		Waite and Sack (2010)
Ceratodon purpureus	Short turf	129		Simon (1987)
Ctenidium molluscum	Weft		11.8–12.0	van der Hoeven et al. (1993)
Distichophyllum freycinetii	Rough mat	8.4		Waite and Sack (2010)
Drummondia prorepens	Rough mat	19.6 (15.0)[c]		Vitt (1990)
Fissidens pacificus	Short turf	4.1		Waite and Sack (2010)
Holomitrium seticalycinum	Short turf	6.1		Waite and Sack (2010)
Hookeria acutifolia	Rough mat	6.5		Waite and Sack (2010)
Hypnum cupressiforme	Smooth mat	103		Simon (1987)
Leucobryum seemannii	Large cushion	11.8		Waite and Sack (2010)
Macromitrium microstomum	Short turf	9.6		Waite and Sack (2010)
Macromitrium piliferum	Short turf	9.6		Waite and Sack (2010)
Mnium hornum	Tall turf	18.0		Proctor (1979)
Pleurozium schreberi	Weft	13.0		Tobias and Niinemets (2005), Tobias and Niinemets, unpublished
Pleurozium schreberi	Weft		1–5	Rice et al. (2011)
Pyrrhobryum pungens	Tall turf	4.7		Waite and Sack (2010)
Rhytidiadelphus squarrosus	Tall turf/weft		8.8–20.6	van der Hoeven et al. (1993)
Scleropodium purum	Weft	22.5		Proctor (1979)
Tortula ruralis	Small cushion	6.0		Proctor (1979)
Tortula ruralis	Small cushion	44		Simon (1987)

Table Estimates of moss leaf area index and shoot area index copied from (Hanson & Rice, 2013)

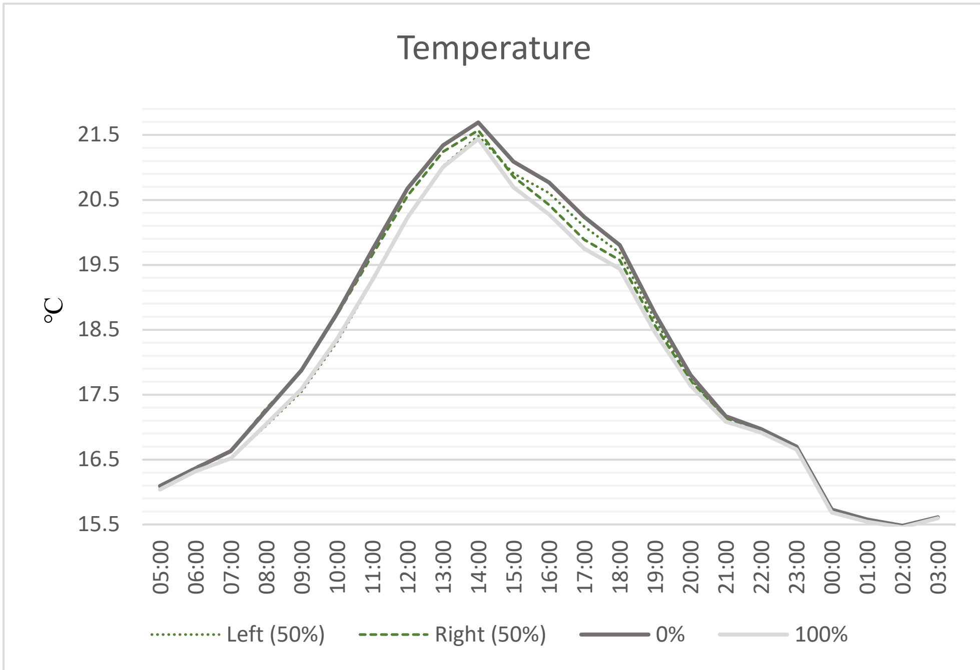
O

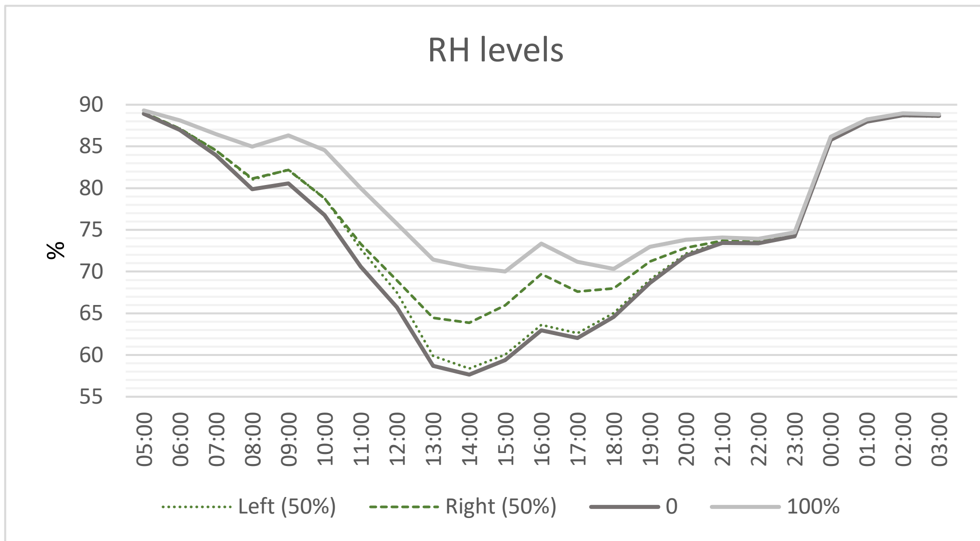
IVY PROPERTIES

Variables	Type 1
Thickness	0.20
With/without substrate	no
LAI	1.5
Leaf angle	0.5
CO2 fixation	C3
Leaf type	deciduous
Albedo	0.2
Transmittance	0.3

Height	0.25
Root depth	0.5
LAD	0.15
RAD	0.1
Season	1

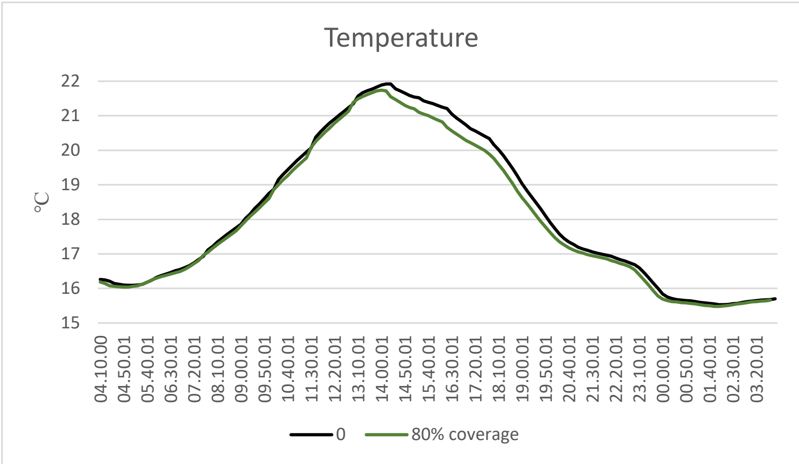
VARIATION 1.1 LEFT AND RIGHT

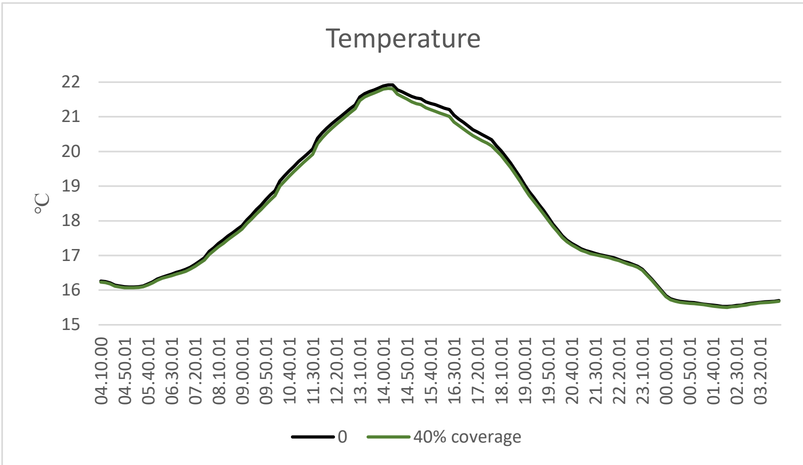


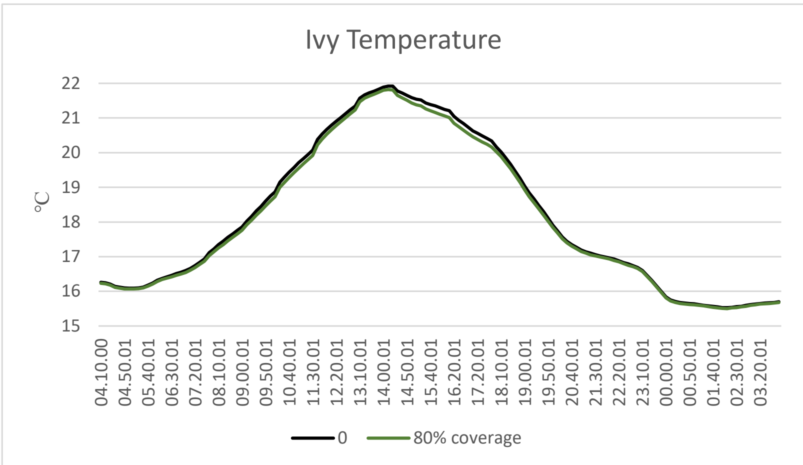


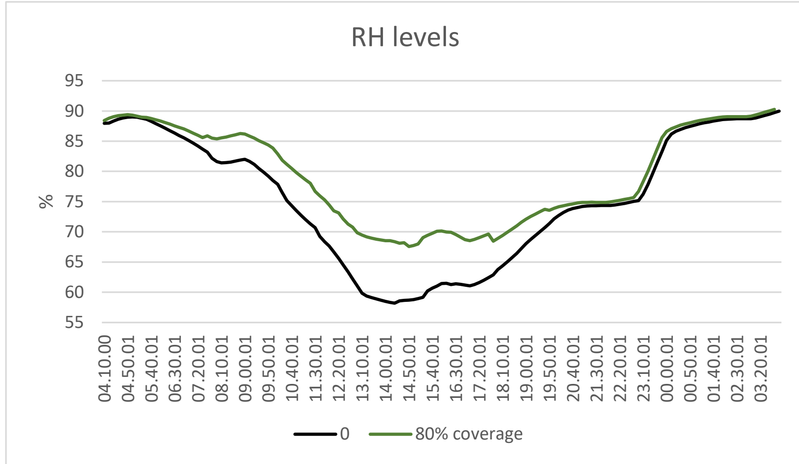
P

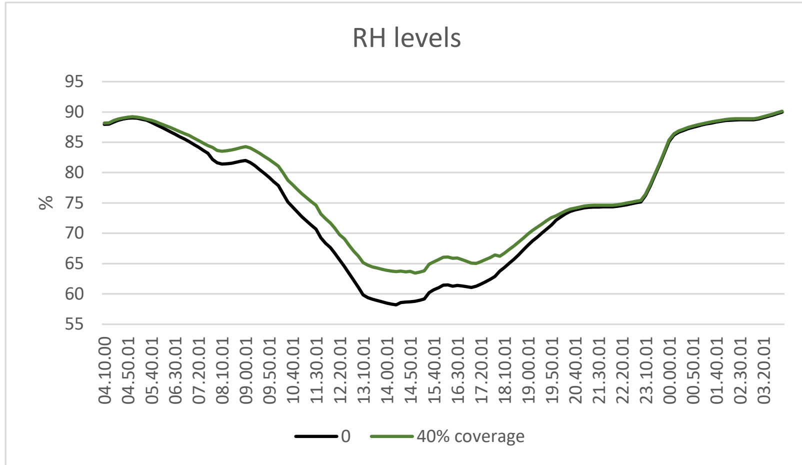
FINAL SIMULATIONS

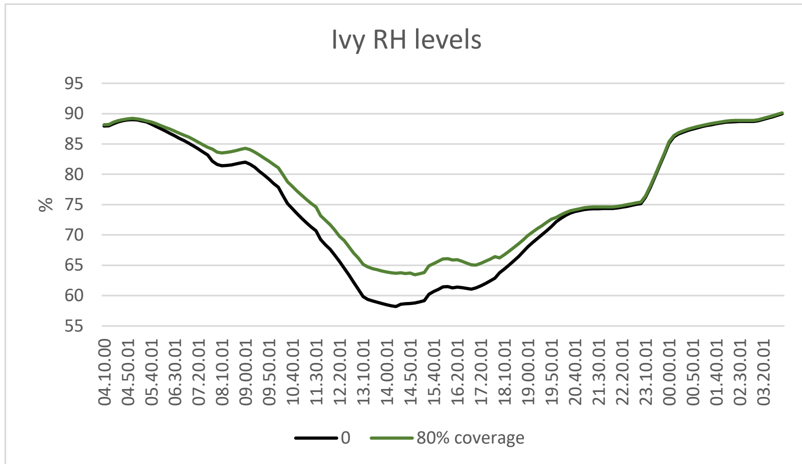


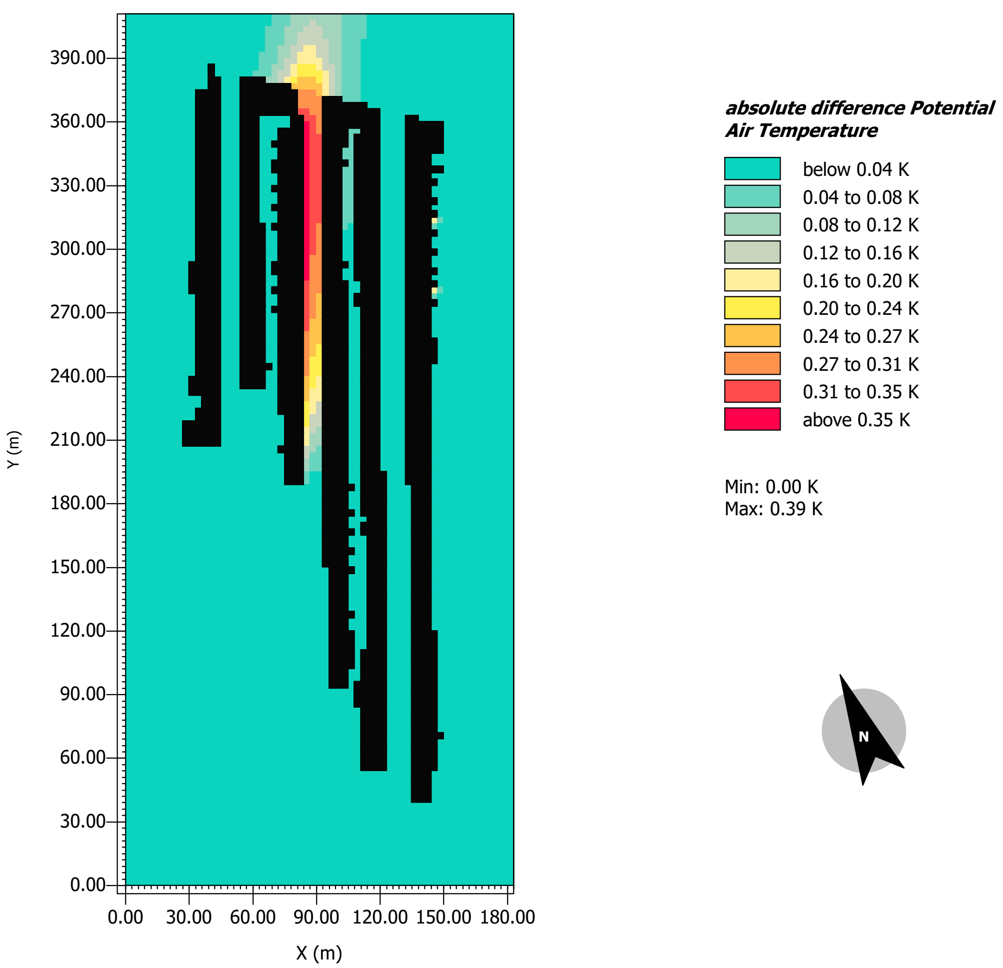


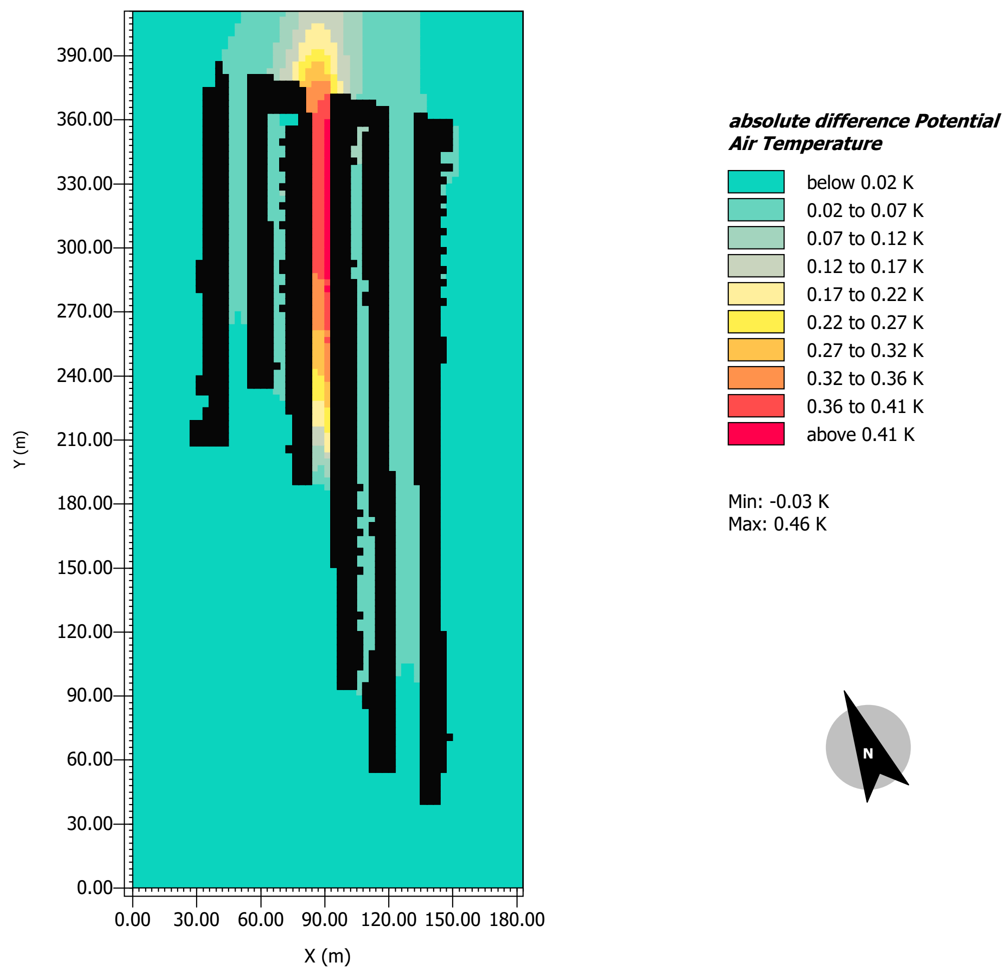


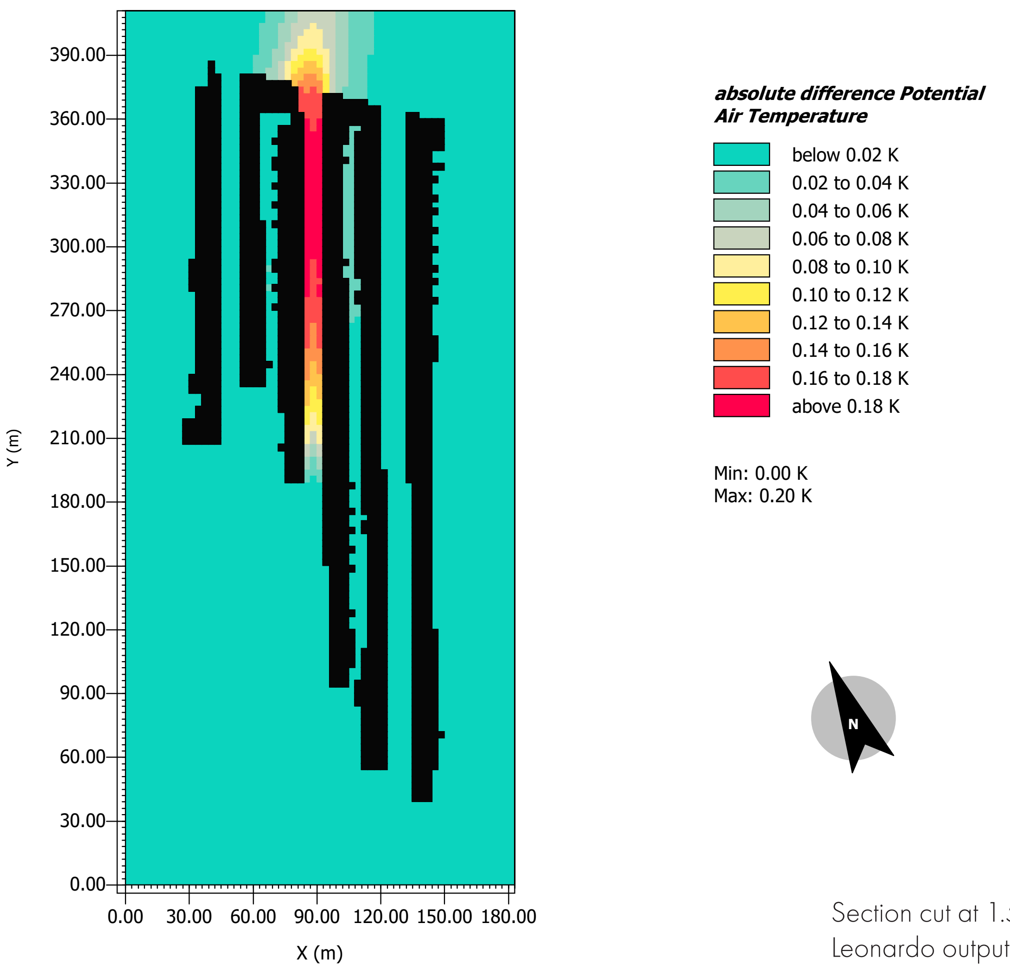




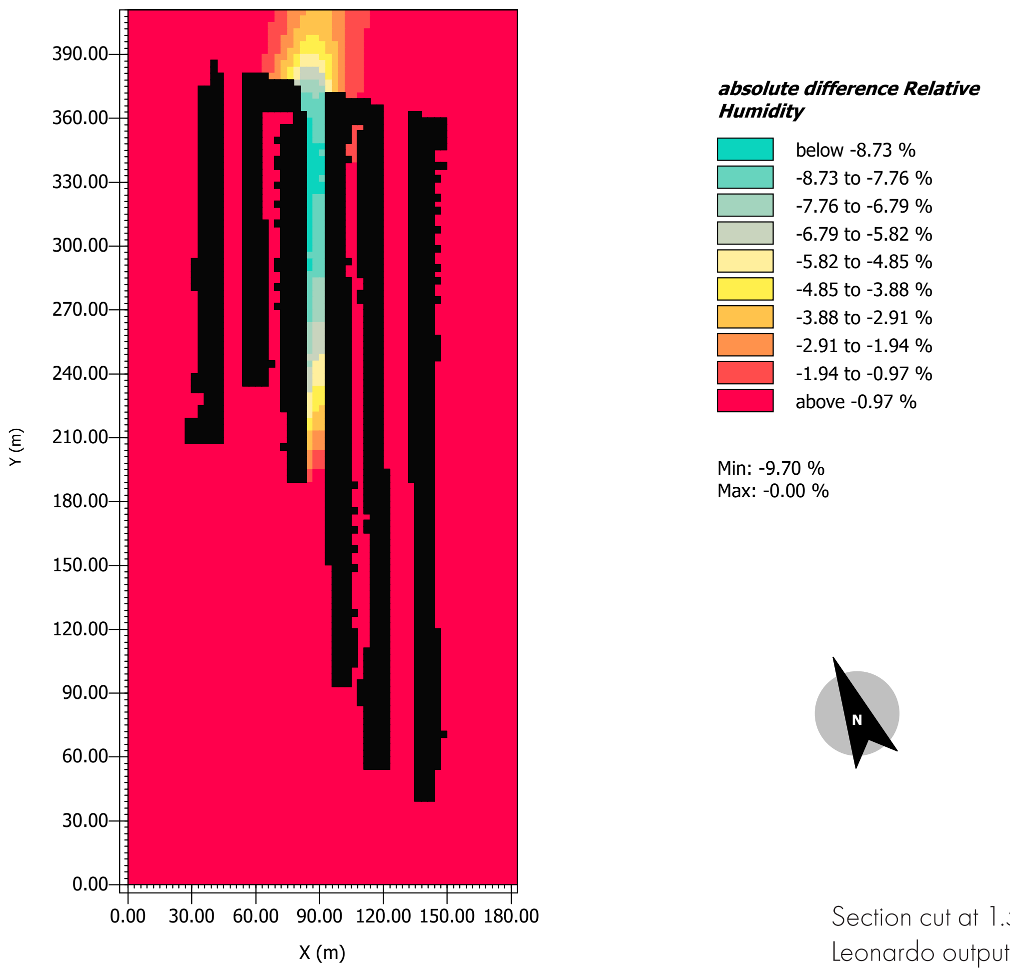








Section cut at 1.5 m height
Leonardo output, ENVI-met



Section cut at 1.5 m height
Leonardo output, ENVI-met