LIVING WALL SYSTEM

As a strategy to mitigate the Urban Heat Island effect in Damascus

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Abstract

Urbanization has led to the accumulation of heat in urban areas. In other words, cities demonstrate higher temperatures than surrounding rural suburbs, known as the Urban Heat Island effect (UHI). This phenomenon has substantial consequences on energy consumption for cooling purposes, air quality, and human health. As a metropolitan city, Damascus experiences a high urban heat island effect due to many factors. The intensity of UHI in Damascus is high and could reach 10˚C. Therefore, a mitigation strategy is a necessity.

A possible solution could be integrating the Living wall system (LWS) into the built environment. However, the living wall system's implementation is still limited due to different factors such as the high initial cost, the complexity of the system, and technical difficulties. Furthermore, the efficiency of this system in mitigating the urban heat island still needs to be further investigated.

Thus, this research focuses on analyzing the UHI effect, designing LWS for Damascus's context, and then investigating the proposed design's efficiency as a UHI mitigation strategy

Keywords:

Urban Heat Island, Living Wall System, Damascus, Outdoor thermal comfort, Urban canyon, Mitigation strategy, Giant reed, micro climate

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Abbreviation

E-W	East- west orineted
H/W	Aspect ratio
h1	Overall thickness of the woven cross-section
HAM	High Albedo Material
HPP	Expanded Polypropylene
LWS	Living Wall System
ma	Mass per unit area
P	Density of the reed
P1	Equivalent Density
PET	Physiological Equivalent temperature
q rel	Relative Humidity
SVF	Sky View Factor
T	Potential Air Temperature
Tmrt	Mean Radiant Temperature
UBL	Urban Boundary layer
UCL	Urban Canopy Layer
UHI	Urban Heat Island
VGS	Vertical Greenery System
W speed	Wind speed

Chapter 01

Introduction

1.1. Problem statement

Intensive urbanization has led to vegetation degradation and air pollution, resulting in heat accumulation in urban areas. In other words, cities demonstrate higher temperatures than surrounding rural suburbs, known as the Urban Heat Island effect (UHI). UHI has substantial consequences on energy consumption for cooling purposes, air quality, and human health. As a metropolitan city, Damascus experiences a high UHI intensity and a low outdoor thermal comfort due to increased population, anthropogenic heat, low albedo material, vegetation degradation, and other factors related to the urban geometry of the city. However, this phenomenon has not been widely studied, and as a result, no measurements are taken to mitigate this effect. Even though the UHI effect in Damascus is more significant than most American and Turkish cities. It is even higher than UHI in Riyadh, KSA. The Urban Heat Island effect in Damascus caused increasing the energy demand for cooling purposes, directly affecting the air quality and human indoor and outdoor thermal comfort.

A practical method to mitigate the UHI effect is to increase Vegetative Green Spaces. However, in such a high-density city like Damascus, it is hard to improve the vegetated spaces. An alternative solution could be the integration of a vertical greenery system (VGS) into buildings. In recent decades, Living Wall System (LWS) is introduced as a vertical greenery system. Despite the benefits of the living wall system, its implementation is still limited due to different factors, such as the complexity of the system, structural challenges, cost. Furthermore, the efficiency of this system as a strategy to mitigate the impact of UHI is not widely studied.

1.2. Research objectives

As a response to the challenges mentioned above, this research aims to:

Design a Living Wall system that can be integrated into the built environment of Damascus and evaluate the efficiency of the proposed design as an Urban Heat Island mitigation strategy.

The research also has the following sub-objective:

Urban heat island related:

• To analyze the Urban heat Island phenomenon and its associated consequences.

• To define the key causes of the Urban Heat Island effect in Damascus.

Living wall system and designing related:

• To learn about the Living Wall System's cooling mechanism on the local climate.

• To learn about the Living Wall System currently available in the market and analyze the system requirements.

• To determine the challenges involved in designing Living Wall System in Damascus.

• To design a living wall system suitable for Damascus's context and meets the designing Criteria.

Evaluation related:

• To evaluate the efficiency of the proposed strategy in mitigating the urban heat island effect and improving pedestrian outdoor thermal comfort on microclimate.

1.3. Research Questions

*“How to design a **Living Wall System** that can be integrated into the built environment Of **Damascus** and how efficient is the proposed design as an **Urban Heat Island mitigation strategy**? “*

To be able to answer the main research question, the following sub-questions are formulated:

- *What is the Urban Heat Island phenomenon, and what are the associated consequences of this phenomenon?*

These consequences show us the necessity of UHI mitigation and monitoring strategies.

- *What are the key causes of the Urban Heat Island effect in Damascus?*

To learn about the causes of UHI in Damascus and see which of these factors can be controlled.

- *How can Living Wall System mitigate the Urban Heat Island effect?*

To learn about the cooling mechanism of the vegetated layer.

- *What are the types of Living wall systems currently available in the market?*

There are different types of LWS available and each system has other system requirements.

- *What are the challenges involved in Designing a Living wall system in Damascus?*

It is necessary to determine the challenges to define the main design criteria and use them in creating the LWS.

- *How can Living Wall System be integrated into the built environment of Damascus?*

Designing criteria are utilized in evaluation and defining the main characteristics of the design to make it suitable for the context of Damascus.

- *How efficient is the proposed strategy to mitigate the UHI effect on microclimate and improve pedestrian outdoor thermal comfort in the urban canyon?*

The goal is to integrate LWS into the urban canyon to improve outdoor thermal comfort and mitigate the UHI effect. Therefore, it is necessary to compare the values of the potential air temperature (Ta), relative humidity (q rel), mean radiant temperature (T mrt), and wind speed (W speed) for different scenarios and analyze them to choose the one with the greatest potentials.

1.4. Research methodology

Research through a design approach with a mix of qualitative and quantitative research methodology is used. Qualitative methodology was applied to analyze and compare different case studies to determine the best option. The quantitative method was used to evaluate the design.

Main objective

Design a Living Wall system that can be integrated into the built environment of Damascus and evaluate the efficiency of the proposed design as an Urban Heat Island mitigation strategy.

Main question

"How to design a Living Wall System that can be integrated into the built environment of Damascus and how efficient is the proposed design as an Urban Heat Island mitigation strategy? "

Sub objectives	Sub questions	Method	Deliverables
To analyze the Urban Heat Island phenomenon and its associated consequences.	What is the Urban Heat Island phenomenon, and what are the associated consequences of this phenomenon?	Theoretical research, analysis and case studies evaluation	Definition of the Urban Heat Island phenomenon and its associated consequences
To define the key causes of the Urban Heat Island effect in Damascus.	What are the key causes of the Urban Heat Island effect in Damascus?		The key causes of Urban Heat Island in Damascus
To learn about the Living Wall System's cooling mechanism on the local climate.	How can Living Wall System mitigate the Urban Heat Island effect?		Learning about the Living Wall System's cooling mechanism
To learn about the Living Wall System currently available in the market and analyze the system requirements.	What are the types of Living wall systems currently available in the market?		Comparison of the different Living Wall Systems currently available and analysis the system requirements
To determine the challenges involved in designing Living Wall System in Damascus.	What are the challenges involved in Designing a Living wall system in Damascus?	Designing	Definition of the challenges involved in designing LWS in Damascus and design main criteria based on the challenges
To design a Living Wall System suitable for Damascus's context and meets the designing Criteria.	How can Living Wall System be integrated into the built environment of Damascus?		design of a Living Wall system that meet the design criteria
To evaluate the efficiency of the proposed strategy in mitigating the urban heat island effect and improving pedestrian outdoor thermal comfort on microclimate in the urban canyon.	How efficient is the proposed strategy to mitigate the UHI effect on microclimate and improve pedestrian outdoor thermal comfort in the urban canyon?	Evaluation	Evaluation of the efficiency of the proposed strategy on micro climate scale

Figure 1.1. An overview of the Research questions and objectives (author)

Three main phases were followed in this research, starting with the literature review phase, where all the background data was gathered, analyzed, and applied in the next phase, the design and optimizing phase, where the initial design concept was created, then optimized. The last phase is the evaluation phase.

Literature review phase

First, theoretical research was conducted to provide background knowledge about the UHI phenomenon and its associated consequences in general. Then, further analysis on the UHI effect and its controllable and uncontrollable key causes in Damascus was done. Obtaining information about the UHI in Damascus was challenging, especially that it has not been widely studied and there is only one reference about it created by Al-Bakheet, 2017.

In parallel, a study was carried out on LWS and VGS to learn about its cooling mechanism and how vegetation could help in reducing the effect of UHI. Furthermore, to gain a better insight into the system requirements and materiality, an analysis on the most commonly used LWSs was done. This analysis demonstrated that, in general, there are three main types for the LWS: LWS based on planter boxes, LWS based on felt layers, and LWS based on Rock wool. Research Gate, TU Delft repository, and LWS brochures provided by the manufacturing companies were the primary sources of information in this phase.

Design integration phase

The data extracted from the theoretical research phase, assists in determining the challenges involved in the integration of LWS into the built environment of Damascus. Based on the challenges, the design criteria were defined and used to subjectively evaluate the different LWSs case studies to determine which type is more suitable for Damascus. The results of this evaluation demonstrated that LWS based on planter boxes is the most proper. The design criteria were also utilized to determine which species and materials to apply. Then a Grasshopper plugin called -Karamba- was used to check the structural performance of the system and optimize it. Also, the connectors between the units were optimized, and a more detailed version of the design was created.

Evaluation phase

As a means of evaluation and to investigate the impact and efficiency of the proposed mitigation strategy on microclimate, a 3D representation of a suggested urban canyon in Damascus with a high UHI intensity was established in ENVI-met. ENVI-met is a microclimate software that can simulate climates in urban environments and assess the effects of climatic conditions, vegetation, and materials.

The used boundary condition and climatic data for the simulation represent a typical summer day in 2018.

These inputs were used to simulate air temperature (Ta), wind speed (W speed), mean radiant temperature (T mrt), and relative humidity (q.rel) for four different scenarios and compare the outputs with the base case. The outdoor thermal comfort indicator PET is used to measure the outdoor thermal comfort level for each scenario.

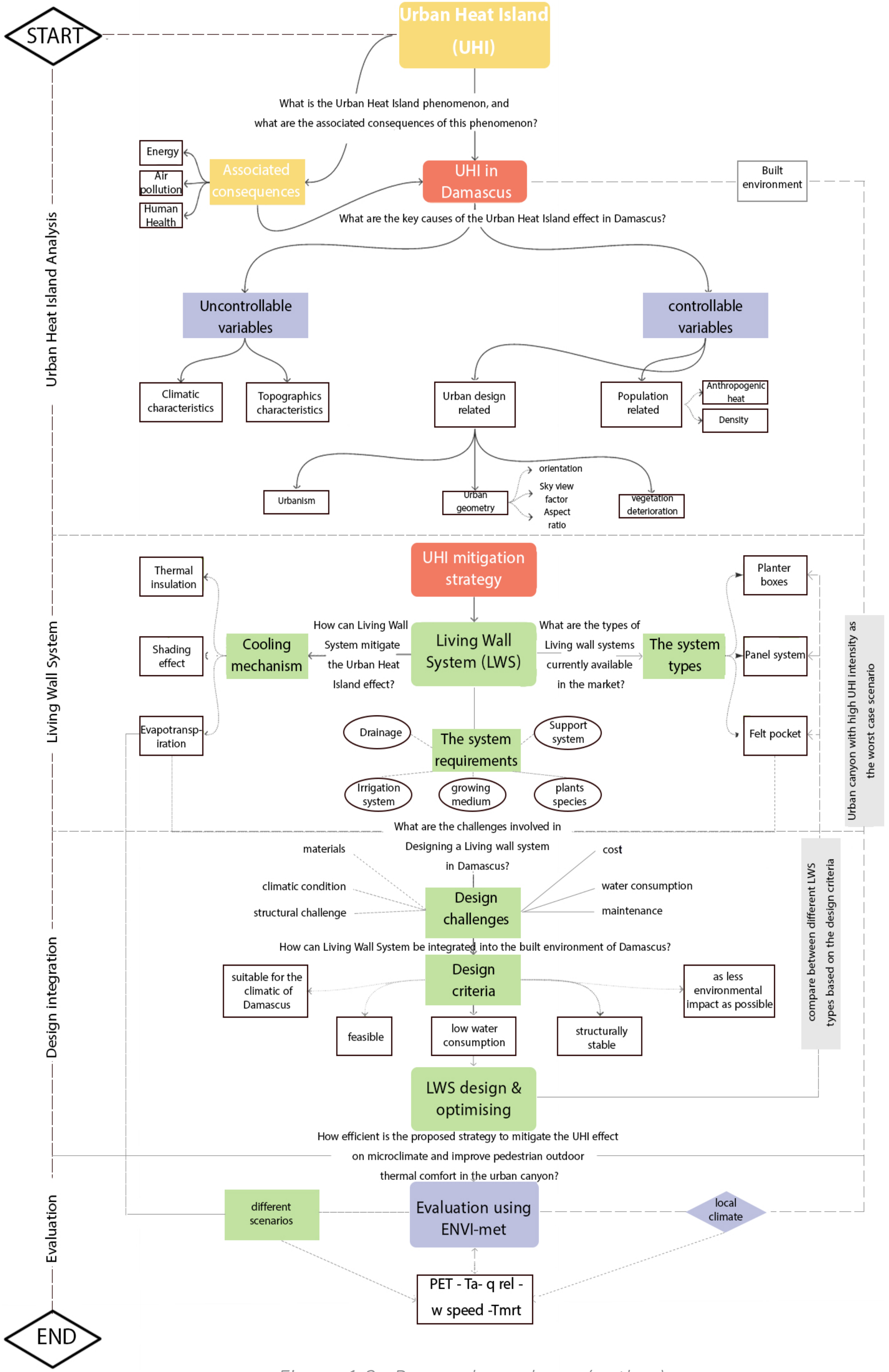


Figure 1.2. Research roadmap (author)

Chapter 02
Literature Review

Chapter overview

This chapter is divided into three main sections. The first section provides an overview of the UHI and its associated consequences in general.

The second section discusses the UHI effect in Damascus and links it to its fundamental causes. In addition to information about Damascus' built environment.

The third section gives an overview of LWS, its cooling mechanism, the system's main requirements with examples of LWSs currently available in the market.

2.1. Urban Heat Island (UHI)

Urban Heat Island is one of the biggest challenges cities are facing. It is defined as a climatic phenomenon noticed in urban areas where the ambient air temperature and surfaces temperatures are higher than surrounding rural areas. Two types of heat island can be distinguished: the surface and atmosphere heat island. Both types occur day and night. However, the surface UHI effect tends to be higher during the day while the sun is shining, contrary to atmospheric urban heat island, which is weak and becomes more intense after sunset when the absorbed heat is gradually released from the urban surface to the atmosphere. (Aboulfetouh, 2011)

Moreover, atmospheric heat island is also classified into layers:

1. Urban Canopy layer (UCL)

This occurs in the air layer between the ground and the tops of trees and roofs. This layer is the most commonly observed, and the layer where people mainly experience the high temperature.

2.Urban Boundary Layer (UBL)

It occurs between trees and roofs tops and the point where urban landscape no longer influences the atmosphere. This area extends to a maximum of 1,5 Km from the surface (Aboulfetouh, 2011).

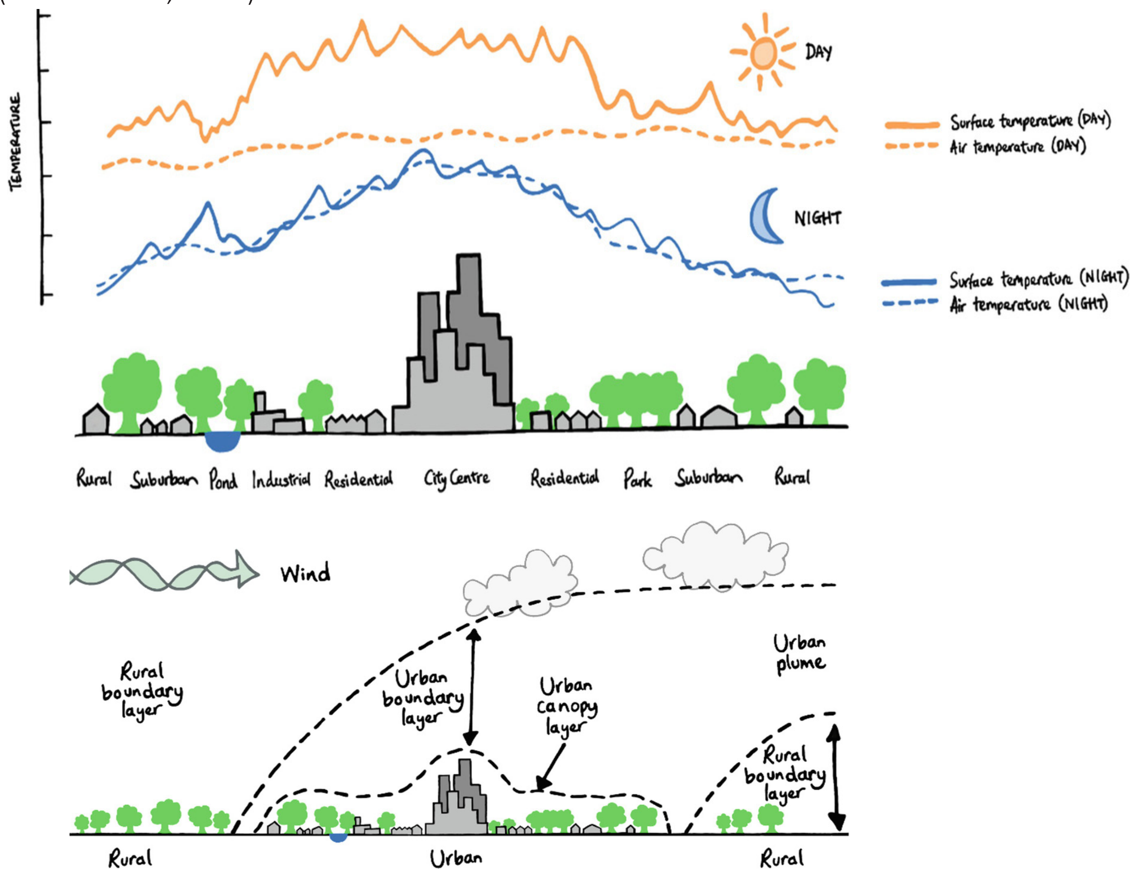


Figure 2.1. Urban Heat Island layers (Gorse et al., 2019)

2.1.1. Associated consequences of UHI

The UHI effect has substantial consequences on the energy consumption in the built environment, air quality and greenhouse emissions, as well as human health. These consequences show us the necessity of UHI mitigation and monitoring strategies. (Price et al., 2015)

2.1.1.1. Energy

As a result of the UHI effect, the ambient temperatures rise, causing an increase in cooling demand. Consequently, a significant increase in electricity consumption for cooling purposes. However, the heating demand is reduced as well. (Santamouris et al. 2001) According to a study by Santamouris et al. (2001) to assess the impact of the UHI on energy consumption of typical office buildings in Athens, Greece, in 1996, It has been found that the monthly cooling loads during summer in the city center were around 120% higher than the cooling loads at the reference zone (climatic stations around the city). In contrast, the heating load was reduced by 34%. Therefore, mitigating the UHI will positively affect the excessive electricity consumed by air conditioners in urban areas and lower the amount of heat released by them.

2.1.1.2. Air quality in the urban areas

According to a report published by the Environmental Protection Agency, UHI can lead to worsening air quality for the following reasons:

- The accelerated rate of photochemical ground-level Ozone production at higher temperatures. (Price et al., 2015)

Ground-level ozone or Tropospheric ozone is a pollutant, unlike stratospheric ozone, which protects us from ultraviolet (UV) radiation.
It forms when heat and sunlight stimulate the reaction of nitrogen oxides (NOx) and volatile organic compounds (VOC). High heat accelerates this process causing ground-level ozone accumulation to an unhealthy level. (climate center, 2019)

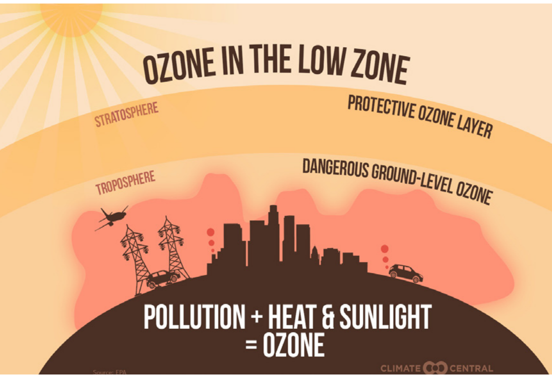


Figure 2.2. Ground level ozone (climate center,2019)

- The increase in temperature-sensitive emissions of ozone precursors. Another critical source of air pollution resulting from UHI's effect is excessive energy consumption. As mentioned before, when the temperature rises, more electricity is utilized in the built environment for cooling purposes. Electricity can be traced back to power plants which are probably based on fossil fuel. Consequently, generating more air pollutants and increase the intensity of UHI, and so on (Price et al., 2015). Therefore, Urban heat island mitigation is effective in reducing urban air pollution.

2.1.1.3. Human health

UHI has a direct and indirect negative impact on human health in urban areas due to raised temperature and air pollution (Shahmohamadi et al., 2011). Raised temperatures can lead to heat stress-related injuries that can threaten health as the body's temperature rises above its normal range of 36-37 °C. (Price et al., 2015) Furthermore, the risk of smog formation increases. Photochemical reactions of air pollutants create smog, and as mentioned before, these reactions accelerate by high heat (Shahmohamadi et al., 2011).

in addition, according to a report published by World Health Organization (WHO), 70,000 diseases were recorded in the extreme heat in 2003 in Europe and about 800,000 deaths globally due to urban air pollution each year, mainly by increasing mortality from cardiovascular and respiratory diseases. (WHO, 2008). Moreover, in the USA between 1979- 2003, 8015 deaths, are reported due to excessive heat exposure. There were also approximately 54,983 cases treated in emergency departments for heat-related injuries between 1997 and 2006 in the US (Yee Yong et al., 2014).

2.1.1.4. Outdoor thermal comfort

Thermal comfort is a complex matter defined as the condition of mind that expresses satisfaction with the thermal environment. As a result of the physiological and psychological variations from a person to another, the environmental conditions required for comfort are not the same for everyone (ASHRAE, 2010). Human thermal comfort is affected by the exchanges of energy between the body and the surrounding environment, primarily by the mean radiant temperature (T mrt), convection as a function of ambient air temperature(Ta), wind velocity (W speed), and sweat evaporation rate, which is limited by relative humidity (q rel) (Calfapietra et al.,2017).

In order to assess human thermal comfort, various indices combining meteorological parameters with thermo-physiological parameters are developed. The most commonly used is the Physiologically Equivalent Temperature (PET) for outdoor assessment, whose values express the hypothetical temperature of a standard room that is thermal "equivalent" to the actual conditions in a complex environment (Calfapietra et al., 2017).

Calfapietra et al. also reported that outdoor Thermal stress harms the functioning an- people's health. The increase in the intensity and duration of heatwaves due to the UHI effect and global warming in cities will aggravate citizens' thermal discomfort, leading to a significant impact on human health and increasing morbidity and mortality of the population in urban areas. Thus, by mitigating the UHI effect, the outdoor thermal comfort will increase and the quality of outdoor spaces improved (Calfapietra et al., 2017).

Table 2.1. PET index (École normale supérieure Paris-Saclay, 2018)

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

As shown in Table 2.1., when PET values are between 18°C and 23°C, they are considered comfortable. In comparison, values between 29°C, 35°C, and 41°C are considered between moderate-strong to extreme heat stress (Calfapietra et al., 2017).

2.2. Urban Heat Island in Damascus

Like any other metropolitan city, Damascus experiences UHI effect for many reasons which will be disccussed in this section. UHI effect caused an increase in the energy consumption for cooling purposes during Summer in addition to other consequences on human health, thermal comfort, economy, and air quality.

2.2.1. Site Analysis

Damascus in Arabic "Dimashiq" the capital of Syria, and it is one of the oldest continuously inhabited cities in the world. According to the Syrian Central Bureau of Statistics, the population of Damascus city was 1.78 million in 2011, whereas the population of rural Damascus was about 2.74 Million. (Yahia, 2014) Damascus is located in the southwest of Syria on the eastern foothills of Anti-Lebanon mountain. The mountain range peaks over 3000 meters which blocks precipitation from the Mediterranean Sea. As a result, the city is sometimes subjected to drought, previously mitigated by the Barada River, which flows through Damascus. However, this river is almost dry and suffers from severe drought in the last decades, mainly due to lower rainfalls and the significant increase in the population. Damascus city has an area of 105 km2, out of which 77 km2 is urban while the rest is occupied by Qassion Mountain (Jabal Qassion in Arabic) (Wikipedia, 2020).

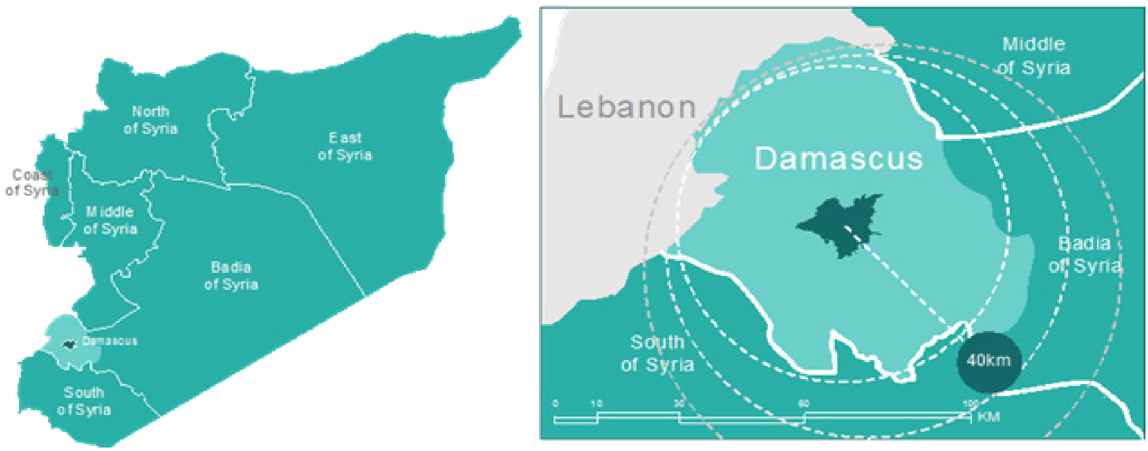


Figure 2.3. Syria map with Damascus metropolitan area (

Damascus built environmnet

Damascus is divided into Old Damascus and Modern Damascus. The old city walls enclose old Damascus, and it has in general, irregular planning with narrow streets. The urban design of Old Damascus, like in most vernacular architecture of old cities in the Islamic world, responds to the social and environmental conditions, where most of the residences are courtyard houses with less opening to the busy streets and more to the airy and planted courtyard. Furthermore, local materials (such as clay, stone, and wood) and traditional techniques were utilized in this part of Damascus. In contrast, modern building materials such as concrete, steel, glass, artificial and natural stone are utilized in the modern city. Moreover, the urban fabric in Modern Damascus has attached and detached buildings created according to detailed rules for spaces between buildings, set-backs, building heights, building footprints, projections, Etc. (Yahia,2012)

There are also informal settlements located at the edges of the city boundaries, such as Tabala and Dweilaa. These areas have attached buildings with deep canyons. The buildings in these informal settlements are built using conventional constructions techniques without engineering supervision. Consequently, they do not meet the standards and regulations set by Damascus Municipality. However, the physical condition of these buildings is good. (Yahia, 2012)

Figure 2.4. Urban environment Damascus , from left to write , Old city, modern city , informal settlements

2.2.2. Key causes of UHI in Damascus

Many factors contribute to the development of the UHI in Damascus. Some of these factors are uncontrollable, like climatic and topographic characteristics, and others can be controlled. In this section, the different factors will be discussed.

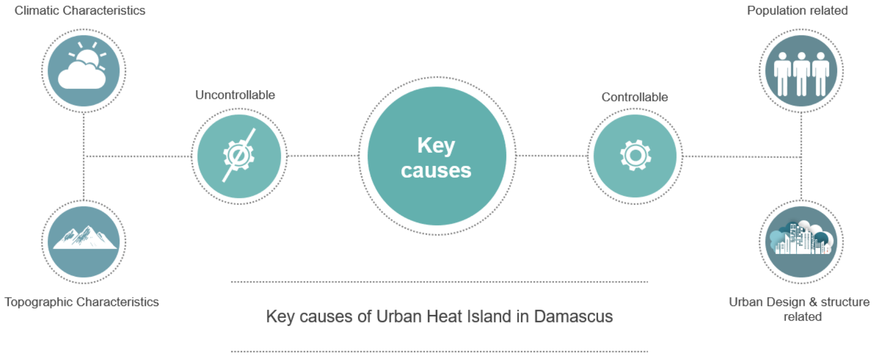


Figure 2.5. The key causes of UHI in Damascus (author)

2.2.2.1. Uncontrollable variables

The formation of the UHI is greatly influenced by the climatic and topographic characteristics of the location. Furthermore, these factors are permanent parameters that can not be controlled.

2.2.2.1.1. Climatic characteristic (Wind- Relative Humidity and Precipitation-Temperature)

Damascus experiences a cold semi-arid climate (BSK) as given by Köppen climate classification because of the rain shadow effect of the Anti-Lebanon mountain and the dominant ocean flows. This type of climate receives precipitation below potential evapotranspiration but not as low as a desert climate. Damascus has dry and less humid summer and cold mild rainy winter with a chance of snowfall (Wikipedia, 2021).

• Wind

The wind received the most attention among all the climatic factors in studying their impact on the UHI. It has been observed that the intensity of UHI is inversely related to wind velocity, and the faster the wind blows, the less intense the UHI is. Moreover, the wind direction also plays a vital role in lowering the city's temperature(Al-Bakheet, 2017).

The most predominant wind direction in Damascus is southwest. However, when the wind blows north or northeast in winter, the intensity of UHI reduces. While in summer, the east wind contributes to increasing the UHI effect due to the heat it gained during its passage over the desert areas (Al-Bakheet, 2017).
The highest wind speed reaches a maximum of 28 km/h (meteoblue, 2020). This considerably low wind speed keeps pollutants concentrated over urban areas. Moreover, The wind direction contributes to the concentration of air pollutants in the eastern and southeastern regions, which contributes to the formation of UHI.

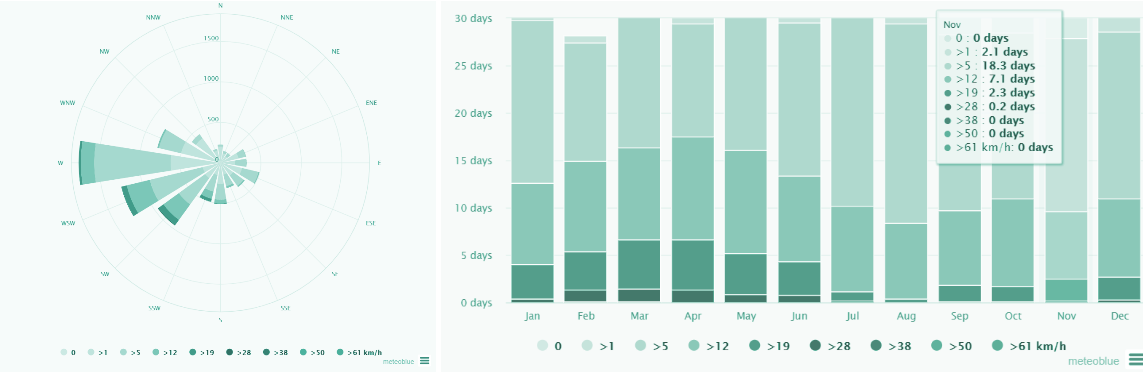


Figure 2.6. Wind rose and speeds (meteoblue,2020)

- **Relative humidity and Precipitation**

According to Mohajerani et al. (2017), the intensity of UHI decreases with higher relative humidity (q.rel). The relative humidity in the basin of Damascus varies with the different seasons of the year, and it is reversely related to temperature. It is between 70% and 73% in the winter due to the ocean flows coming from the west. Q rel falls to its minimum in the summer, particularly in June and July and Damascus city is less humid than surrounding rural areas, which means less heat is consumed in evaporating moisture. Thus, contributing to the formation of UHI (Al-Bakheet, 2017).
Al-Bakheet also mentioned that rainfall contributes to raising the atmospheric humidity and weakens the intensity of UHI. However, its impact is limited to the period in which it falls. The annual precipitation in Damascus is around 130mm, occurring from October to May (Wikipedia, 2020).

As seen in Figure 2.7., the wettest month is January (27,9 mm), and the driest are July and August, with 0 mm (weather atlas).

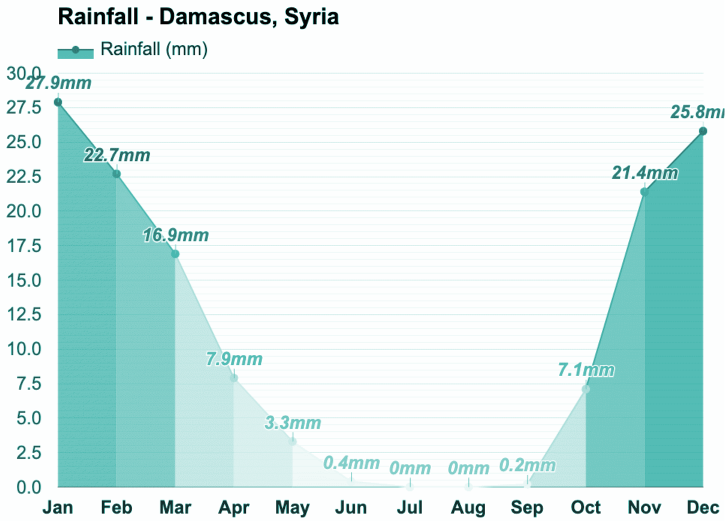


Figure 2.7. Precipitation in Damascus (weather atlas, n.d.)

• Temperature

The average annual minimum to maximum temperature ranges from 6°C, the lowest in winter to 35°C the highest in summer.
As seen in figure (x), in January, the coldest month in Damascus, the average low temperature is 0,4°C, and the average high temperature reaches 12,6°C.
In July, the hottest month in the year, the average low temperature is 18,9°C, and the high temperature is 36,5°C (weather atlas).

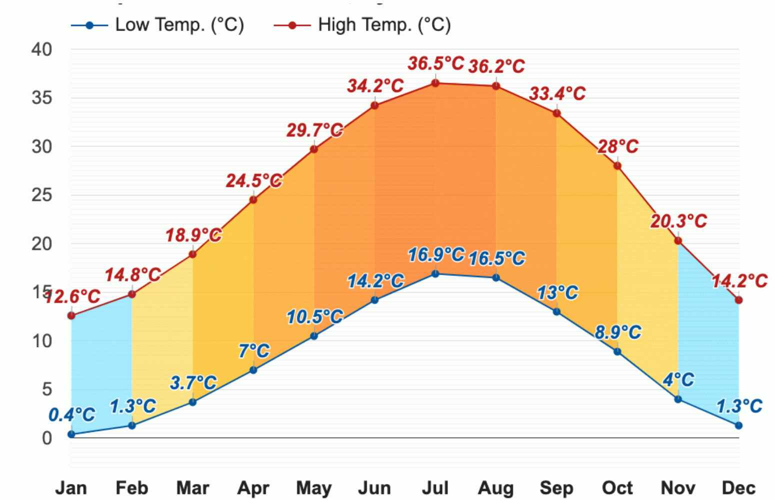


Figure 2.8. The average temperature in Damascus (weather atlas, n.d.)

2.2.2.1.2. Topographic characteristic

Since Damascus is located at the Anti-Lebanon mountain range foothill as seen in figure(x), extending from the southwest to the northeast, the precipitations and wind flow from the Mediterranean Sea are mostly blocked. Furthermore, the topographical situation of the city as a basin increases the concentration of air pollutants, which leads to an increase in the intensity of UHI.

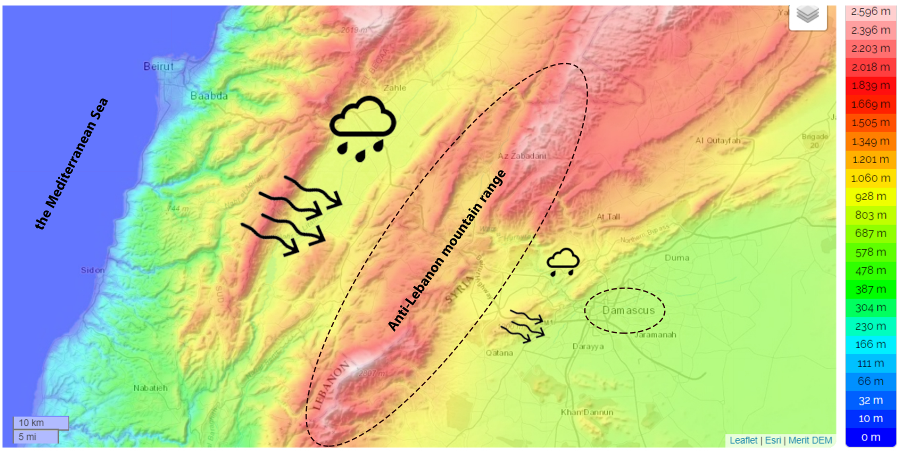


Figure 2.9. Damascus elevation map edited by the author (topographic-map.com, n.d.)

2.2.2.2. Controllable variables

2.2.2.2.1. vegetation degradation

The rapid urbanization of cities led to vegetation degradation, which is a fundamental cause of UHI because vegetation represents an essential means to control solar radiation. It provides shading and air cooling throughout Evapotranspiration (Price et al., 2015).

Evapotranspiration (ET) is the sum of evaporation from the land surface and transpiration from plants' leaves. This process contributes to lowering air temperature by using heat to evaporate water (USGS, n.d.).

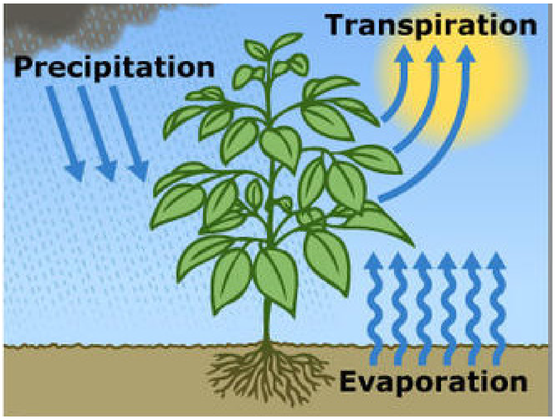


Figure 2.10. Evapotranspiration process (USGS, n.d.)

As shown in Figure 2.11., Damascus used to be surrounded by an oasis called Al-Ghouta, which separates the city from the dry land in the Syrian desert. It had also provided its inhabitants with vegetables and fruits (Wikipedia, 2020).
However, Al-Ghouta oasis has been decreasing in size since 1970 due to the urban development of Damascus. It has become almost dry. The city's urban area increased from 2000 ha in 1965 to 5800 ha in 1994 (Abdin and Al-Dajani, 2009).

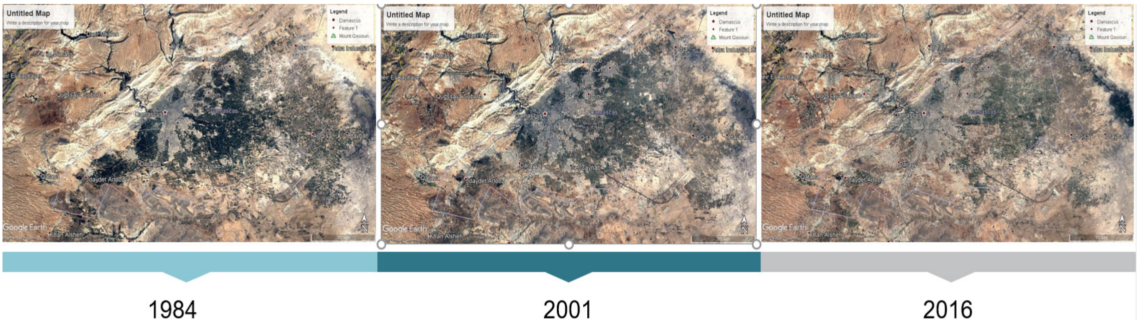


Figure 2.11. Damascus urban development, (author)

The current land uses are 50% urban, 18% gardens and agricultural facilities, 30% bare land and dry soil, and nearly 2% water; Represented by the Barada River and the water located in the lakes of public squares (Al-Bakheet, 2017).

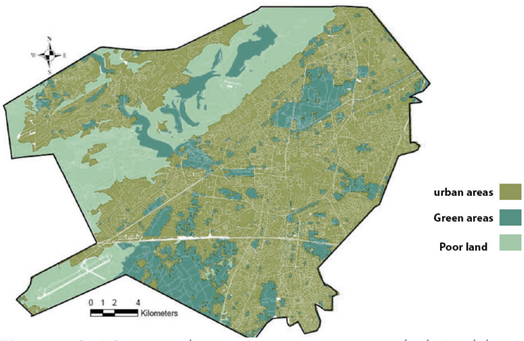


Figure 2.12. Land use in Damascus (Al-Bakheet, 2017)

2.2.2.2.2. Urban Albedo

In addition to the loss of vegetation, urbanization led to increasing paved surfaces, resulting in a change in the albedo throughout the city (Price et al., 2015).
As mentioned before, albedo is the portion of solar radiation reflected by the surfaces in the built environment. Urban albedo is one of the most important contributors to the changes in outdoor temperature.
A surface with an albedo of 0 absorbs 100% of the incoming solar radiation. While a surface with an albedo of 1 reflects 100% of the radiation to the environment. For instance, Fresh asphalt has an albedo of around 0,05, which means that only 5% is reflected, and 95% of the solar is absorbed (Hinkle, 2016). The absorbed radiation is then converted into heat energy and increases the surface temperature, contributing to UHI formation (van Hov et al., 2011).
Using materials with high thermal capacity for urban surfaces also contributes to the nighttime heat island since large part of the incoming radiation is absorbed during the day and released back to the environment during the night.

AS mentioned previously, concrete, steel, and asphalt are mainly utilized for the urban surfaces in modern Damascus (see Figure 2.14.). These materials have low albedo and high thermal capacity, which explains why UHI is at its maximum during the night.

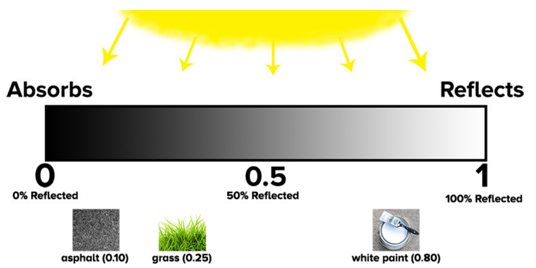


Figure 2.13. Urban Albedo (Hinkle, 2016)

Figure 2.14. Urban surfaces in Damascus taken by Dimashqi Lens (pinterest, 2018)

2.2.2.2.3. Urban geometry (Sky view factor (SVF) - Aspect ratio (H/W) - Orientation)

The complex urban geometry is characterized by a simple repetitive element called the "urban canyon" (Emmanuel, 2005). As Oke and Nunez (1976) mentioned, the urban canyon is defined as a 3D space surrounded by the street and buildings. It consists of the floor, the walls, and the air mass between the walls. According to Boeters et al. (2012), three parameters influence the climate of the urban canyon the sky view factor (SVF), the Aspect ratio, and the orientation.

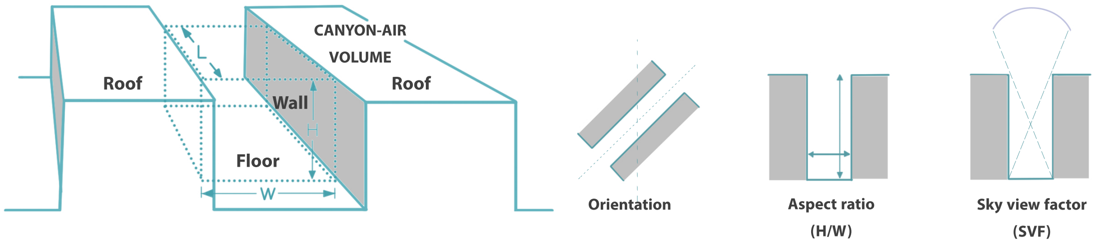


Figure 2.15. Urban canyon main parameters (author inspired by Boeters et al., 2012))

- **Sky view factor (SVF)**

SVF is the index of the visibility of the sky from a given point in the canyon. It ranges between 0 and 1 and helps determine the amount of heat the urban canyon will gain during the day and release at night.

For instance, a narrow canyon has a small SVF which means less solar radiation comes into the canyon during the day (cold island), and more heat is trapped in the canyon during the night (Boeters et al., 2012) &(Jamie et al., (2014).

- **Aspect ratio (H/W)**

Aspect ratio is the ratio between the height (H) of the canyon and the width of the street (W) between them. H/W influences the wind speed in the canyon and the incoming and outgoing solar radiation (Boeters et al., 2012) .

H/W < 0-----------------Shallow canyon

H/W ≈ 1 ---------------Regular canyon

H/W ≈ 2 -----------------Deep canyon

In Hot-dry climate:

High H/W = low SVf = less wind flow =more heat is trapped => higher UHI
Low H/W = high SVF = more wind flow =less heat stored => lower UHI

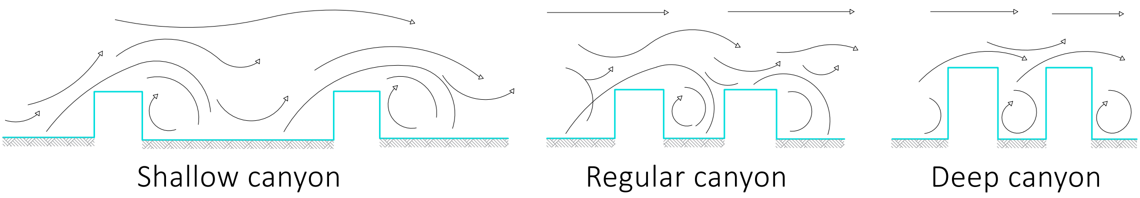


Figure 2.16. Aspect ratio and the effect of wind speed (author inspired by Boeters et al., 2012)

In modern Damascus, the urban canyons have a low H/W ratio, which means more wind flow between the building, vacuuming air pollutants, and dissipating excess heat from urban areas (Al-Bakheet, 2017).

In comparison, in old Damascus, even though SVF is low and H/W is considered high, the temperature is lower, and RH is higher during summer due to the increased shading effect. While in winter, the old city has a higher temperature than the modern part due to the high H/w ratio, which helps reduce the wind speed by 20% and prevents thermal loss from the building (Al-Bakheet, 2017).

In the informal urban areas characterized by medium-height buildings (two to three stories) with narrow streets (in its best cases, it does not exceed 8 meters), the H/w ratio is high, contributing to the formation of UHI in the city (Al-Bakheet, 2017).

- **Orientation**

Orientation is the direction of the street in relation to the north. It determines the solar access and wind velocity in the urban canyon (Jamie et al., 2014). Furthermore, In Hot-dry climates, streets with east-west orientation suffer from higher solar exposure during summer than north-south oriented streets. This accelerates the development of UHI during the night and reduces outdoor thermal comfort (Jamie et al.,2014).

Regarding urban canyons' orientation in Damascus, Al-Bakheet (2017) mentioned that there is no specific orientation for the streets and buildings in the old city due to the normal growth of the urban fabric. While in modern parts, there are wide streets with east-west direction such as Fayez Mansour and Omar bin Abdul-Aziz Street which receive more solar radiation than the north-south oriented street like El-Galaa street.

2.2.2.2.4. Population related - population density and anthropogenic heat

The City population increased from 914,000 in 1970 to 2,401,000 in 2010 (Macrotrends, 2020). The increase in population caused a rise in anthropogenic flux, which leads to an increase in UHI intensity. Wherever the density is high, the anthropogenic heat increases due to air pollutants in the city.

There is no detailed information about the amount of anthropogenic heat emission in Damascus. Still, the main sources of anthropogenic heat as seen in figure (x) are transportation, which contributes to more than 40% of the total pollutants, followed by industrial facilities 30% and houses 30% (Al-Bakheet, 2017).

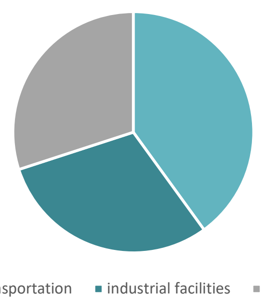


Figure 2.17. The main source of anthropogenic heat in Damascus (author)

Table 2.2. A summary of the UHI causes in Damascus

Summary of the key causes of UHI in Damascus			
Uncontrollable variables	Climatic Characteristic	wind	Low wind velocity When wind blows from east in summer and it contributes in increasing the UHI effect as a result of its passage over the desert areas.
		Relative Humidity	Less humid than surrounding rural areas
		Precipitation	Annual precipitation 130 mm and dry season from June to October.
		Temperature	Hot season from June to September.
	Topographic Characteristic	The city is located at the foothill of the Anti lebanoon mountain. Therefore, the precipitation and wind flow from the Mediterranean Sea are mostly blocked.	
Controllable variables	Urban design and structure related	Urbanization & vegetation degradation	The city area increases from 2000ha in 1965 to 5800ha in 1994. The Gouta Oasis has been decreasing in size since 1970 and it becomes almost dry.
		Urban albedo	Concrete , steel, and asphalt are the materials used for urban surfaces. These materials have low albedo and high thermal capacity.
		Urban geometry	Low SVB and High H/W ratio which means heat is trapped in the urba canyon in the old city. East- west oriented streets suffer from high solar exposure during. summer which accelerates the development of UHI during the night.
	Population related	Population density	population increased from 914,000 in 1970 to 2,401,000 in 2010.
		Anthropogenic heat	Anthropogenic heat from transportation, industrial facility and house

2.2.3. Urban Heat Island in Damascus analysis

Al-Bakheet (2017) has researched the UHI effect in Damascus. In his research, he used Satellite data from Modi's sensor (Terra and Aqua) and field study to determine the daily surface temperature and air temperature for 01/03/2014 to 01/03/2015.

2.2.3.1. Urban Heat Island in summer

According to the satellite images, there was no heat island during the day. While at night, there was a UHI with an intensity between 3 °C to 4°C (Al-Bakheet, 2017).

In contrast, field study results showed that the UHI intensity is between 6°C to 10°C during the day and between 8°C to 10°C during the night.

As seen in Figure 2.18., the UHI effect is higher in the city center northwest of the old city. Even though it is an organized urban area and has low H/W. However, this area includes traffic nodes (*Saba'a Bahrat square, Arnous Square and Shah-Bandar Square*) and contains the city's main roads; the most important are *Baghdad and Al-Thawra*. These streets receive greater traffic than their capacity, which leads to traffic jams. Consequently, it leads to an increase in anthropogenic heat and air pollutants.

Figure 2.18. The area with the highest UHI during summer in Damascus (author)

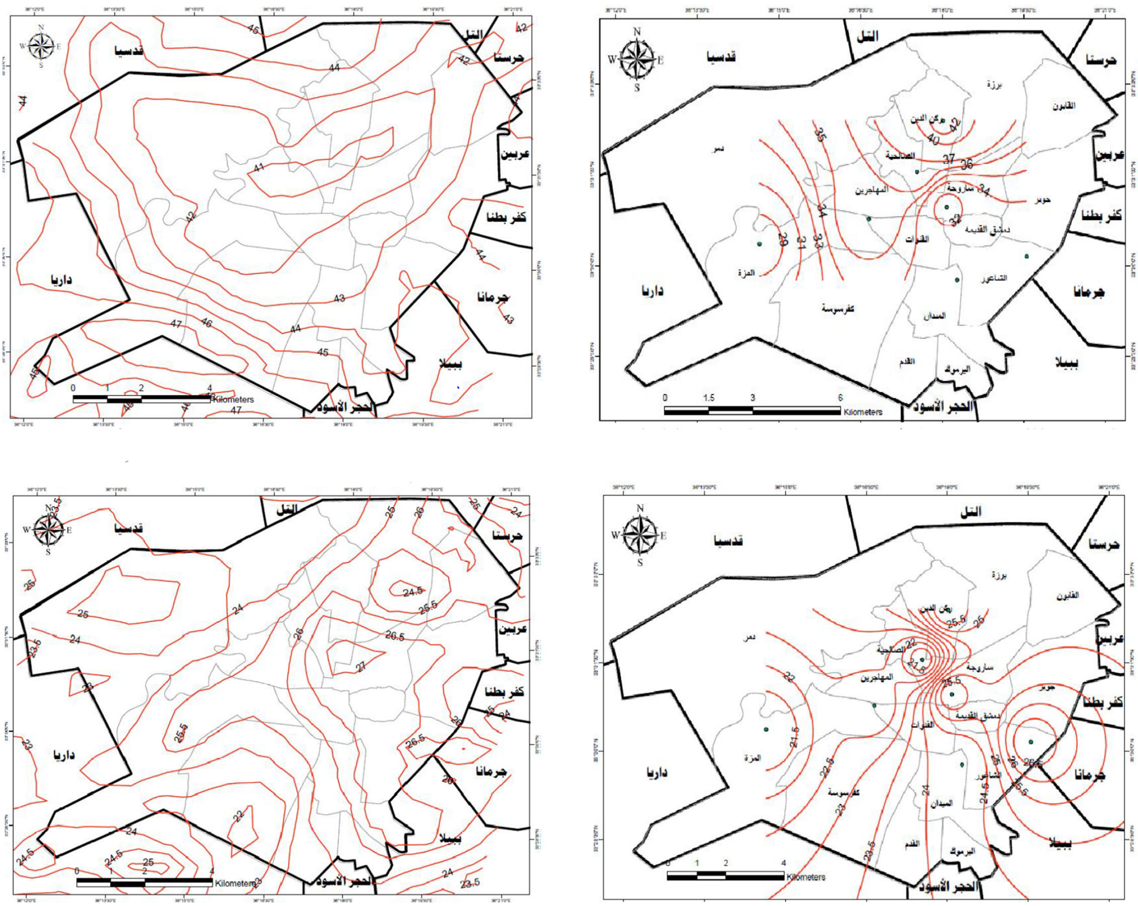


Figure 2.19. Top left summer morning (satellite result), top right summer morning (field study) Bottom left, summer night (satellite result, bottom right summer night (field study) - (Al-Bakheet, 2017)

2.2.3.2. Urban Heat Island in Winter

According to Al-Bakheet, 2017, when studying the satellite images at 10:30 and 13:20 for a regular winter day, a cold island occurred in the city's atmosphere due to pollutant concentration which reduced the amount of solar radiation reaching the land surfaces compared to surrounding suburbs. In addition to the height of the buildings, which also limited the amount of incoming radiation reaching the surfaces.

While during the night, a heat island, with an intensity between 5°C and 5,5°C, was noticed. As a result of the high density and the increased energy consumption for heating. Furthermore, the urban geometry also reduced the amount of wind flows between the building, leading to heat trapped in its canyons.

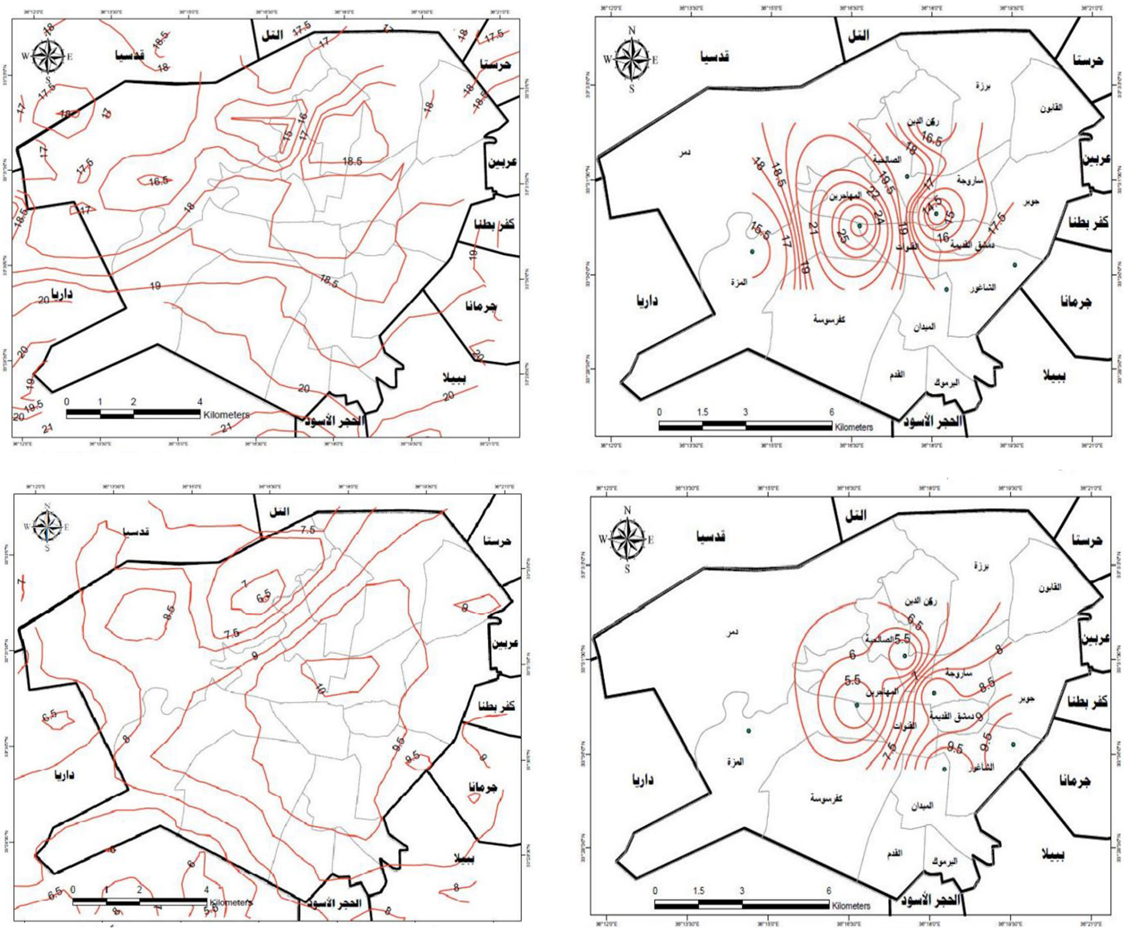


Figure 2.20. Top left Winter morning (satellite result), top right winter morning (field study) Bottom left, winter night (satellite result, bottom right winter night (field study)- (Al-Bakheet, 2017)

2.3. Living wall System as cooling strategy

The UHI effect can be mitigated by diminishing the accumulation of heat by applying cooling techniques that decrease or compensate for the impact of UHI causes discussed in the previous section (kleerekoper, 2011).

Therefore, increasing vegetation in the city could be a possible solution. However, in high-density cities like Damascus, it is hard to improve the horizontal vegetation. Therefore, an alternative solution is to use a vertical greenery system (VGS).

VGS can be classified, as reported by Ottele' (2011), into two major categories: Rooted into the ground and rooted into an artificial substrate or potting soil. Another way to classify VGS is by dividing them according to their relationship with the façade into two groups: direct greening and indirect greening (Ottele', 2011).

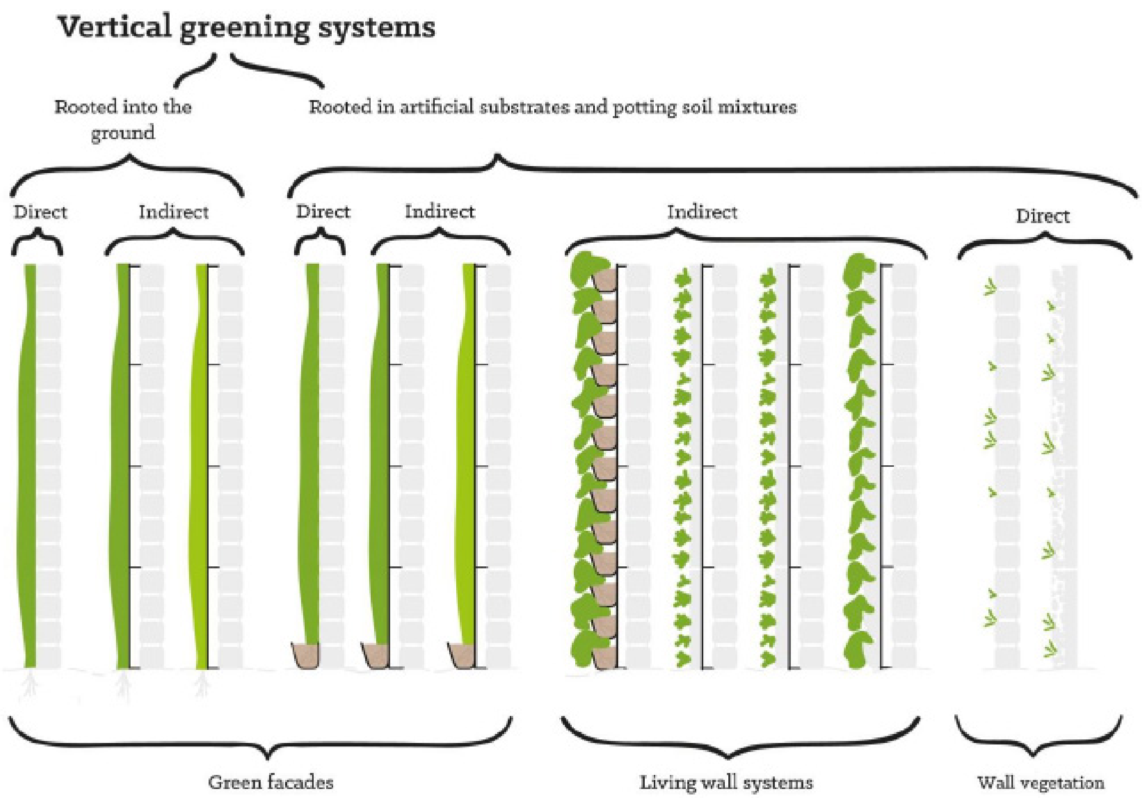
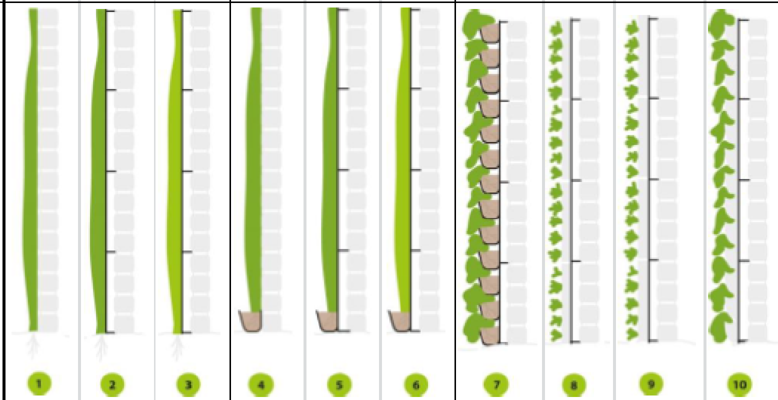


Figure 2.21. Vertical greenery system types (Wegemans, 2016)



Vertical green type		Rooted into the ground			Rooted in artificial substrates and potting soil mixtures						
type		Green façade						Living wall system			
direct or indirect		direct	indirect	indirect	direct	indirect	indirect	indirect	indirect	indirect	indirect
Effects	Can be optimized for modular desing (Y/N)	1	2	3	4	5	6	7	8	9	10
Reduce the urban heat island effect	N	+	+	+	+	+	+	++	++	++	++
External shading	Y	+	+	+	+	+	+	++	++	++	++
Create a microclimate	N	+	+	+	+	+	+	+	+	+	+
Improve insulation properties	Y	-	-	-	-	-	-	+	+	+	+
Improving air quality	Y	+	+	+	+	+	+	++	++	++	++
Provide sound insulation	Y	+	+	+	+	+	+	++	++	++	++
Increase biodiversity	Y	+	+	+	+	+	+	+	+	+	+
Aestetical effects	N	+	+	+	+	+	+	+	++	++	++
Social and psychological benefits	N	+	+	+	+	+	+	+	++	++	++

Table 2.3. Comparison between different Vertical Greenery System (VGS) (Wegemans, 2016)

Both Mir (2011) and Wegemans (2016) made a comparison between VGS's different types. Based on the comparison results shown in Table 2.3., the Living Wall system delivers the most potential benefits when speaking about UHI mitigation and improving the urban environment. Therefore, in this research, the benefits of LWS on mitigating the UHI impact will be investigated.

Living Wall System (LWS) is a type of vertical greenery system as mentioned above. Professor Stanley Hart White invented the first LWS in 1938, and it was called "Botanical bricks". However, this system did not become popular until Patrick Blanc introduced his first living wall system for the museum of science and industry in 1988 (Figure 2.23.) (Culver et al., 2014).

LWS is a modular system that can be utilized for indoor and outdoor applications in different sizes and climates, from tropical to temperate (Mir, 2011). They are not limited by any height constraints as they are not rooted into the ground and can be installed on new facade construction or existing exterior Walls (Susorova, 2013) (Guzmán,2019). Therefore, LWS allows for rapid coverage for large vertical surfaces and integrates a wide variety of plant species (Manso and Gomes, 2014).

Figure 2.22. Vertical garden, Musée du Quai Branly, Paris (Patrick Blanc, 2005)

2.3.1. Cooling impact of LWS

Three main factors are reported by researchers as the mechanisms through which LWS and VGS mitigate the UHI effect. These factors are the cooling effect of plants and substrate throughout evapotranspiration, thermal insulation, and shading effect.

2.3.1.1. Evapotranspiration effect

Evapotranspiration is the most important benefit of vegetation systems in the built environment. Vegetation creates a milder micro-climate around the building as a large amount of solar radiation is converted into latent heat used for evapotranspiration and, as a result, reduces the amount of long-wave radiation released back to the environment at night (Wong et al., 2009).

Ottele' (2011) has reported that evaporation of 1 kg of water requires 2.5 MJ of energy, and plants store water on their leaves surfaces longer than building materials. This water can be added to the air through the evapotranspiration process, causing a more pleasant climate in the urban areas.

Furthermore, a field study conducted by Wong et al. (2009) to observe the influence of different VGSs on the ambient air temperature showed that the best cooling effect was measured in the surrounding area of the LWS at the distance of 15 and 30 cm with a reduction of 3.3°C and 1.6°C, respectively. However, for a distance of more than 60 cm, the vegetated layer does not influence the ambient temperature.
Cooler ambient air temperature is translated into a reduction in the cooling load of the building and less UHI intensity.

2.3.1.2. Thermal insulation

The vegetative layer, the growing media, and the supporting system reduce the effect of solar radiation, thermal radiation, air temperature, relative humidity, and wind speed on the façade exterior. Consequently, they reduce the heat transferred through the façade and the energy consumption for cooling and heating purposes (Susorova, 2013).

Furthermore, as mentioned by Ottele' (2011), 5 - 30% of solar radiations falling on the green facade are reflected, 50- 20% used in photosynthesis, 10- 50% transfed into heat, 20- 40% used in evapotranspiration, and only 5- 30% pass through.

Moreover, the air cavity between the building and the LWS acts as a thermal buffer which slows down the rate of heat transfer and improves the Thermal insulation of the facade (Susorova, 2013). The thickness of the air cavity also plays a role in determining the efficiency of LWS in reducing the wind speed around the façade. For instance, LWS with a 4 cm air cavity is more effective in reducing wind speed and improve the thermal insulation of the façade than LWS with a 20 cm cavity. (Raji et al., 2015).

2.3.1.3. The shading effect

The shading effect is important during hot summer when there is excessive solar radiation and temperature difference between exterior and interior façade surfaces. Previous studies demonstrated that the façade temperature could be reduced by an average of 1- 9°C by using vegetation, and this reduction could reach a maximum of 15- 20°C (Susorova, 2013). While during the night, the temperature of the vegetated façade is 1 - 2°C Higher than the bare wall. Because the vegetated layer does not release longwave radiation back to the atmosphere (Susorova, 2013). Thus, less UHI effect during the night.

Susorova (2013) also reported that the highest temperature reduction is recorded during the peak exposure to solar radiation on the eastern and western façade. Therefore, to improve façade thermal performance, placing vegetation on the east and west face is more beneficial than on the north or south-oriented wall.

It has also been reported that the amount of solar radiation transmitted through the façade decreases with the increase of leaf area index (LAI), which is a ratio between the leaf surface in m 2 and the wall surfaces in m2 (Ottele', 2011).

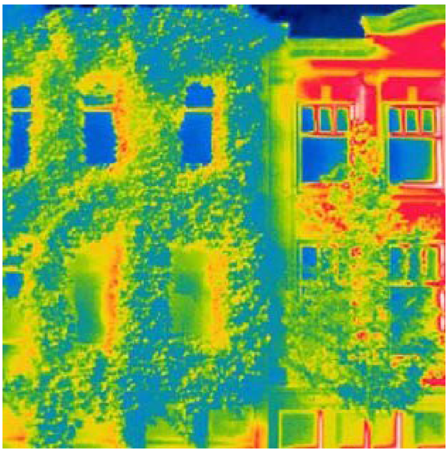


Figure 2.23. Facade covered by Boston ivy taken with ifrared camera in summer shows that the temperature of the vegetation is less than the bare wall (perini et al., 2011)

2.3.2. Other benefits of The Living wall system

2.3.2.1. Improve air quality

Plants have the capacity to reduce air pollution caused by PM2, CO_2, and volatile organic compounds as they use them through photosynthesis (Guzmán, 2019). Plants can also filter out particulate matters such as dust and PMX by capturing and adhering them to the leaf stems. Then, they can be washed away by rain. (Ottele', 2011).

The efficiency of a plant's ability to filter air is influenced by different factors, such as its leaf stomatal conductance and the contact between pollution and the leaves (Wagemans, 2016).

2.3.2.2. Biodiversity

LWS offers resting habitats for birds such as house sparrows and blackbirds. It can also provide food for insects, beetles, spiders, and, most importantly, bees. However, the increase of insects and birds can also be a disadvantage (Wagemans, 2016).

2.3.2.3. Sound absorption and insulation

LWS can reduce noise pollution as plants absorb, reflect, and diffuse noise, especially in areas where noise pollution is high.

Many factors influence the efficiency of LWS in reducing noise pollution; these factors are the plant type, the plant density, location, substrate material and its thickness, the texture of the planter boxes as well as the sound frequency (Wagemans, 2016).

2.3.2.4. Aesthetics value

LWS is a perfect example of how plants can be featured as artwork. These walls can be utilized as attraction points, indoors and outdoors.

When mixing plants with different colors and textures, you can create clever designs. Furthermore, as plants and blooms grow and seasonally change their colors, a green wall can become a living piece of art (Culver et al., 2014).

Figure 2.24. Living wall system in Mexico City, (matadornetwork,2020)

2.3.3. Requirements of Living wall System

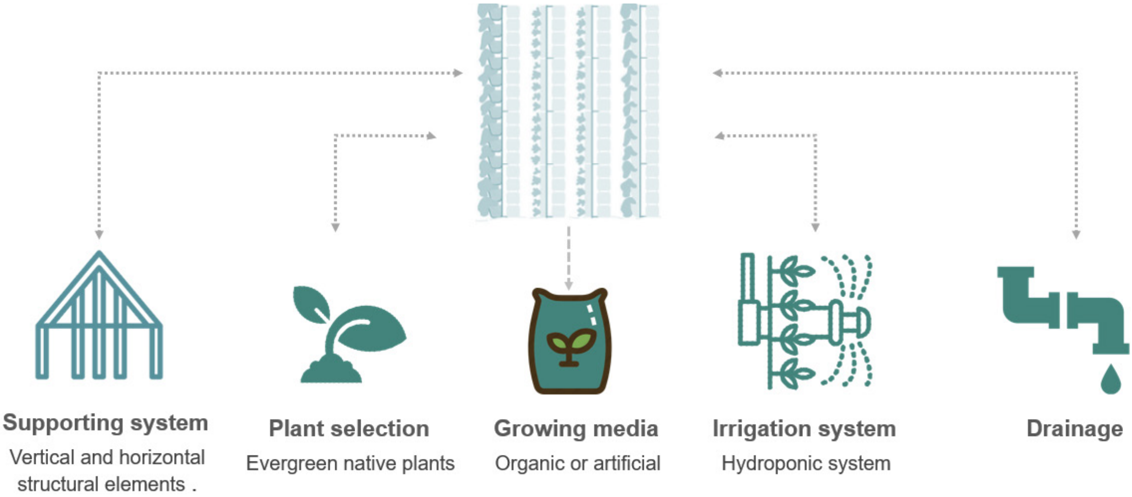


Figure 2.25. Living wall system requirements, (author)

2.3.3.1. Supporting system

The LWS acts as a second skin to the façade. However, covering a large façade with vegetation could become too heavy. Therefore, to ensure structural stability, a supporting system is needed.

LWS can be modular or continuous, and each type requires a different kind of structure. For instance, Continuous LWS or vegetation wall "Mur Vegetal", which is a frame that contains a lightweight base layer covered by root proof, water insulation membranes, and an outer layer cut to form pockets, Uses anchors to hold the vegetation weight, ensure structural stability and resistance against wind load (Manso and Gomes, 2014). While Modular LWS, which is composed of lightweight, interlocked units, uses vertical and horizontal substructural elements fastened to the exterior surface of the façade with an air cavity (Manso and Gomes, 2014).

2.3.3.2. Plant selection

Plants selection depends on climatic conditions, the orientation of the wall where the LWS is installed, building characteristics, and the surrounding conditions. From a sustainable point of view, vegetation should adapt to the local climatic conditions (solar exposure, wind, rainfall.), requires low irrigation and low maintenance (Manso and Gomes, 2014). Therefore, the most suitable plants for LWS are the climatic zone dense, compact with low growth rate, evergreen native plants. (Susorova, 2013).

2.3.3.3. Growing Medium

There are two different types of growing mediums: organic and inorganic. They can be used alone or mixed. Artificial substrates have more benefits as pests are less, and their weight is less than their soil-based counterparts (Manso and Gomes, 2014).

Expanded clay pebble

Coco coir

Growstones

plastic-based growing media

Gravel

Rockwool

Figure 2.26. Examples of organic and inorganic substrate, (Epicgardening, 2021)

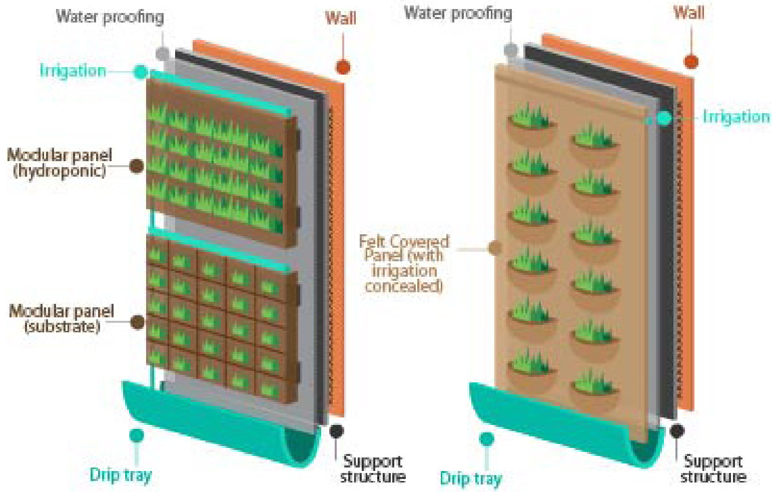
2.3.3.4. Irrigation system

LWS requires an irrigation system to provide the required water for the plants' development. The irrigation system consists of tubes made of different materials, such as rubber, plastic, thermoplastic, silicone, etc. It also contains different outputs (drip, sprinkler, holes) with intensity and distribution that meet the plants' needs.

For continuous LWS, a recirculating irrigation system is utilized. The water supply tube is placed at the top of the structure, and gravity plays a role in pulling the excess water down, collected then in a tank at the bottom of the wall and pumped back.

For modular LWS, pipes are placed at the top of each module (direct irrigation system). The bottom of the tray has several drainage holes allowing for excess water to irrigate the module underneath it. Moreover, Sensors can be installed in the growing medium to control irrigation time based on the plants' needs (Moawad et al., 2018) (Manso and Gomes, 2014).

Figure 2.27. Irrigation system in modular and continuous Living Wall System(ArchaNatura , 2016)



LWS based on the artificial substrate uses the hydroponic method, which allows the plants' growth without soil. Hydroponic has two main systems (Moawad et al., 2018):

- **<u>An active hydroponic system</u>** This system requires mechanical water pumping with chemical nutrients soaked in it directly to the plants' roots. This is the system commonly used in LWS.
- **<u>A passive hydroponic system</u>** without pumping

The Nutrients utilized in the hydroponic system, As mentioned by Moawad et al., differ from those used for soil-based growing medium, and to absorb these nutrients, the PH level has to be in a range between 6.5 and 7, as this the best pH range for most plants' growth.

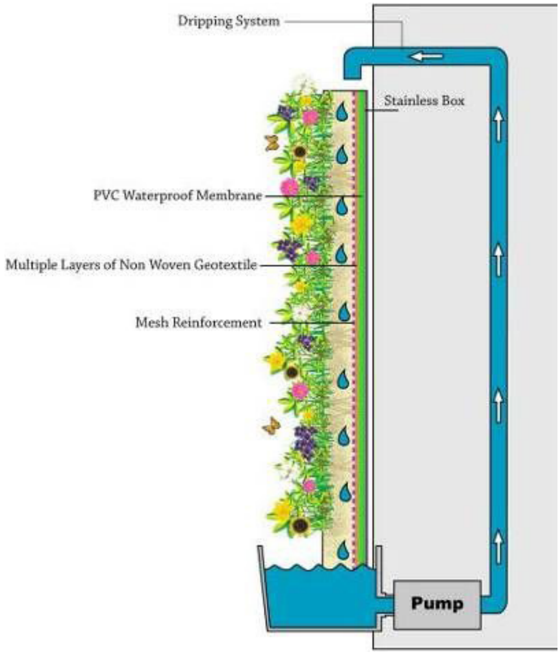


Figure 2.28. An active hydroponic System

(Pinterest , 2012)

2.3.3.5. Drainage

Excess water drainage in the LWS takes place by gravity. Geotextiles are utilized to encourage drainage while avoiding roots proliferation. Modular system, such as trays systems, takes advantage of the overlapping between the containers and uses drainage water to irrigate the module underneath it.

2.3.4. Types of living wall system

2.3.4.1. Living wall system based on planter boxes

This system contains lightweight planter boxes to hold the plants. The planter containers are fixed above each other on the supporting system with a 20 cm cavity. Soil and organic plants are usually utilized as growing media, and 30 species can be implemented per m2 (Mir, 2011). Generally, The life expectancy of this system is over 15 years (Ottelé, 2011).

- **Example. 1: Modulogreen**

This system is made from recycled plastic. It is suitable for indoor and outdoor applications. Each module can hold a considerable amount of substrate, around 4 L per plant, and it supports a variety of plants species.
Life expectancy is +20 years - Dry weight of this system is 29kg/m2 - Wet weight of this system is 39 kg/m2-Water consumption is 1L / m2/ day.

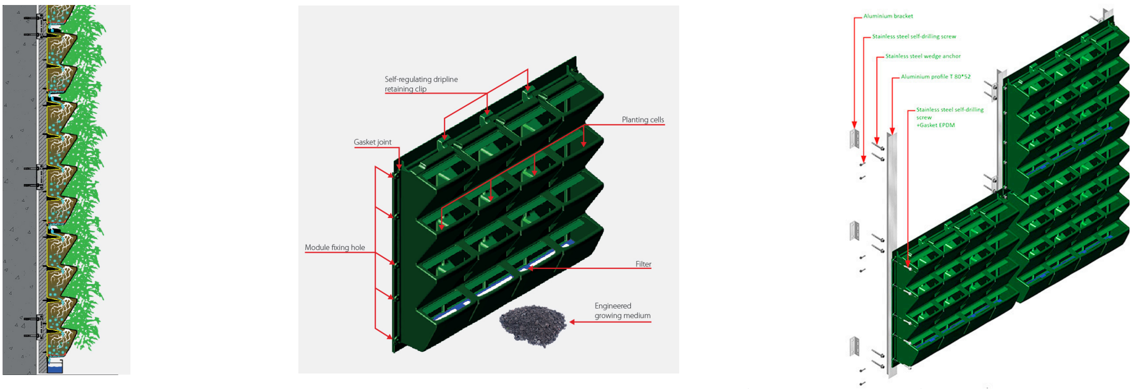


Figure 2.29. Modulogreen living wall system (greenplus, n.d.)

- **Example. 2: Greenwave**

This system is made of high-density polypropylene (HDPP) planter boxes. Two rows of boxes and a back sheet form one module. The size of each module is 515 * 600mm.
Wet weight of this system is 120kg/m2 - Water consumption is 1.5L / m2/ day.

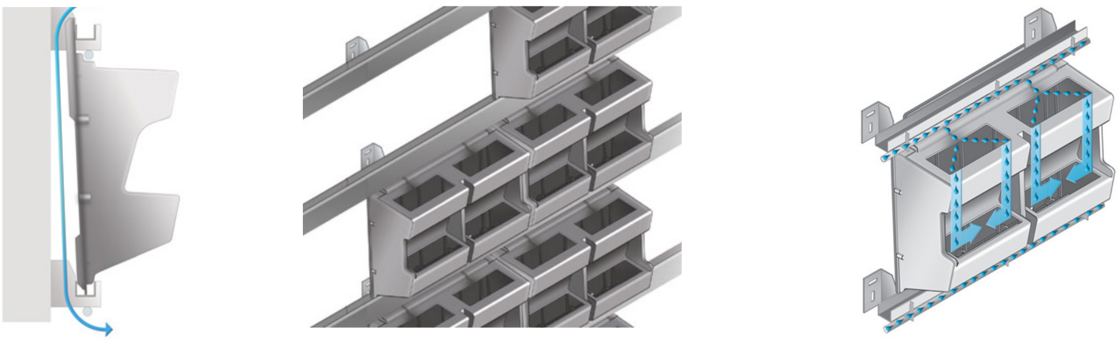


Figure 2.30. Greenwave system (greenwave system, n.d.)

- **Example. 3: ANS living walls**

The ANS ensures that the assembly is fast and straightforward. The units are made of recycled High-density polyethylene (HDPE). The size of each module is 250 * 500 * 100 mm and can hold up to 12 plant species

Life expectancy is +20 years -Wet weight of this system is 72kg/m2 - Water consumption is 1.5L / m2/ day

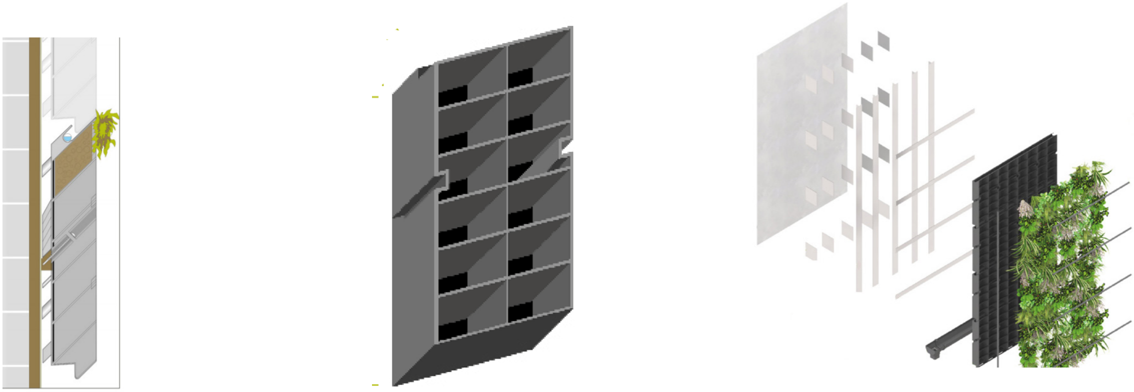


Figure 2.31. Ans living wall system (ansglobal, 2021)

- **Example. 4: Vertiss green walls**

This system is ideal for planting small areas and 100 m2 facades. It is made from High Density expanded polypropylene (HDP). Each module is 800 * 600 * 190 mm, holds 16 Planting cells and 32L of the substrate. The irrigation in this system is an open system.

Life expectancy is 15 years - Dry weight of this system is 32kg/m2 - Wet weight of this system is 53 kg/m2-Water consumption is 2.5L / m2/ day.

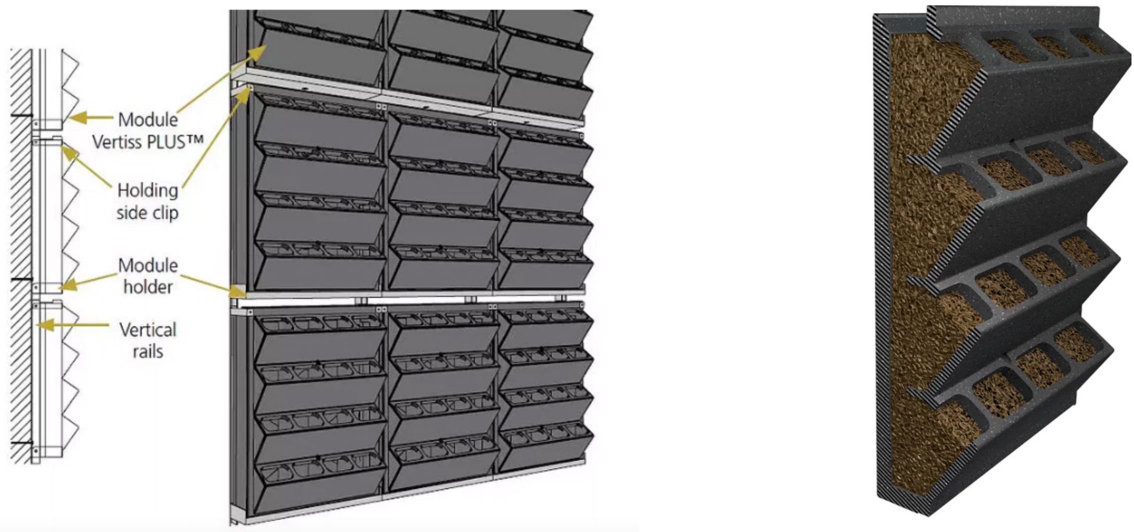


Figure 2.32. Vertiss plus (vertiss, n.d.)

2.3.4.2. Living wall system based on panels

This system consists of mineral wool panels as it is not loose, lightweight, and can stand by itself. The plants are rooted into the substrate before they are installed on the wall. This makes it easier to install the panel on the wall and have a direct effect (Mir, 2011). Foam can also be utilized, and it offers a pH-neutral growing medium. However, they are rarely used.

- **Example.1: Flexipanel**

Flexipanel is a lightweight modular system based on mineral wool. The element consists of a substrate bag fixed to TPO rear plat (waterproof layer). The size of each module is 720 * 620 mm, and the substrate bag is 620 * 520 mm with a thickness of 60mm. There is also a 300 mm air cavity behind the panels.
<u>Life expectancy is 10 years - Dry weight of this system is 25kg/m2 - Wet weight of this system is 45kg/m2-Water consumption is 2.5L / m2/ day.</u>

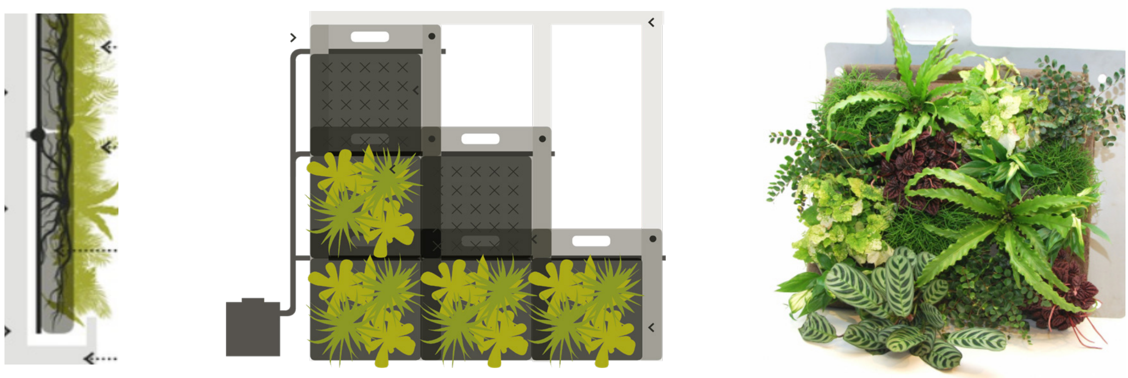


Figure 2.33. Flexipanel (sempergreenwall, n.d.)

- Example. 2: LivePanel

This panel is made of pressed rock wool with hollows and filled with organic soil. Potting plants can be done in the holes connected to a soiled vertical cylinder in the panel. The size of the panel is 400 * 400 * 55 mm.
<u>Life expectancy is 20 years - Wet weight of this system is 30-40kg/m2 -Water consumption is 3L / m2/ day.</u>

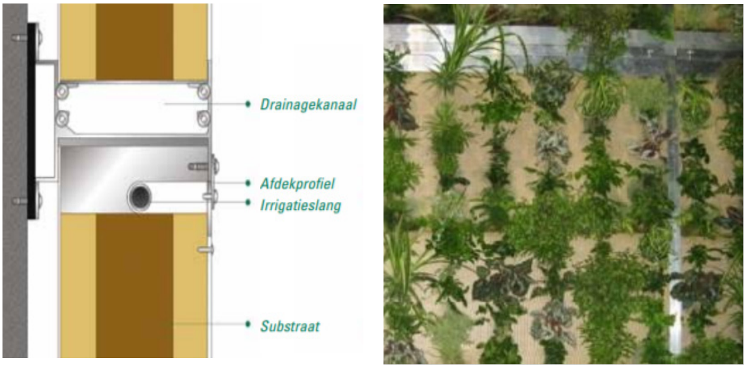


Figure 2.34. Livepanel (Ooster, 2013)

- **Example.3: Wallflore**

Wallflore is also made of pressed rock wool with hollow. The panels come in different sizes, and they support plants with short roots.

<u>Life expectancy is 20 years - Wet weight of this system is 50kg/m2 -</u>

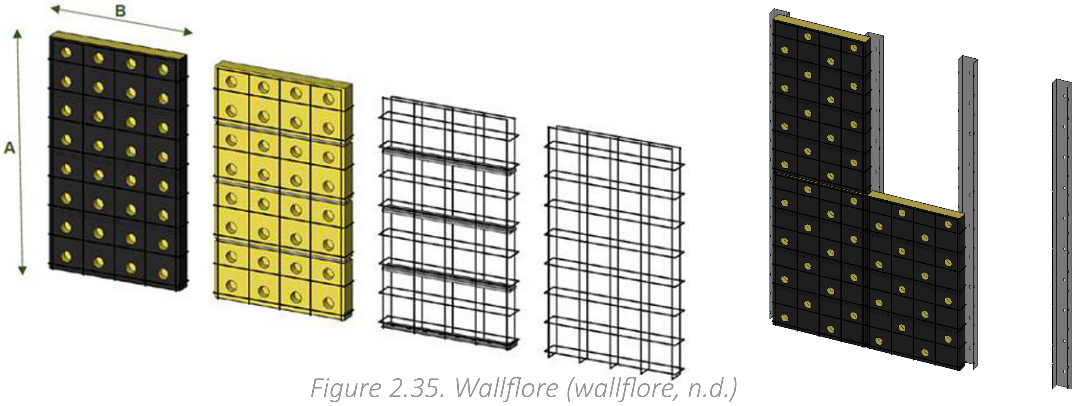


Figure 2.35. Wallflore (wallflore, n.d.)

2.3.4.3. Living wall system based on felt layers

This system consists of pockets made from multiple layers of fabric. This system is suitable for plants with short roots as the room inside the bags is small. Furthermore, the life expectancy is brief compared to other living wall systems, around ten years. Moreover, these pockets need to be regularly replaced due to substrate degradation (Mir, 2011).

- **Example.1: Fytotextile**

The Fytotextile system comprises flexible multilayer modules hanged on a substructure anchored to the exterior wall. This system can adapt to curved walls as well. Each pocket is made out of three synthetic, flexible, organic, and thin layers. Back layers protect the wall from moisture. Irrigation tubes are placed at the top of each module within a circular system.

<u>Life expectancy is 10 years - Dry weight of this system is 25kg/m2 - Wet weight of this system is 39 kg/m2-Water consumption is 1.4L / m2/ day.</u>

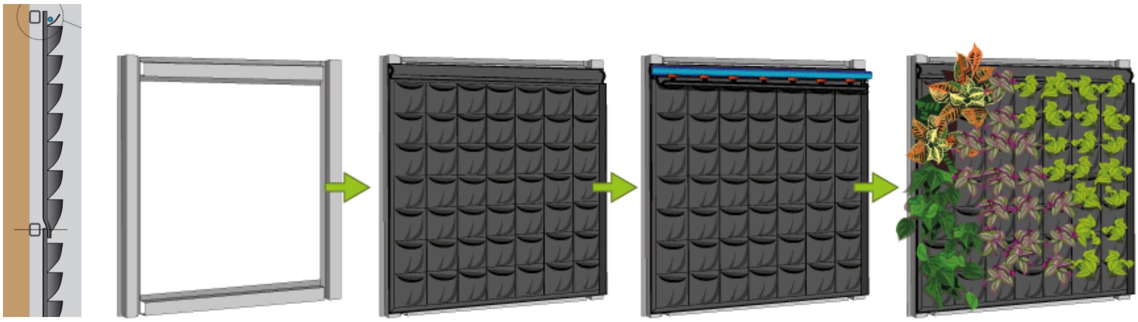


Figure 2.36. Fytotextile (terapiaurbana, n.d.)

For more information about the LWSs mentioned above check index .1

2.3.5. Conclusion

This chapter has reviewed the literature on UHI in general, UHI in Damascus, and links it to its causes, LWS and its cooling mechanism, the system main requirements, and types with examples for each one.

There are two types of UHI: Urban Canopy Layer (UCL) and Urban Boundary layer (UBL). This research will focus on UCL as it is the layer where people experience high temperatures.

Moreover, UHI has substantial consequences on the energy consumption for cooling purposes which could be 120% higher than surrounding suburbs as in Athens. UHI leads to worsening air quality as it accelerates the production of ground-level ozone and increases the ozone precursors emissions, which has a direct and indirect negative impact on human health. UHI also leads to outdoor thermal stress, which harms the functioning and people's health.

As a metropolitan city, Damascus experiences a high UHI effect for different uncontrollable factors like climatic and topographic characteristics and other controllable factors that can be summarised as vegetation degradation, using low albedo material, low SVF, high H/W ratio, high density, and anthropogenic heat. After analyzing the UHI effect in Damascus, it has been found that the intensity of UHI is higher at the city center northwest of the old city where the city's primary traffic nodes are located.

this chapter also introduces LWS as a UHI mitigation strategy and discusses its cooling mechanism, which can be summarised as the evapotranspiration effect, thermal insulation, and shading effect.

LWS has five main system requirements. These requirements are the mounting system, organic or inorganic growing medium, plant species, Irrigation system, and drainage. Artificial substrates have more benefits than soil-based substrates as pests are less, and they are lightweight. Moreover, LWS with artificial substrate usually uses a hydroponic recirculated irrigation system where excess water is collected at the bottom and then pumped back to the top.

Last but not least, there are three types of living wall systems: LWS based on planter boxes, LWS based on panel, and LWS based on felt layers. Each type has a different weight, life expectancy, and estimated water consumption. Different LWSs currently available in the market have also been analyzed, and they will be further evaluated in the next chapter after defining the main challenges and design criteria.

Chapter 03

Design Integration

3.1. Challenges involved in implementing LWS into the built environment

After learning about the system requirements, cooling mechanism and analyse different LWSs currently available in the market, the following challenges can be extracted:

Figure 3.1. Challenges involved in implementing LWS into the built environment

3.1.1. Water consumption

Water consumption of LWS depends on the climatic condition, the growing medium, plants selection, and the moisture exchange between the system and the surrounding environment through evapotranspiration. In general, each square meter of LWS requires from 1 to 2L of water each irrigating time. Furthermore, as discussed previously, Damascus experiences a dry season from June to October, and the average annual precipitation is 13mm, which is considered relatively low. Therefore, it is essential to provide enough water to keep the foliage in a healthy condition. But at the same time, find another source of water, and that could be challenging.

3.1.2. Cost

LWS is considered to be more expensive compared to direct and indirect green façade. The cost of the system depends on the used materials, fabrication techniques, installation process, maintenance rate, and the type of irrigation system. Therefore, more development is needed to reduce the cost of LWS and take full advantage of it. So that it can be implemented on a larger scale as the effect of a single LWS does not contribute to a significant change.

3.1.3. Environmental performance

The sustainability of the LWS is questioned. Many studied were conducted to evaluate the environmental performance of different LWSs during their lifecycle. Ottele' (2011) found that using stainless steel as a supporting system has an ecological impact ten times higher than recyclable materials. However, the durability of stainless steel is higher. For instance, PVC has limited durability, and it needs to be replaced many times during the system lifecycle. Overall, materials used in LWS have a high environmental impact. And even though recent studies proved that LWS could have less environmental impact through the contribution to the façade thermal resistance, which leads to a reduction in the energy demand for cooling and heating purposes (Manso and Gomes, 2014). Still, this environmental performance can be improved by using materials with less environmental impact.

3.1.4. Structural stability

When applying LWS on the existing façade, the weight and structural stability of LWS are a great challenge. Therefore, the system's dry and saturant weight should be taken into account to determine the type of supporting system and whether it can be mounted on the façade or sub-mounting structure is required. Furthermore, the less the weight is, the less material is needed for the mounting frame.

3.1.5. Maintenance

The maintenance labor of LWS has a high degree of complexity, and it does not only include trimming and removing the dead plants. Plants might need to be replaced, and the irrigation system needs to be regularly checked to ensure sufficient water and nutrient supply. The ease of replacing damaged parts without removing the whole system is also crucial. Therefore, a maintenance plan needs to be a part of the early design phase. Moreover, LWS increases biodiversity and provides ecological and habitats for insects. However, the increased number of insects can negatively affect LWS as it can lead to the destruction of plants. One example is vine weevil which targets plants in containers and eats the outer edge of leaves. Another example is the grubs that target the plants' roots and cause severe damage (Wagemans,2016).

3.2. Design Criteria

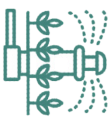
Based on the challenges discussed above, Design Criteria are defined. These criteria are linked to the system's main components to see how these criteria will affect the choice of each element.

3.2.1. Low water consumption

Choosing the living wall system with the least moisture exchange with the surrounding environment.

Choosing evergreen species that are drought tolerant with low watering demand.

Using Substrate with high water capacity.



Using recirculating irrigation system (Close loop Irrigation system)
Retreating domestic grey water

3.2.2. Feasibility

Using local material and local fabrication techniques

Choosing native evergreen species which is available on Damascus market.

Low cost durable growing medium.

Using as little material as possible and taking an advantage of the overlapping between the units so that the container at the top irrigates the one underneath it.

3.2.3. Less environmental impact

Using material with low environmental impact.

Using as little as possible energy.

3.2.4. Structural Integrity

Check the structural stability of the system.
Using lightweight but stiff units.

x

Light weight growing medium.

X

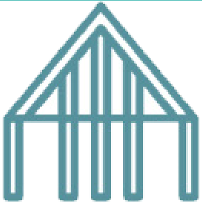
3.2.5. Low maintenance

Ease of replacing damaged parts.
The accessibility of the system.

Using plants with a low growth rate.
Using plant that prevents insects.

Using artificial growing medium.

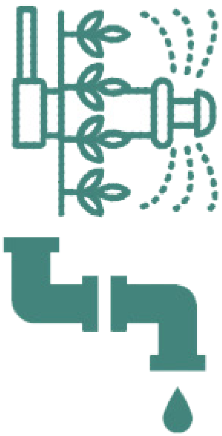
Ease of replacing and repairing damage parts.



- Choosing the living wall system with the least moisture exchange
  Using local material and local fabrication techniques.
  Using material with low environmental impact.
  Using as little as possible energy.
  Check the structural stability of the system
  Using lightweight but stiff units
  Ease of replacing damaged parts.
  The accessibility of the system.

- Choosing evergreen species that are drought tolerant with low watering demand.
  Choosing native evergreen species which is available in Damascus.
  Using plants with a low growth rate.
  Using plant that prevents insects.

- Using Substrate with a high water capacity.
  Low cost durable growing medium.
  Using material with low environmental impact.
  Light weight growing medium.
  sing artificial growing medium.



- Using recirculating irrigation system (Close loop Irrigation system)
  Retreating domestic greywater
  Using as little material as possible and benefits from the overlapping between the units. So that the container at the top irrigates the one underneath it.
  Using material with low environmental impact.
  Ease of replacing and repairing damaged parts.
  Using as little as possible energy.

How to achieve ?

Evaluate different LWS types

Evaluate different plant species

Compare the different growing mediums.

Choose local material as the primary fabrication material.

Looking into the potential of retreating domestic greywater

Design LWS which has self-standing overlapping between its units and using a close loop irrigation system

Check the structural performance of the system.

Compare the price with the design with the systems available in the market.

3.3. Evaluation of LWSs available in the market

Table 3.1. Evaluation result of LWSs available in the market

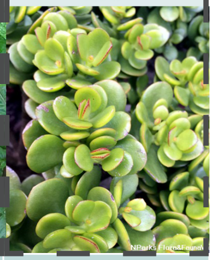
Evaluation criteria		Explanation	Modulogreen	Flexipanel	Fytotextile	ANS	Vertiss plus	LivePanel	Greenwave	wall flore	weight	total weight
Feasibility	Cost per square meter	The price of the LWS system with growing medium	1	-1	-1	1	-1	0	1	0	25%	25%
	Amount of material used	The more materials the system uses the less feasible it is	1	0	-1	1	1	0	1	-1	10%	
	Ease of fabrication	Is the system easy to be fabricated in Damascus	1	-1	0	1	0	-1	1	-1	25%	
	Ease of installation	Does the system require special equipements	1	0	1	1	0	0	1	0	10%	
	Transportion cost	The bigger the system is the higher the transportaion cost	1	0	1	1	-1	-1	1	0	10%	
	Life expectancy	Life expectancy of the system as given by the manufacturer	1	-1	-1	1	0	1	1	-1	20%	
		score	**1**	**-0.45**	**-0.5**	**1**	**-0.25**	**-0.3**	**1**	**-0.55**	**100%**	
Water consumption	Irrigation system	Is the system active or passive	1	1	1	1	-1	1	-1	1	15%	35%
	Water consumption	the amount of water required to maintain the system in good condition	1	0	-1	1	0	-1	0	-1	50%	
	Risk of dehydration	the risk of dehydration	1	-1	0	1	1	-1	1	-1	10%	
	Hydroponic system	if the system uses Hydroponic system it is less Feasible	1	-1	1	1	1	-1	1	-1	25%	
		score	**1**	**-0.3**	**-0.1**	**1**	**0.2**	**0.7**	**0.2**	**-0.7**	**100%**	
Vegetation	Plants per unit	The amount of plants per units	1	0	1	1	0	-1	-1	1	20%	20%
	Plant selection	Does the system support wide range of species	1	0	-1	1	1	1	1	-1	40%	
	Growing medium	Is the growing medium artificial or organic	1	-1	-1	1	1	-1	1	-1	40%	
		score	**1**	**-0.4**	**-0.6**	**1**	**0.8**	**-0.2**	**0.6**	**-0.6**	**100%**	
Maintenance	Maintenaning growing medium	The easy of keeping the growing medium in a good condition without the need of detaching the whole unit	1	-1	1	1	1	0	1	-1	25%	20%
	Ease of replacing plants	The ease of replacing the dead plants without affecting other plants	1	-1	-1	1	0	0	1	-1	25%	
	Ease of replacing damaged parts	Accessibility to all the system parts in case of damage	1	0	-1	0	1	1	1	-1	25%	
	plant maintenance	if the system supports a wide range of species, low maintenance plants can be utilised	1	0	-1	1	1	1	1	1	25%	
		score	**1**	**-0.5**	**-0.5**	**0.75**	**0.75**	**0.5**	**1**	**-0.5**	**100%**	
		1= fulfills the criteria, 0= neutral, -1 = does not fulfill the criteria — **total score**	**1**	**-0.39**	**-0.38**	**0.95**	**0.317**	**0.28**	**0.76**	**-0.6**		100%

After defining the design criteria, the LWSs mentioned in the previous chapter have been subjectively evaluated to determine which type is more suitable for the context of Damascus.
Feasibility and water consumption are given a higher weight of 25% and 35%, respectively. Structural stability and environmental impact have not been used as the primary evaluation criteria.

From the evaluation results shown in Table 3.1., it is observed that LWS based on planter boxes is the most suitable for Damascus because it requires less water consumption than other systems, especially that this system loses less water to the environment through evapotranspiration. Moreover, This system requires less maintenance, supports a wide range of species, and has more than 15 years of life expectancy. Moreover, LWS based on planter boxes is modular and can support different facade typologies.

3.4. Evaluation of Plant species

Table 3.2. Evaluation result of Plant species

criteria	*Asparagus setaceus*	*Alternanthera ficoidea*	*Mentha piperita*	*Crassula ovata*
common name	*asparagus fern*	Joseph's coat	*Peppermint*	*jade plant*
Maintenance	Moderate	Moderate	Moderate	low
growth rate	normal	normal	relatively fast	normal
frost tolerant	-3	0	-15	0
evergreen	yes	yes	yes	yes
drought tolerant	sensitive	sensitive	sensitive	yes
height	0.3-3m	0.1m	0.3-0.6 m	0.5-1.2 m
expansion	0.6-2m	0.2m	0.4-0.8 m	0.3-1 m
leaf area index	3.5	4.5	3	4.5
light intensity	semi shade	bright light	Full Sun, semi shade	Semi-Shade, Full Sun
Plant Growth Form	Shrub	Shrub	Shrub	Shrub
Life span	perennials	perennials	Perennial	Perennial
native environment	Mediterranean Subtropical	tropical	Mediterranean	Tropical, Sub-Tropical
Water Preference	Moderate	Moderate	high	Little
photo				

criteria	*Ipomoea pes-caprae*	*Hedera helix*	*Chlorophytum comosum*	*sedum*
common name	*goat's foot*	*English ivy*	*spider plant*	*oblongleaf stonecrop*
Maintenance	low	Moderate	low	low
growth rate	Fast	Fast	normal	low
frost tolerant	0	-10	0	0
evergreen	yes	yes	yes	yes
drought tolerant	yes	yes	yes	yes
height	0.1-0.2 m	max 2 m	0.3 - 0.6	0.5-1.2 m
expansion	5-30 m	max 2 m	0.3 - 0.6	0.4-0.8 m
leaf area index	4.5	5 - 3	3.5	4.5
light intensity	Full Sun	Semi-Shade, Full Sun,shade	Semi-Shade	Full Sun
Plant Growth Form	Shrub	Shrub, climber	Herbaceous	Shrub
Life span	Perennial	Perennial	Perennial	Perennial
native environment	Tropical, Sub-Tropical	Mediterranean	Sub-Tropical	Mediterranean Subtropical
Water Preference	little	Moderate	Little	Little
photo				

criteria	*Lantana camara L*	*Portulaca oleracea*	*Ophiopogon jaburan*	*Aglaonema*
common name	*lantana*	*purslane*	*White Lilyturf*	*Chinese evergreen*
Maintenance	low	low	low	low
growth rate	normal	low	normal	normal
frost tolerant	0	0	0	0
evergreen	yes	yes	yes	yes
drought tolerant	yes	yes	yes	yes
height	max 1.2 m	0.05- 0.15 m	0.1-0.5 m	max 1 m
expansion	0.3 - 0.6	0.2-0.5	0.1-0.5 m	0.3-1 m
leaf area index	-	-	3.5	3.5
light intensity	Semi-Shade, Full Sun	Full Sun	Semi-Shade, Full Sun,shade	semi-shade, shade
Plant Growth Form	Shrub	Shrub,creeper	Herbaceous	Herbaceous
Life span	Perennial	annual	Perennial	Perennial
native environment	Tropical	Mediterranean	Mediterranean Subtropical	Tropical
Water Preference	little	little	low	Moderate
photo				

Presents the plant species that are suitable for the context of Damascus

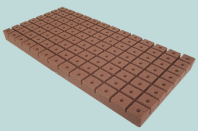
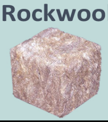
- Mentha piperita Prevents beetles, caterpillars, shield insects, and whiteflies. Hedra Helix has a high leave index. However, it requires more water than other species. Therefore, it will be botted in the bottom part of the living wall system where the moisture is maximum.
  The rest have a low growth rate, are drought-tolerant, suitable for Full Sun, semi-shade with little water consumption.

3.5. Advantages and disadvantages of different growing medium

As shown in Table 3.3., it can be seen that Growstone is the best option, as it is light-weight and cheap. Moreover, Growstones are made from 100% recycled glass. It has a highly porous and uneven shape which allows for sufficient Oxygen between the roots. Growstones have a density of 0,2 g/cm^3 and can hold up to 30% of their volume in water. The water holding capacity of Growstones can be improved by mixing them with peat. Peat has been traditionally used as the prime raw material for soil mix because of its excellent agronomic properties (planetnatural.com).

Therefore, a Mixed substrate of Growstones and peat will be used as a grow medium.

Table 3.3. Advantages and disadvantages of different growing medium

Substrate	pro's	con's
Expanded clay pebble 	high pore space which means fewer blockage	Low water holding capacity
	Good air holding capacity which keep root zone oxygenated	Fairly costly
	Fairly renewable and	Can cause problem with pumps
	Easy to plant and harvest	Relatively heavy
Coco coir 	Sustainable	Hard to find
	High water holding capacity	Problems from salt
	It doesn't cost much	
	Light weight and compact	
plastic-based growing media 	roots embed deeply into the medium and the plants and medium become one	Need to have a top layer that stays 100% dry or it promotes algae growth
		Expensive, not re-usable
Oasis Cubes 	Inexpensive	Not sustainable and Not organic
	No pre-soaking	Useful for germination only, not as a full growing medium
Rockwool 	Great water retention	It's Not Environmentally Friendly
	Easy to dispose of	
Growstones 	Lightweight	Hard to clean
	High water, air capacity	Not reuse able
	Sustainable	
Gravel 	Easy to clean	Heavy
	Very inexpensive	Low water holding capacity
	Drains well	

3.6. Materialization - Giant Reed

After researching for local, eco-friendly material and still suitable as potting boxes, it has been found that Giant Reed (Arundo Donax L.) is a material with great potential.

Giant reed grows naturally along streams and river banks. It has a hollow stem similar to bamboo and can grow up to 6m. the nodes are located at a distance of about 20cm from each other and give it more strength. The hollow stems have a thickness of 0.2 cm-0.6 cm and 2 cm- 3 cm external diameter (Wikipedia, 2021) (Barreca et al., 2019).

Figure 3.2. Culm of Arundo donax L. (Barreca et al., 2019)

It is native to the middle east and the Mediterranean regions. In Syria, it grows along the rivers and the coastal areas. Moreover, Giant Reed has been traditionally utilized for creating woven baskets for different purposes, wind bearing panels, musical instruments. Although the mean tensile strength of the giant reed culm (Ts=248 Mpa) is higher than bamboo (Ts=230 Mpa), it is not widely utilized as a structural material like bamboo (Barreca et al., 2019). In dry climates, the giant reed is used as a building construction material. For example, in Al-Chibayish south Iraq, Large and thick giant reeds are used in the traditional Mudhif houses (Barreca et al., 2019).

Figure 3.3. A mudif house in Iraq (atlasobscura, n.d.)

Moreover, Giant reed is a raw material for economically feasible fiber production, which can be woven in different patterns to form rigid geometrical volumes.

In Damascus, weaving reed is one of the traditional handicrafts. Therefore, using giant reed will add extra social and economic value to the design. Especially that will provide job opportunities, preserve the cultural heritage and find a new application for the traditional handicrafts.

Giant reed fibers come in a variety of sizes and types, and mainly there are five different types (textileindie, n.d.):

Figure 3.4. Reed fibers (textileindie, n.d.)

The mechanical properties of Giant Reed fibers as reported by (V. Fiore et al., 2014)

Mechanical properties	Density [g/cm3]	Tensile strength [MPa]	Young's modulus [GPa]	Elongation at break [%]	Allowable deflection l/360
Giant reed fibre	1.168	248	9.4	3.24	0.04 cm

Figure 3.5. Pictures from weaving Barada workshop in Damascus (IWLab, n.d.)

3.7. Design integration

Four steps were followed to create the final design; starting with creating the initial concept, then the structural analysis and optimization, then designing the irrigation system, and eventually, creating the final design.

3.7.1. Initial design concept

The hexagonal grid is chosen as the primary grid for the design because the hexagon is the best geometric shape to fill in a plane with an equal size of modules with fewer leftover spaces. It is known as the most mechanically stable shape (abroots.com). After choosing the design grid, 3D volumes were created. The goal was to have a relatively small width while ensuring they support the plants' normal growth direction and support a wide range of species.

Two options were created; option 1 has less potting basket but has larger depth. The second one has less depth but more potting basket. Eventually, option 2 was chosen to be further developed Figure 3.6.

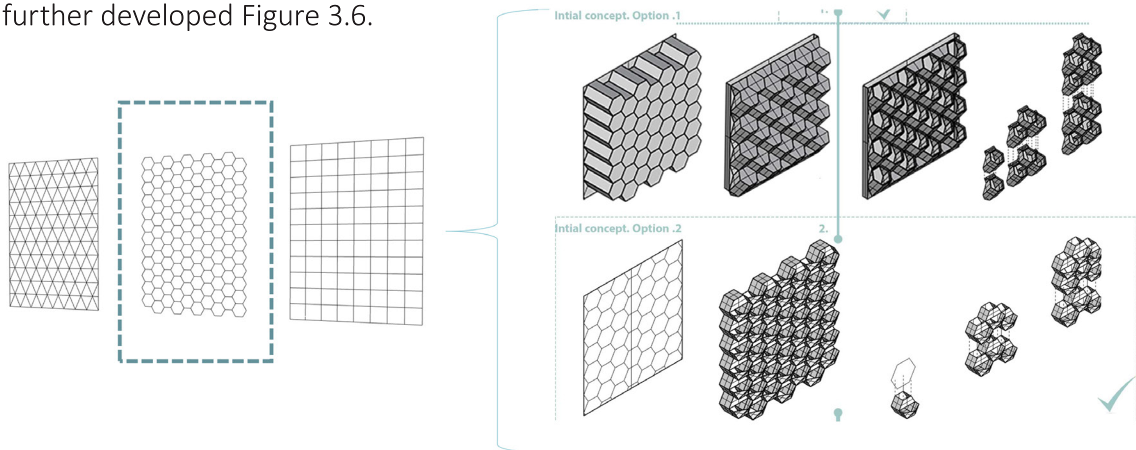


Figure 3.6. Intial design concept

The size of each unit is 30 * 15 cm (diameter * thickness). The dimensions are chosen with consideration to the expansion and root growth of the plants evaluated previously. Each module is fixed from four sides with the modules next to it. Moreover, they are vertically mounted above one another. There are two holes at the top and bottom of each module to benefit from the overlapping between the units and allow for excess water to irrigate the unit underneath it, as seen in Figure 3.7.

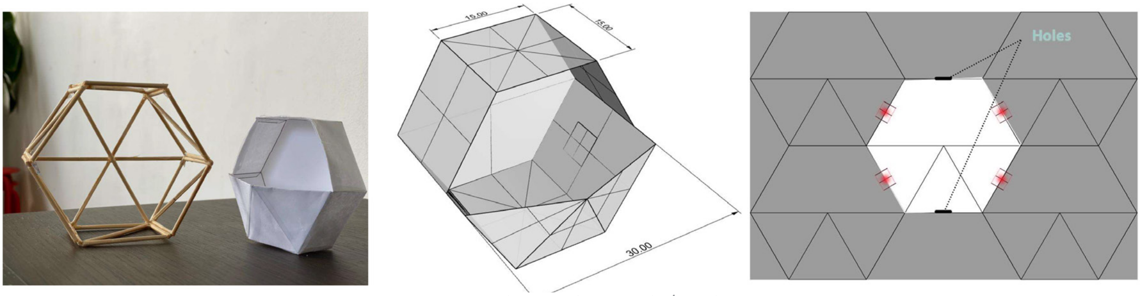


Figure 3.7. Intial unit

Woven reed fibers with a width of 0.5 cm and a thickness of 0.2 cm will be the main components for the units. Many different patterns can be made. However, for ease of fabrication, the plain pattern is chosen.

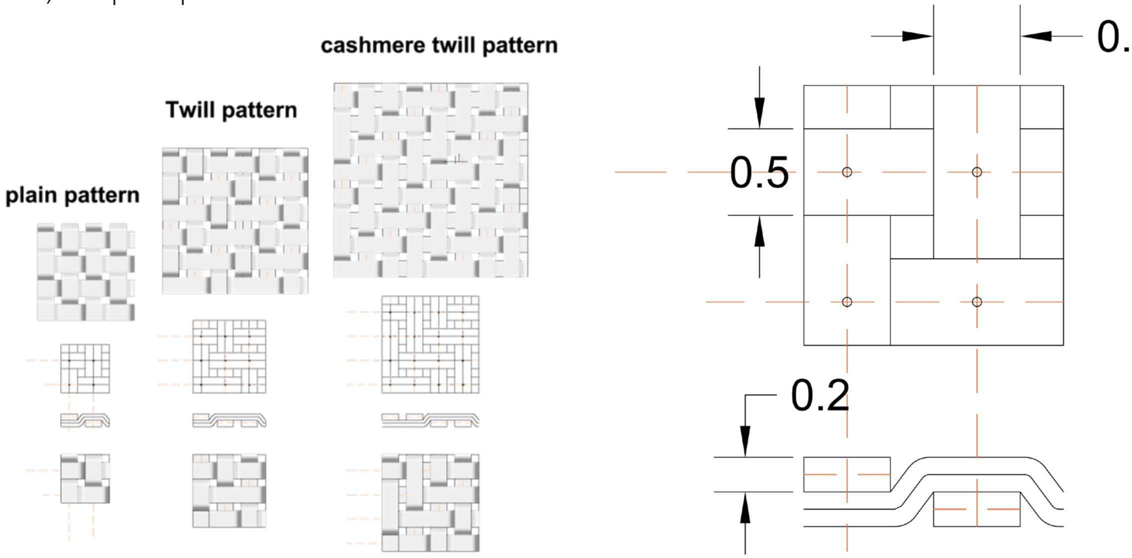


Figure 3.8. Weaving patterns

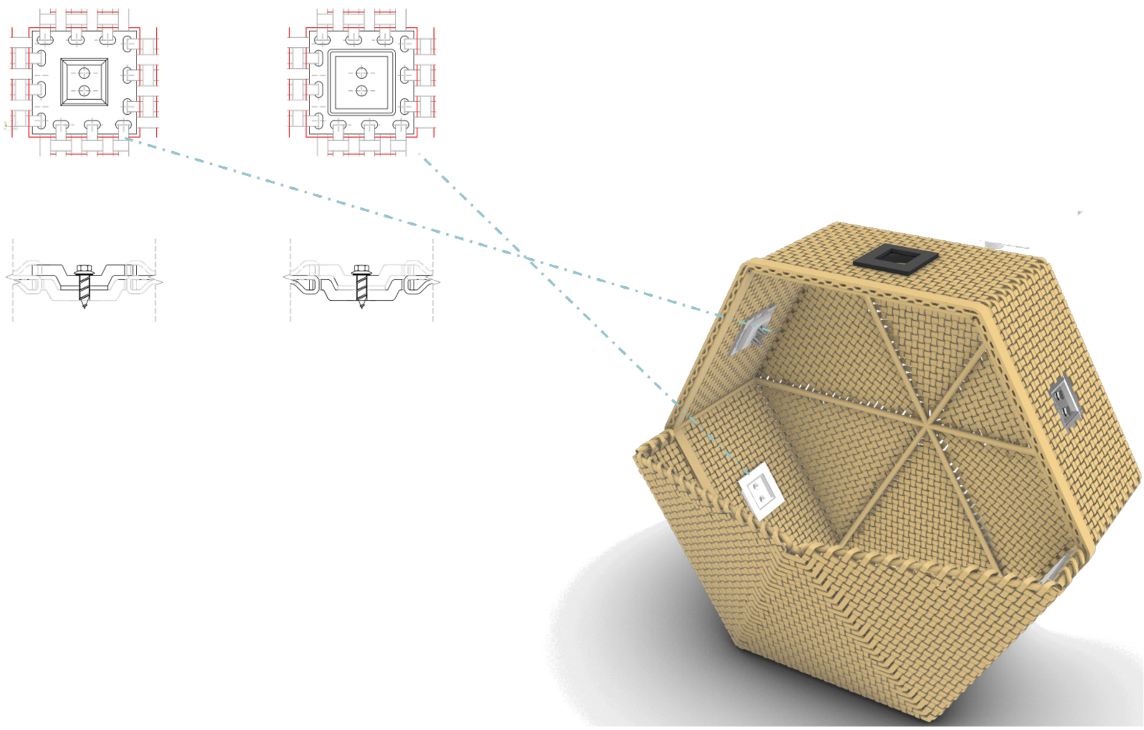


Figure 3.9. Designing the connectors

Simple environmental analysis for the most commonly used materials in CSS has been conducted to choose the connector's material. These materials are Aluminum, stainless steel, and Polyethylene (PE). From this analysis, it has been found that PE is the most environmentally friendly. See Figure 3.10.

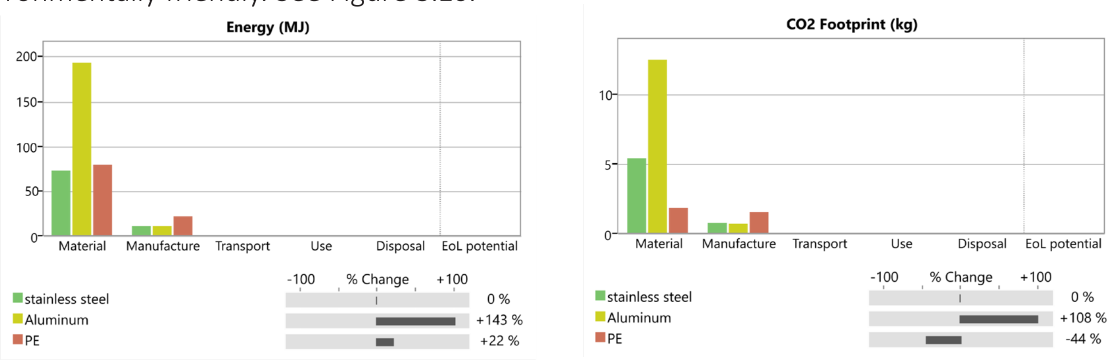
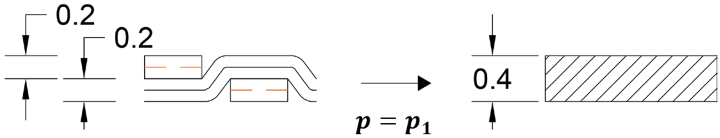


Figure 3.10. Environmnetal analysis for stainless steel, Aluminum and PE

3.7.2. structural analysis

After creating the initial design for the units, structural analysis using Grasshopper plugin called Karambs is conducted to check their performance under their self-weight.

In order to simulate the structural behavior of the woven cross-section, an equivalent homogeneous material is defined where the complex cross-section is simplified into a solid cross-section with a thickness of 4 mm and Young's modulus of 9.4 Gpa (Young's modulus of giant reed fiber) but a lower equivalent density p1.



where $p_1 = \frac{m_a}{h}$ =>

$$p_1 = 1.03\ g/cm^3 = 1030\ Kg/m^3$$

m_a : the mass per unit area = 0.41 g/cm^2

h : the overall thickness of the woven cross section (4mm)

The resulted equivalent density is utilised to calculate the dry self-weight of the reed basket (m dry), then the saturant self-weight considering that each basket contains approximately 1265 g of Growstones, which can hold up to 30% of its weight water.

Load due to Self-weight of the basket without substrate = 0.906 * 9.81 = 8.88 N ≈ 9 N

Load due to the saturant Self-weight of the Growstone = 1.644* 9.81 = 16,12 N ≈ 16 N

The saturant weight of the saturant basket with the substrate is 2550 g

3.7.2.1. Result and optimisation

The simulation result shows that the maximum deformation of the units under its saturant weight is minimum and does not exceed 1.55 * 10-4 cm. it is way less than the maximum deformation of a rectangular basket with the same substrate capacity 2.22 * 10-2 cm. as seen in figure 3.11.

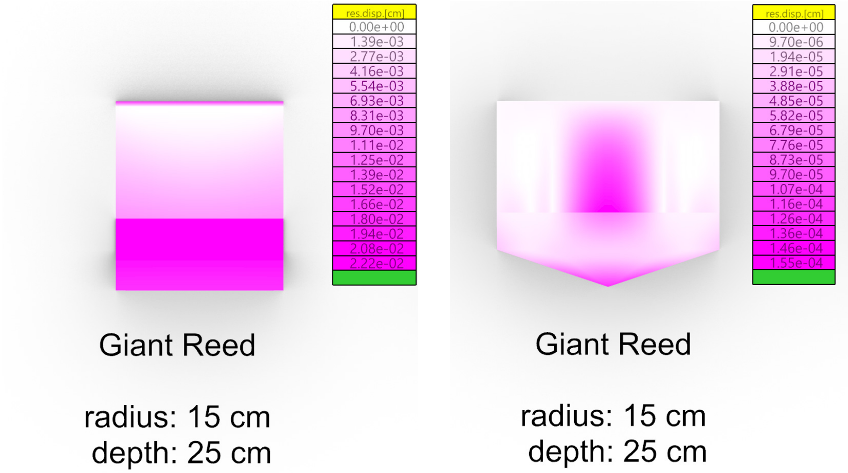


Figure 3.11. Structural analysis of hexagonal and rectangular basket with the same capacity

To optimise the design further, the diameter of the basket was increased from 30 cm to 45 cm. Consequently, the maximum deformation increases from 1.55 * 10-4 cm to 1.12 *10-3 cm. However, this deformation is still negligible.

when comparing the deformation of the 45cm reed basket with a polypropylene container with the same shape and capacity. it is observed that the polypropylenes container has less deformation of 6.74 * 10-4 cm but the difference is also negligible. Figure 3.12.

As a result, woven giant reed baskets can give the same stability as polypropylene containers. It has minimum deflection under its saturant weight. Which means the units are structurally stable and functional.

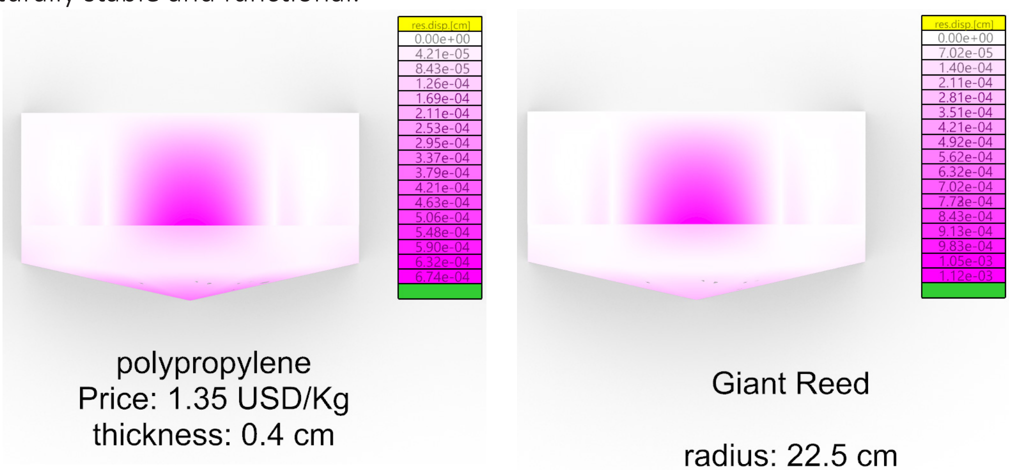


Figure 3.12. Structural analysis of giant reed and polypropylene basket with the same capacity

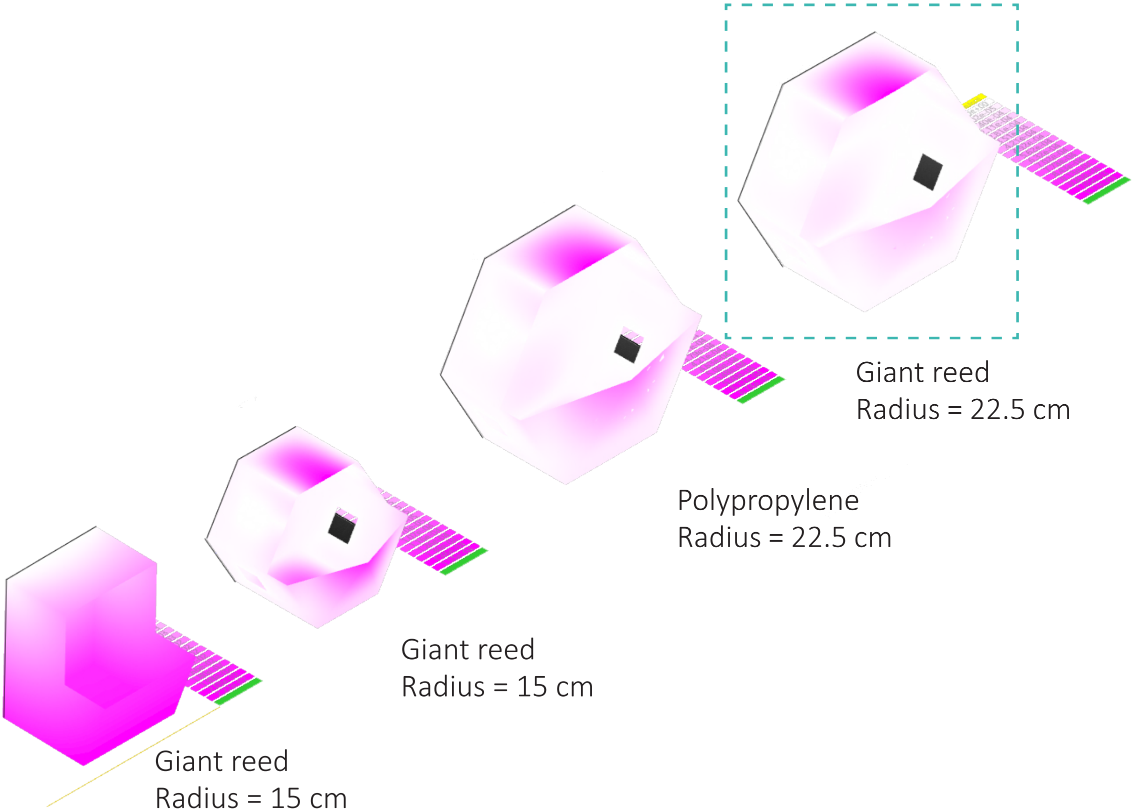


Figure 3.13. Overview of the structural analysis results

To check if the existing facade can safely support the LWS, the vertical gravity load per square meter produced by the saturant weight of the LWS is compared with the structural loading requirements of the Syrian Building Code (SBC). The saturant weight of the LWS per square meter is approximately 20 Kg/m2, which is equal to 0.196 kn/m2

The residential buildings in Damascus are designed and constructed to hold 1700 kg/m2. That is equal to 16.66 Kn/m2 with a 1.5 safety factor for the dead load. That means that, in reality, the structure can hold up to 24.99 Kn/m2.

When comparing the LWS loads with structural loading requirements for the SBC, It can readily be observed that the LWS loads are minimal.

3.7.3. Irrigation system

The irrigation system required custom design in all cases. However, in general, a recirculating irrigation system is used. This system mainly consists of a water tank to store water at the top of the building, a timer, Irrigation tubes, a drainage channel at the lowest module to collect excess water, and a pump to return the water to the tank.

The LWS requires daily irrigation during the summer and two times per week during cold winter. That means that a vast amount of water is needed.

However, Damascus is already experiencing a shortage of water. Therefore, we have to search for an alternative source of water to meet the design criteria.

This alternative could be by retreating the domestic greywater, Figure 3.14. On an average, a family with four members consumes 50 L/day per person, from which 15 L/day per person is greywater. Consequently, each family produces 60 L of greywater per day. That is enough to irrigate 28 square meters of LWS.

Water treating system costs on average 2000$ which considered to be relatively high. However, this will be paid back from the money saved from the water bill over time.ver, this will be paid back from the money that saved from water bill by time.

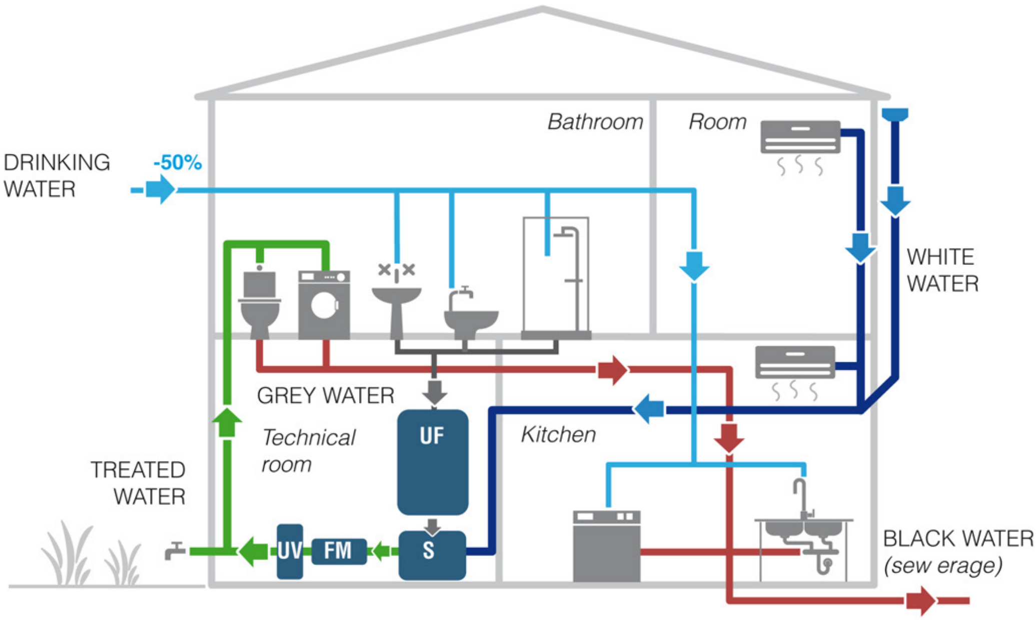


Figure 3.14. Greywater treating system (Aliaxis, n.d.)

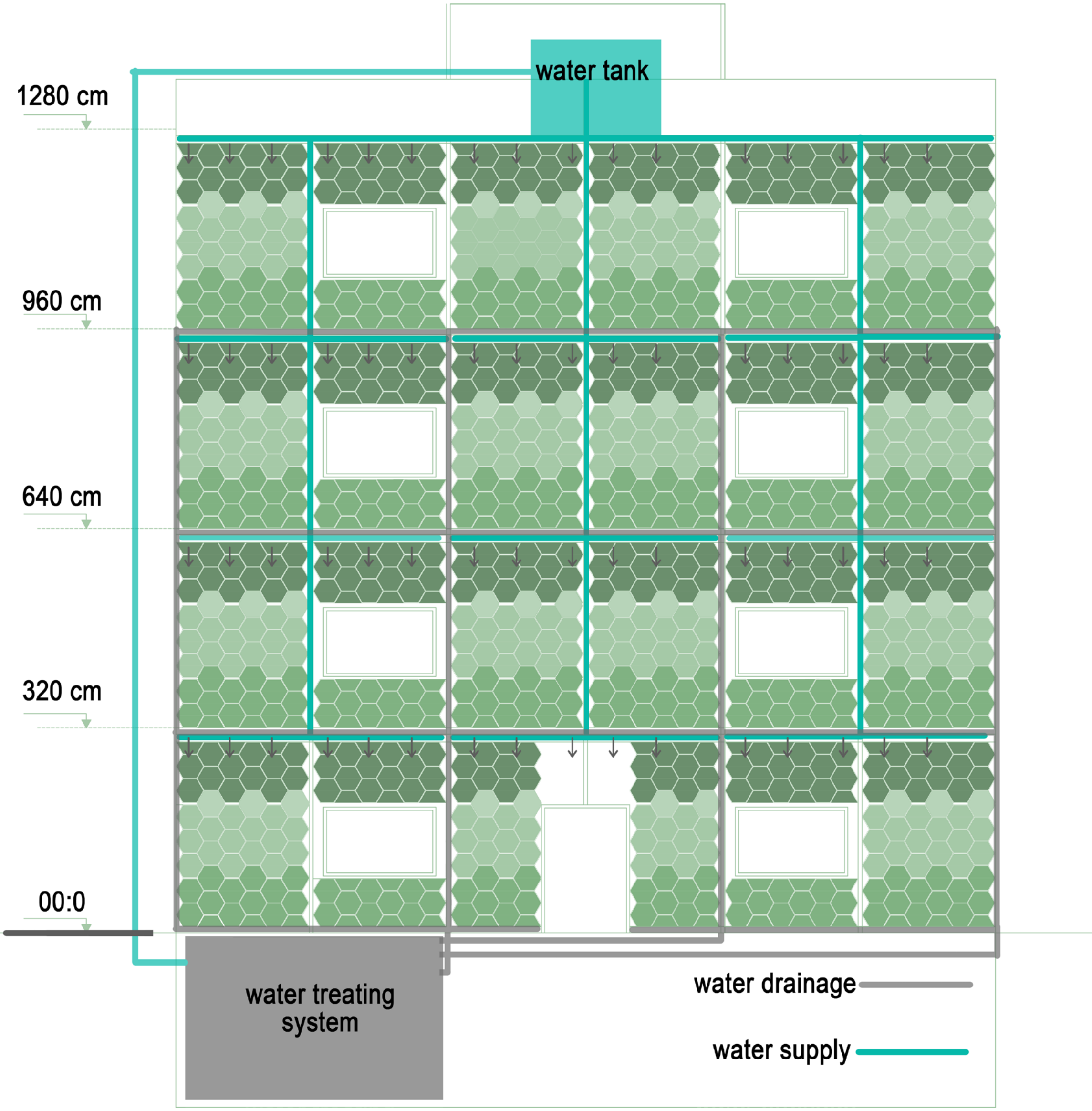


Figure 3.15. schematic diagram of irrigation and drainage water cycle

3.7.4. Living Wall system maintenance consideration

To have low maintenance LWS, measurements before and after installation are considered.

Before installation

1. The plant species are chosen to be suitable for the climatic condition and have low maintenance and growth rate.

2. The system is designed to replace any damaged parts without the need to remove the whole system.

3. Improving the durability of the woven reed basket by following these steps:

- Treating the reed fibers before weaving against potential insects using a mixture of boric acid minerals.
- Sealing the woven basket with a polyurethane finishing product. That adds extra protection against moisture and dirt.
- Adding a plastic layer at the bottom of each basket to ensure that water will not accumulate.
- Placing burlap bag inside the basket before adding the substrate mixture.

After installation

1. Check that there is no water collection buildup as a result of clogged drainage.

2. Check the plants for diseases, damaged leaf or any dead foliage

3. Check the system for any damaged parts.

3.7.6. Final Design - Mosaic Living Wall System

Mosiac living wall system is a modular Living wall system with hexagonal locally fabricated woven reed baskets. The system is considered to be cheaper than LWSs currently available in the markets. The main saving is in the price of the potting baskets, especially that the irrigation and mounting system used are the same as in other LWS.

The average price of the potting containers is between 116 to 139 euros per square meter (greenroof guide, 2021), while the price of woven baskets is 65 euros per square meter.

When comparing the material used regularly in LWS with Mosiac living wall system, It can be clearly seen that the environmental is less.

The saturant weight of Mosiac is 20 kg per square meter which is also less than other LWSs .

Mosiac
Living Wall System

Figure 3.16.Prototype of Mosiac living wall system

Mosiac
Living Wall System

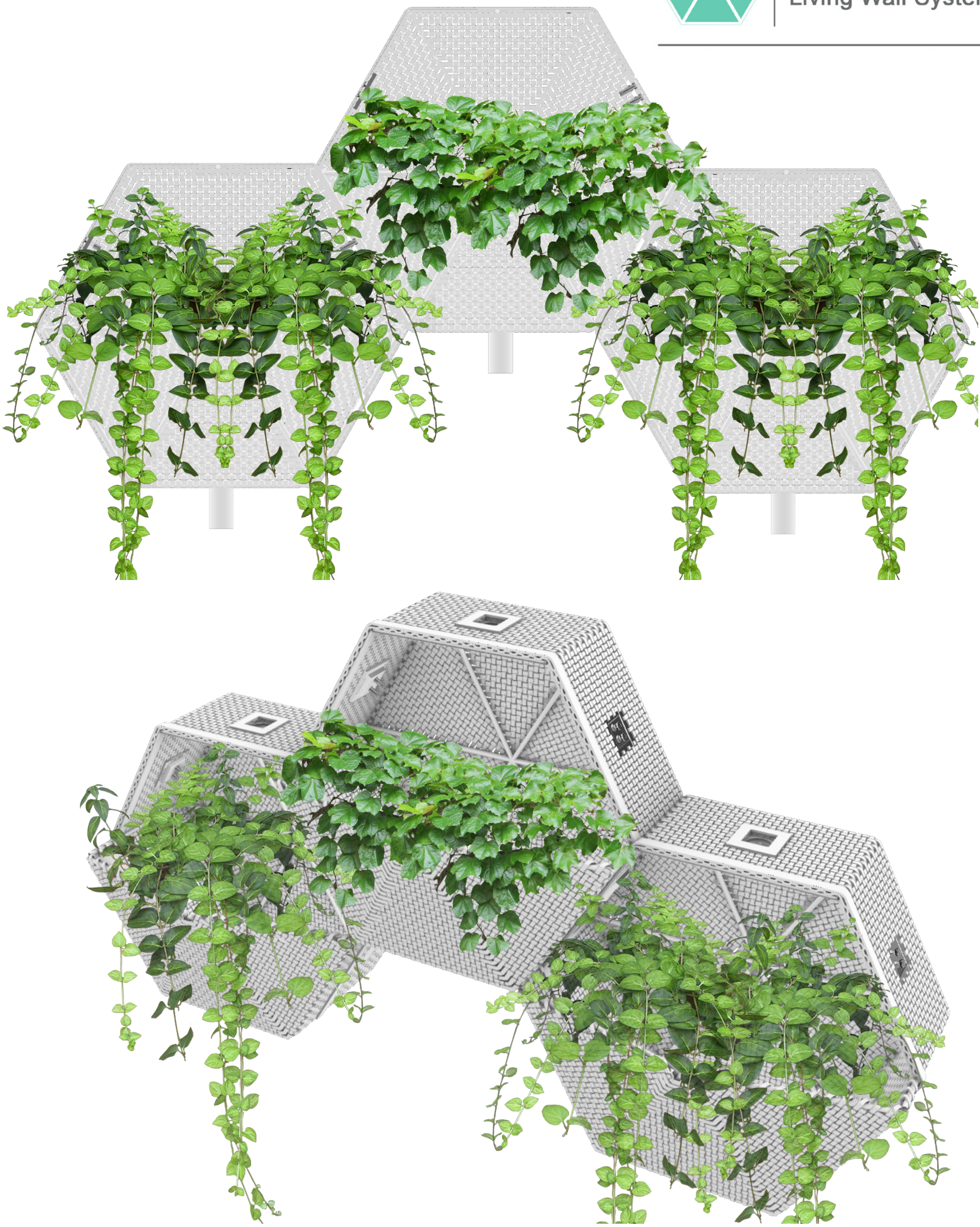


Figure 3.18. Prespective of Mosiac living wall system

Mosiac
Living Wall System

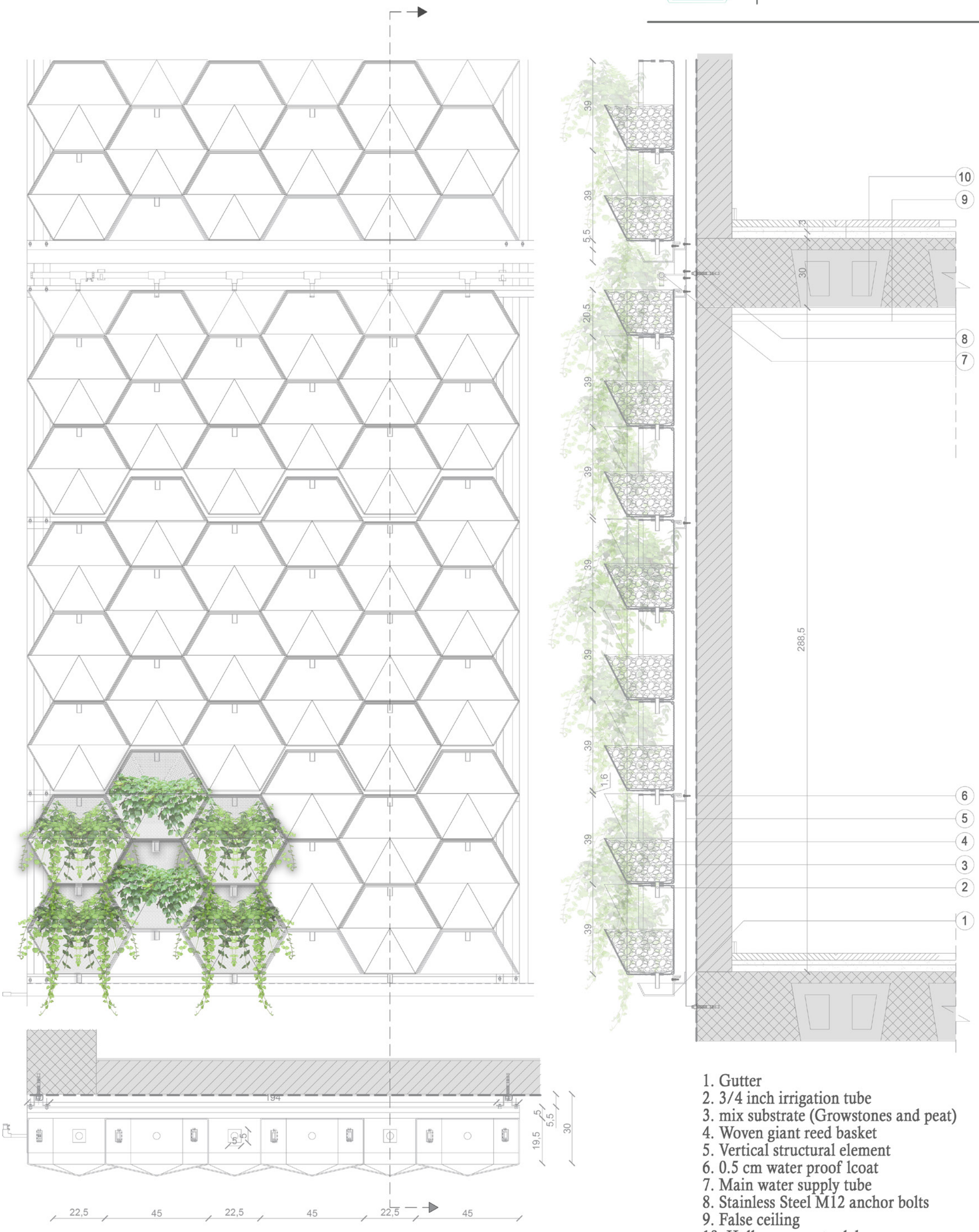


Figure 3.17. Technical drawing of Mosiac living wall system

Mosiac
Living Wall System

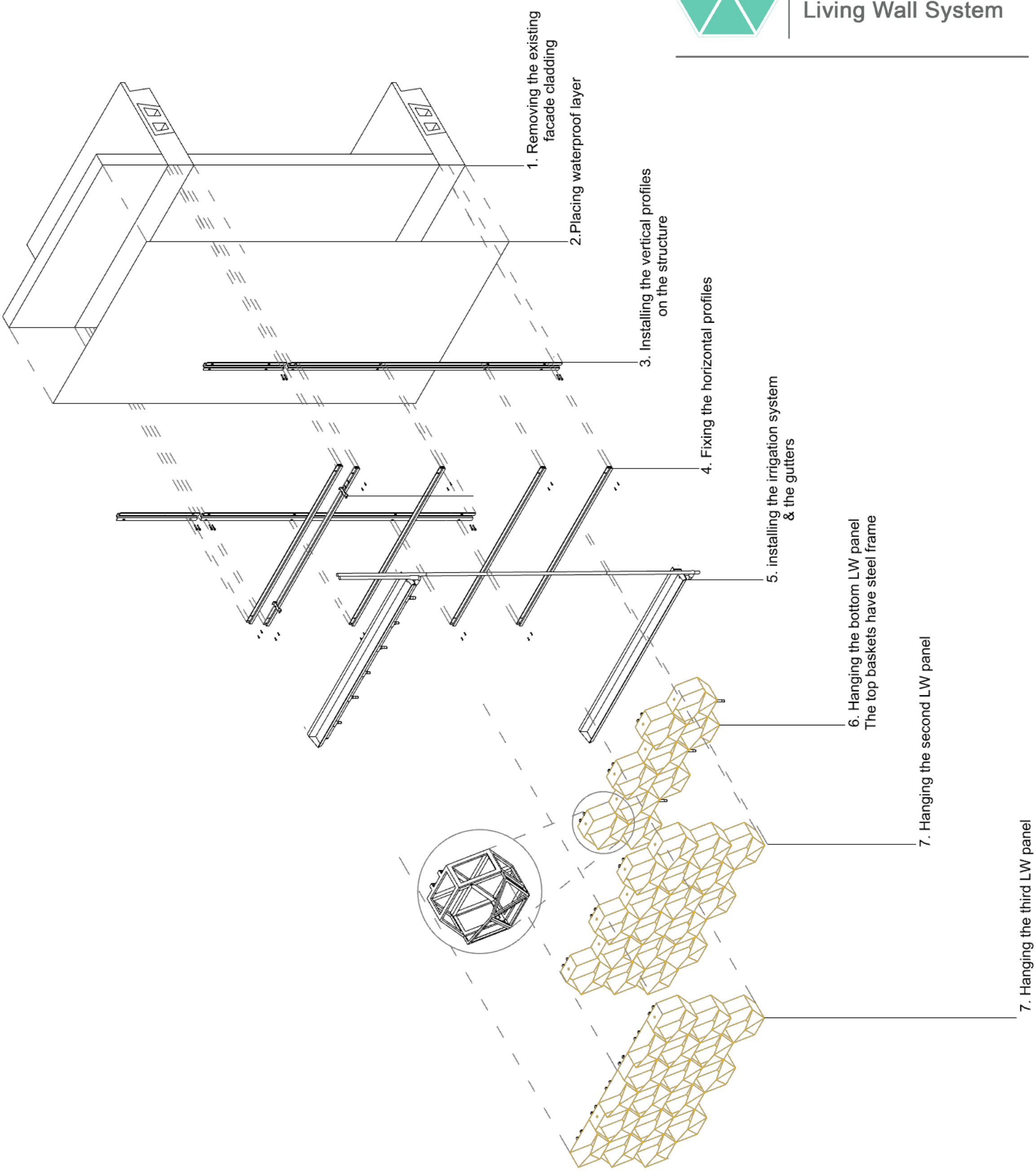
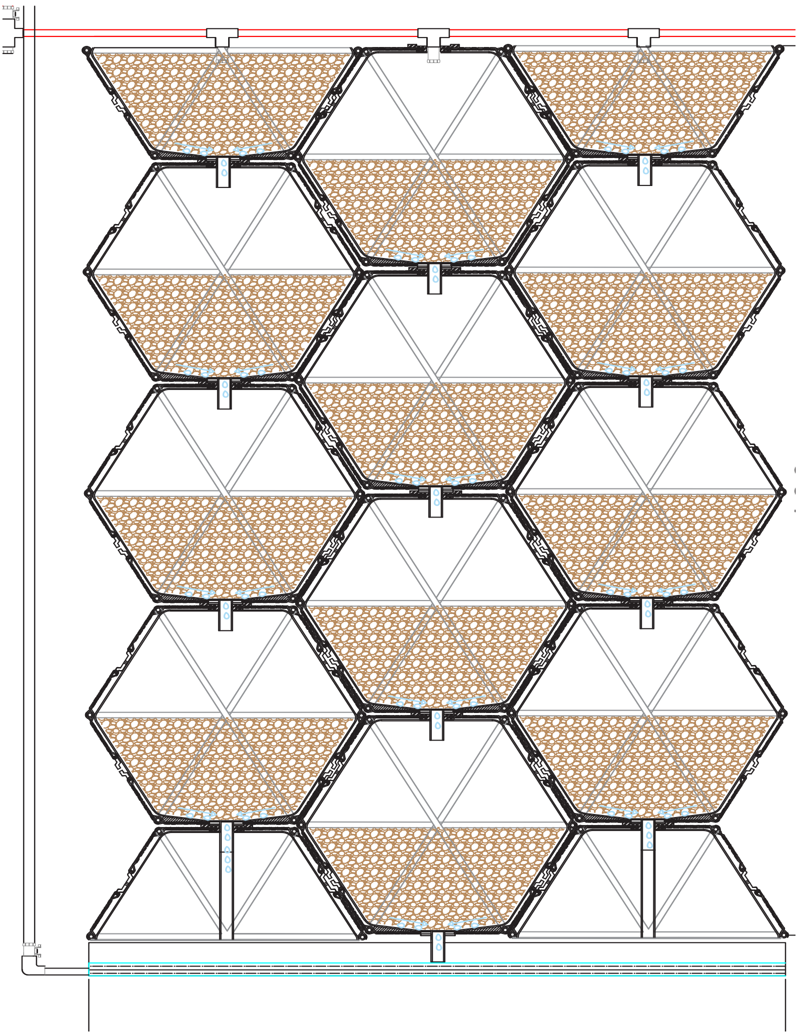
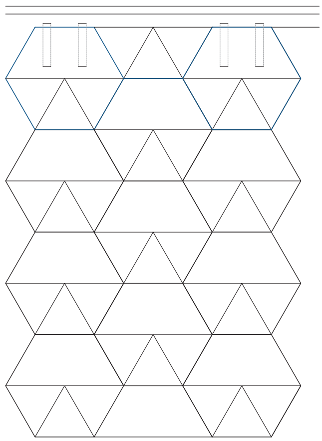
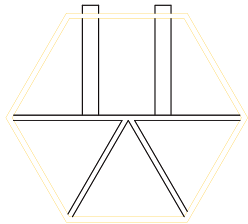


Figure 3.19. Assembly sequence







The units at the top have steel structure and the reed is wo-ven around it

Figure 3.20. Cross section of Mosiac living wall system

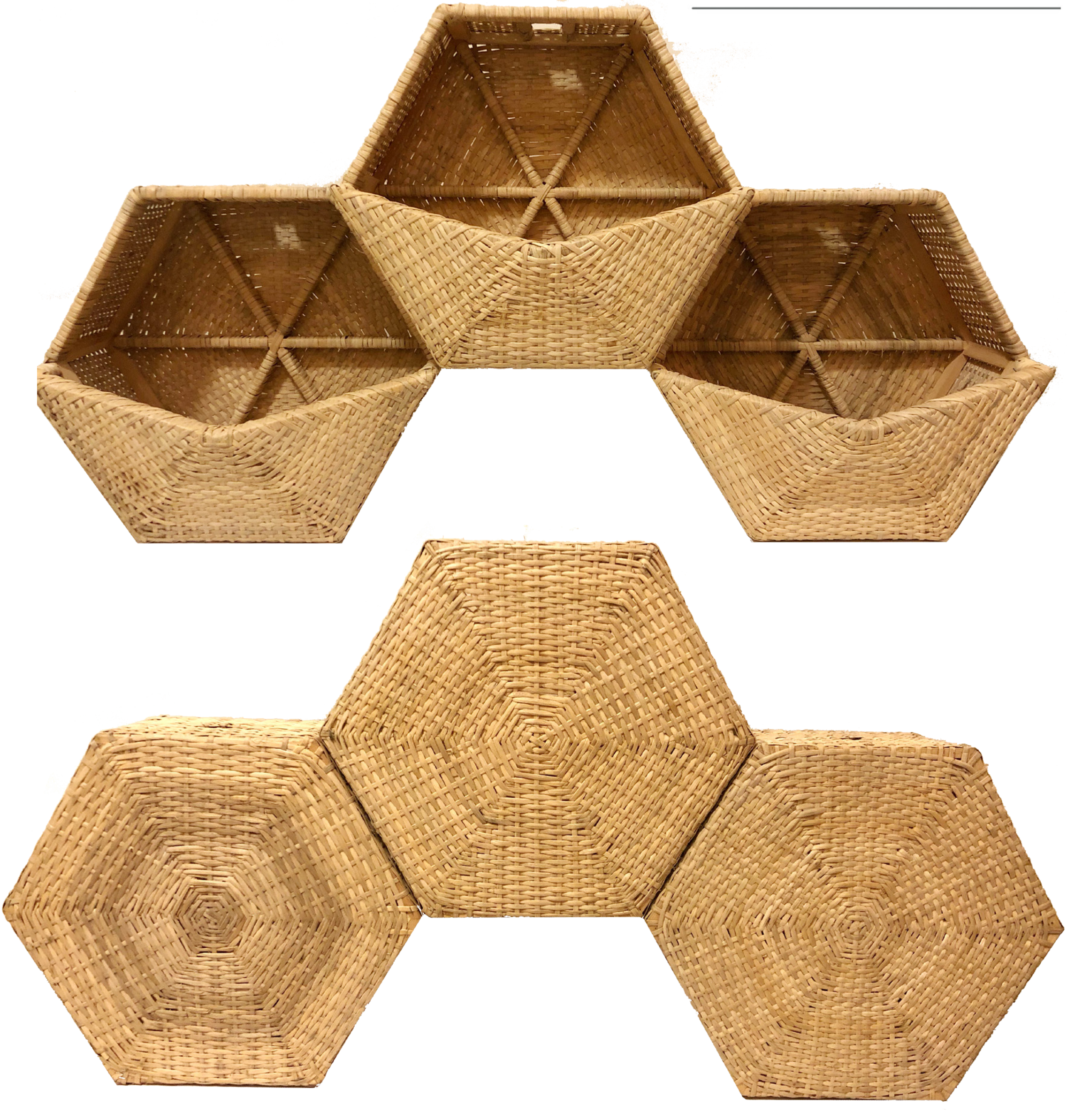


Figure 3.21. Prototype of Mosiac living wall system without vegetation

Chapter 04
Evaluation

4.1. Evaluation

As a means of evaluation and investigating the extent to which LWS may play an effective role in mitigating the UHI effect and improving outdoor thermal comfort, 3D representation for a suggested urban canyon in Damascus is established in ENVI-met. ENVI-met is a microclimate software that can simulate climates in an urban environment and assess the effect of climatic conditions, vegetation, and materials. The main criteria for selecting the case study are to choose an urban canyon with high UHI intensity as a worst-case scenario.

From the literature review, it has been observed that the intensity of UHI is high in the city center northwest of the old city. In that area, there are two main urban canyons. One is east-west (E-W) oriented called Baghdad Street. The second one is north-south (N-S) oriented called 29th April Street. To determine which of these two urban canyons to be further evaluated as the worst-case scenario, solar analysis for a typical summer day using a grasshopper plugin called Ladybug has been performed in Figure 4.1. the simulation results show that the E-W canyon is exposed to more solar radiation compared to the N-S canyon.

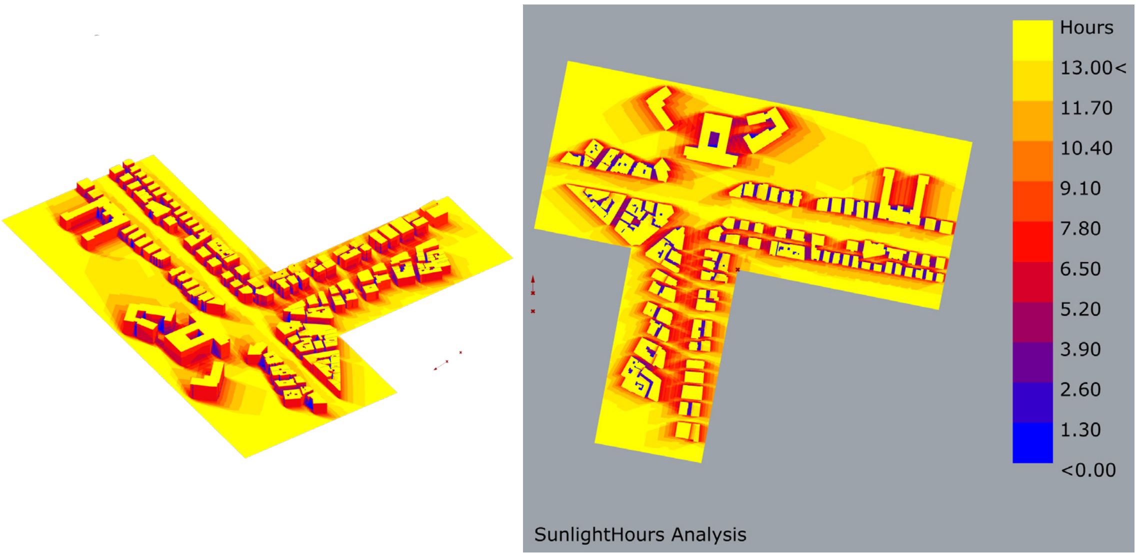


Figure 4.1. Solar analysis of two urban canyons in Damascus

Hence, Baghdad Street (E-W urban canyon) is chosen as the research case study Figure 4.2. This urban canyon is characterized by an aspect ratio of 0.43. Concrete, asphalt, and limestone are the main materials used for the urban surfaces, Table 4.1.

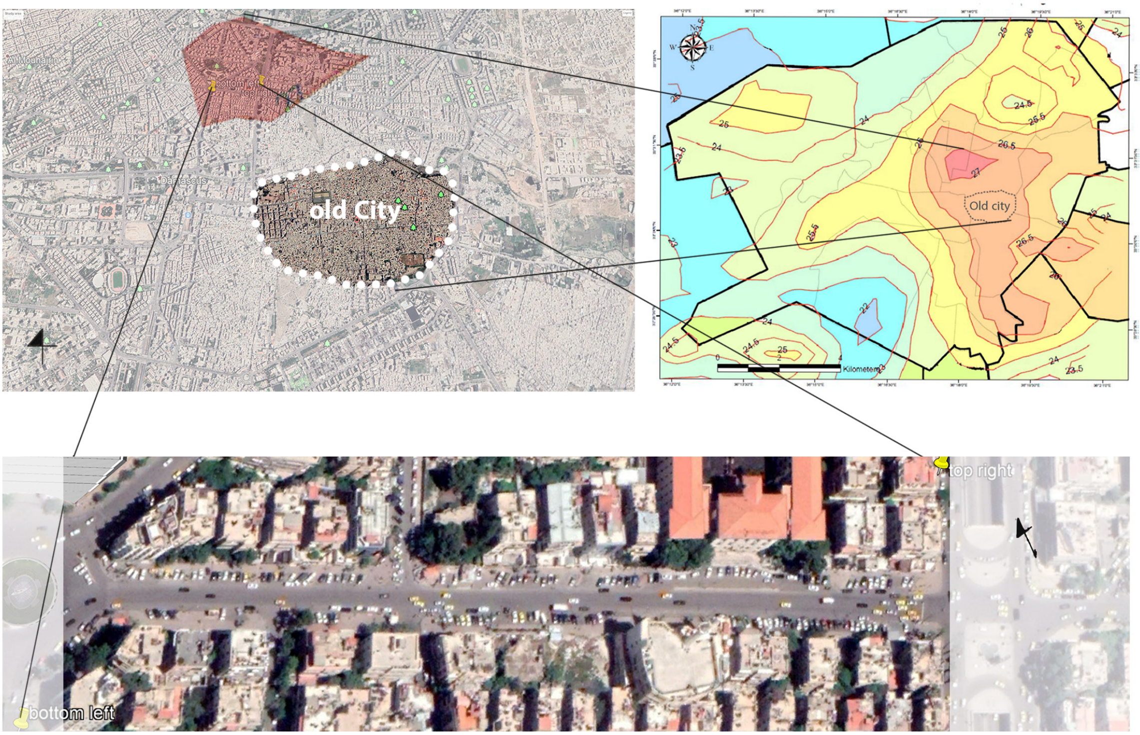


Figure 4.2. The chosen Urban canyon - Baghdad street -

Table 4.1. The characteristics of the studied urban canyon - Baghdad street -

	Orientation	urban canyon width	Urban canyon height	Buildings
Baghdad Ave	E-W with 10 degree in a clockwise direction from the north line	30m	13m	Detached

Characteristic of the road, pavement,wall and roof for the studied area

Surface	Exterior wall	Roof	Road	Pavemnet
Material	Limestone	concrete	asphalt	grey concrete
Albedo	0.45	0.3	0.2	0.5
Emissivity	0.93	0.9	0.9	0.9
Absorption	0.7	0.7	0.8	0.6
Density (Kg/m^3)	2711	2400	2322	2400
Specific heat J (Kg/k)	800	879	900	879
Thermal conductivity (w/mk)	1.26	0.8	0.75	0.8

4.1.1. ENVI-met Simulation setup

The model area has a size of 224*224 m resulting in 112*112*30 cells with a resolution of 2*2*1 m. The simulation boundary condition and climatic data represent a typical summer day in 2018 starting at 8:00 on the 23rd of August, Table 4.2. Three receptors are placed: R1 in front of the south façade, R2 in front of the north façade, and R3 in the middle of the urban canyon.

Table 4.2. Simulation boundary conditions

Boundary conditions	Input
Simulation duration	24h
Starting time	7:00am- 23/06/2018
End time	6:59am- 24/06/2018
Wind speed	1m/s
Wind direction	192 degree with the north direction (south-southwest)
Forcing	Simple forcing
Max. temperature	34 degree
Min . Temperature	20 degree
Simulation period	Typical summer day

Figure 4.3. Simulation base case

- These inputs are utilized to simulate potential air temperature (T), wind speed (W speed), mean radiant temperature (Tmrt), and relative humidity (Q.rel) for four different scenarios and then compare them with the base case.

- **Base case:** bare wall without LWS.
- **Scenario .1:** with LWS on the south façade (max coverage percentage of 45%)
- **Scenario .2:** with LWS on both south and north façades (max coverage percentage of 90%)
- **Scenario .3:** with high albedo materials (HAM) for road and pavements
Grey concrete is replaced by light concrete with an albedo of 0.8 for the pavements, and dark asphalt is replaced by asphalt with a red coat (albedo of 0.5). Researchers have reported this strategy as an effective and feasible strategy to mitigate the effect of UHI.
- **Scenario .4:** combined scenario of LWS on the south façade and HAM material for roads and pavements.

The simulation outputs are then used to calculate the physiological equivalent temperature (PET) in BIO-met utilizing the program's standard body and clothing parameters. All results are obtained at the height of 1.5m.

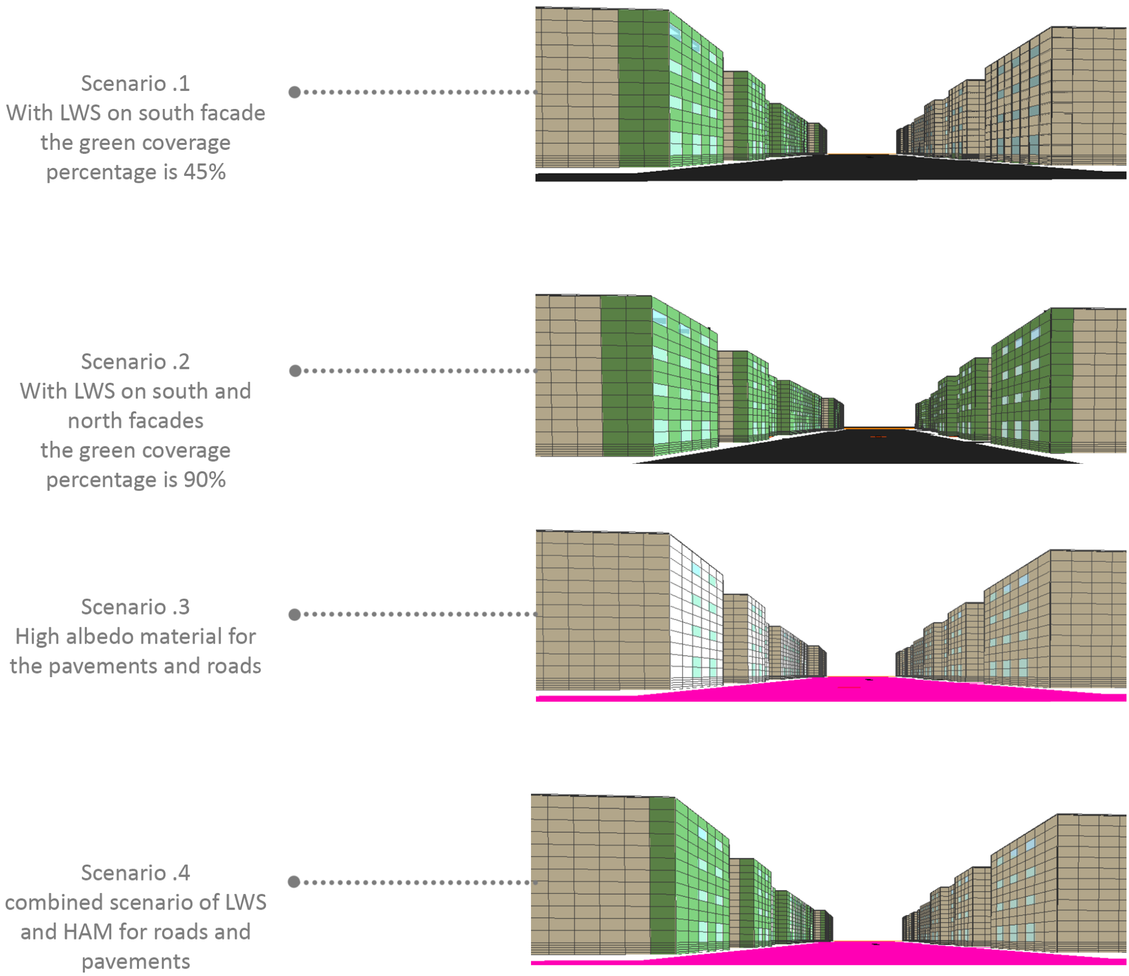


Figure 4.4. Simulation secenarios in ENVI-met

4.1.2.Results and Discussion

4.1.2.1. Potential air temperature (T - °C)

Air temperature is the most critical factor which affects indoor energy consumption.
From the simulation, it has been found that during the daytime, a significant reduction in the potential air temperature is recorded with the use of High albedo materials for the road and pavements in scenarios 3 and 4 (1.24- 1.27 °C respectively compared to the base case). Whereas the use of LWS in scenarios 1 and 2 causes a slight increase in the air temperature at R1, R2.
While during the night, all the scenarios have a cooling impact. Scenario 2 has the highest cooling effect because of evapotranspiration (between 0.29- 0.5°C at R1 and between 0.35- 0.5°Cat R2). However, the cooling impact decreases with the increase in distance from the wall.

Nighttime is a crucial period for air conditioning in the residential areas in Damascus. According to a study on the effect of urban greening and night cooling on energy consumption in Cairo, it has been found that in an east-west oriented urban canyon, reducing air temperature by 0.1°C reduces the cooling energy consumption by 0.5%. This is equal to 0.68 kWh daily and 81 kWh during the summer period for each building (Aboelata, 2020).

When comparing these results with the result for Damascus, especially that both have approximately the same climatic and urban characteristics, It can be found that a reduction of 0.3°C to 0.5°C could help reduce cooling energy consumption by 1.5% to 2.5%. This is equal to 122.4 to 204 kWh and 95$ to 150$ yearly. This saving is significant when calculating it for the whole urban canyon, in addition to that the LWS'S thermal insulation and shading effect.

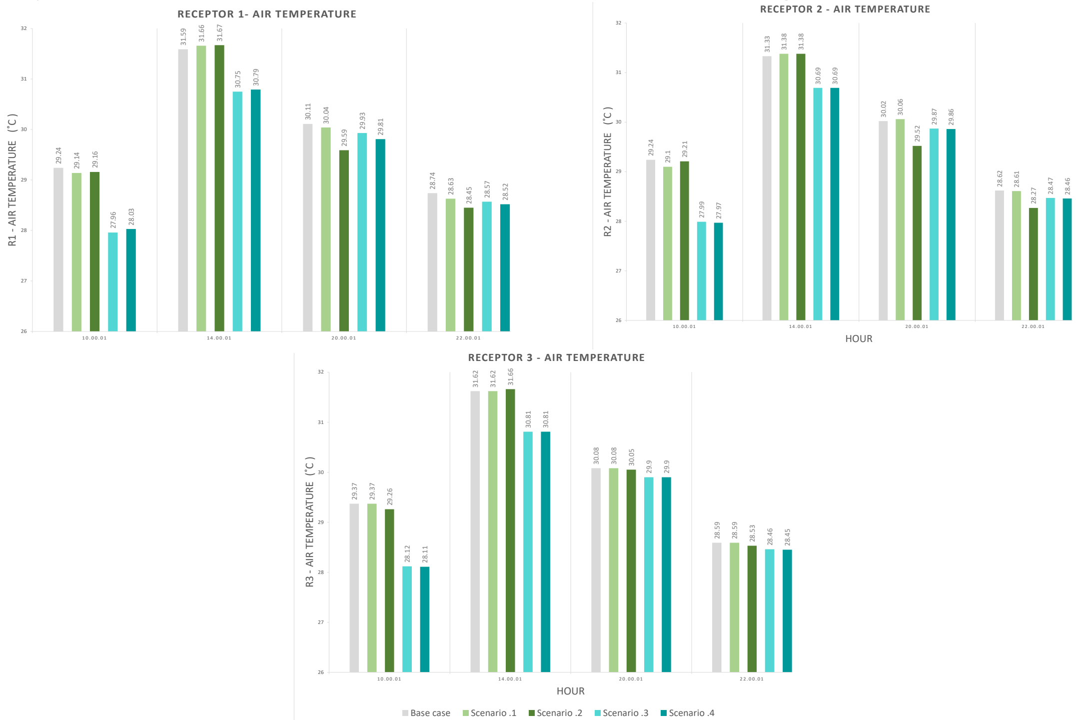


Figure 4.5. Potential Air temperature results at R1,R2,R3

4.1.2.2. Mean radiant temperature (Tmrt -°C)

Tmrt has a substantial impact on the PET index. Thus, it has a strong influence on the occupant's thermal comfort.

The evaluation results show that the use of LWS help in reducing Tmrt at R1 and R2 during the daytime. This is the period where people spend their time outdoor. The highest reduction is achieved using LWS on both façades in scenario 2 (0.7 °C). However, LWS has a negligible impact on Tmrt at R3. Conversely, the use of high reflectance materials for the pavement and road as in scenarios 3 and 4 increases the mean radiant temperature, leading to the increase in the reflected radiation and consequently increases the risk of reducing the outdoor thermal comfort at the street level.

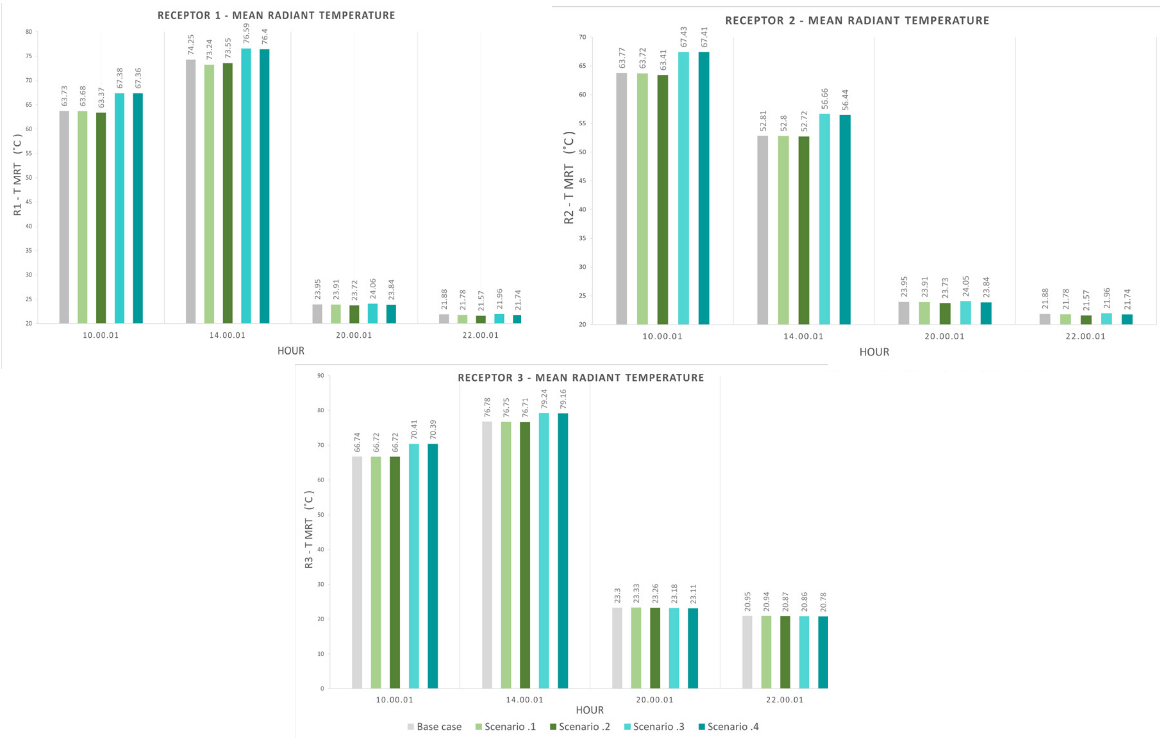


Figure 4.6. Mean radiant temperature results at R1,R2,R3

4.1.2.3. Wind speed (W speed – m/s)

Results show that all scenarios have minor to no impact on the wind speed compared to the base case, especially that the wind speed in the base case itself is low and does not exceed 0.35 m/s.

4.1.2.4. Relative Humidity (q.rel - %)

Results demonstrate that in the morning, the relative humidity in scenarios 3 and 4 increases by 4.22 to 5.7 % compared to the base case at R1, R2, and R3. During the night, scenario 2 recorded the highest increase in relative humidity (0.95% and 1.67% at R1 and R2, respectively, compared to the base case). However, the vegetated layer has a limited impact on relative humidity at R3. As mentioned previously the highest the q.rel the less is the UHI effect.

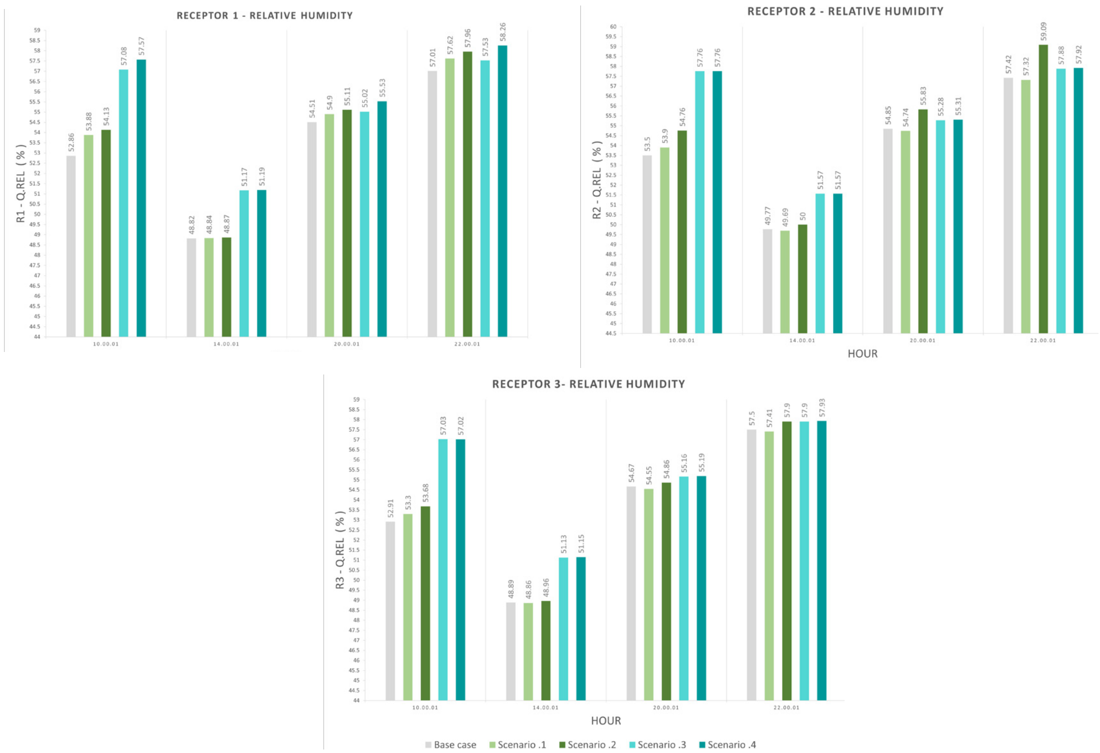


Figure 4.7. Relative humidity results at R1,R2,R3

4.1.2.5. physiological equivalent temperature (PET)

After calculating PET values for each scenario, it has been observed that during the daytime, scenario 1 has negligible impact on the PET while scenario 2 decreases the PET by 0.5°C and 0.3°C at R1 and R2, respectively, compared to the base case because of the evapotranspiration effect. Consequently, the more green-coverage percentage, the higher cooling impact is achieved regardless of the orientation of the wall where the LWS is placed.

However, in both scenarios, there are increases in PET values between 14:00 and 17:30. Conversely, scenarios 3 and 4 have negative impacts on outdoor thermal comfort. Mainly because of the increase in Tmrt because of using high reflectance materials for the pavement and roads. The worst values are recorded in scenario 3. During the nighttime, scenario 2 shows the highest reduction in PET (0.3 °C compared to the base case).

Considering the average PET during the Day, scenario 2 is the most effective. However, the impact is limited to the microclimate around the vegetation and reduces with the distance from the wall. Moreover, this cooling impact is not enough to achieve outdoor thermal comfort levels. Especially that the sun is the main source of heat, and there is a limited shading effect in the canyon.

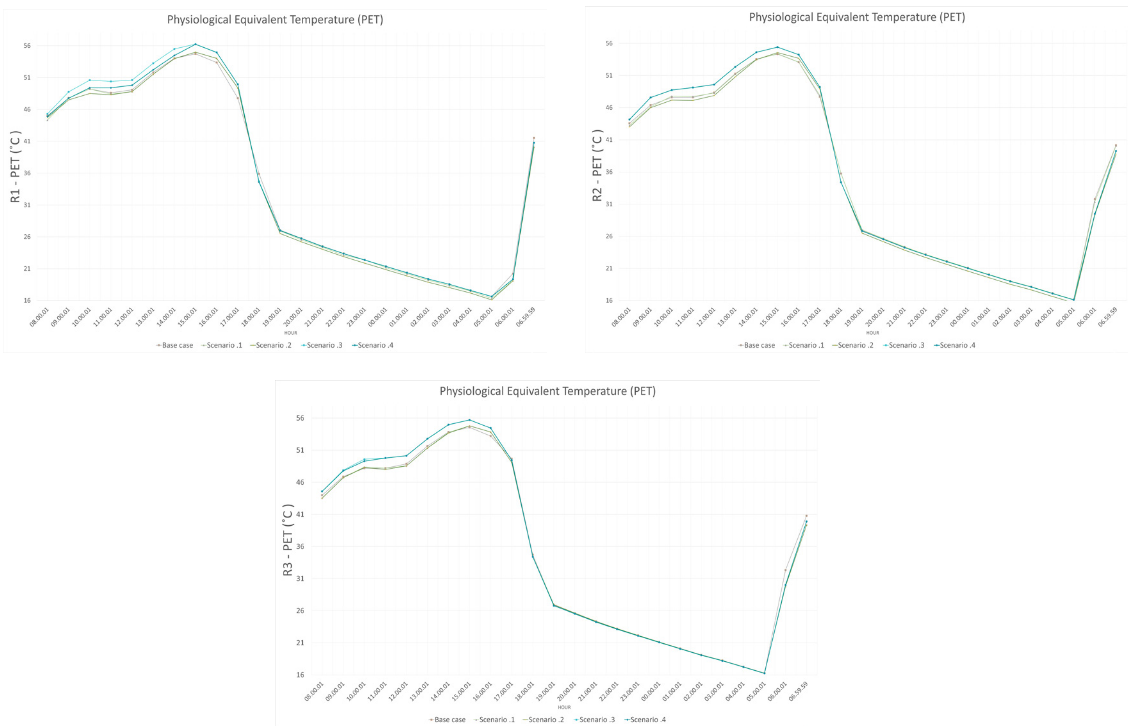


Figure 4.8. PET results at R1,R2,R3

4.2. Conclusion

In this chapter, the efficiency of LWS in reducing UHI and improving outdoor thermal comfort was investigated. An E-W urban canyon with an aspect ratio of 0.43 in Damascus was chosen as the worst-case scenario.

After evaluating different scenarios, It has been found that the higher the green coverage percentage, the more elevated the cooling impact of the LWS regardless the orientation of it. This impact is minimum during daytime and increases during the nighttime.

With 90% green coverage, a maximum reduction of 0.5°C in air temperature is achieved at night. Nighttime is important for air conditioning in the residential area in Damascus. This reduction could help reducing cooling energy consumption by 1,5 % to 2,5 % for each building. This saving is significant when calculating for the whole urban canyon.

Moreover, 90% green coverage caused a maximum reduction of 0.7°C in Tmrt during the day. This helps to improve outdoor thermal comfort during the daytime, which is the period people spend their time outdoors.

Furthermore, 90% green coverage increases relative humidity by 1.67% compared to the base case, and the higher the relative humidity, the less the UHI is.

Regarding outdoor thermal comfort, 90% LWS helps in reducing PET values (between 0.3 -0.5°C compared to the base case) and improves outdoor thermal comfort.

However, the cooling effect is limited to the air layer around the LWS and reduces with the increase in distance from the wall, and it has no impact on the local climate in the middle of the shallow urban canyon.

Chapter 05

Conclusion and Reflection

5.1. Summary

This study focuses on designing LWS suitable for Damascus and evaluating the extent to which LWS may play an essential role in mitigating the UHI effect and improving outdoor thermal comfort.

The research started with the literature review of the UHI phenomenon, the requirements of LWS, and its cooling mechanism. This helped gain in-depth knowledge of the critical causes of UHI in Damascus and determine the challenges involved in designing LWS in Damascus. Based on these challenges, the design criteria were defined and used in the design integration phase. These criteria are Low water consumption, feasibility, structural stability, and low maintenance.

After creating the design, an evaluation of the impact of LWS on the local climate of an E-W-oriented urban canyon using ENVI-met was conducted. The results of this evaluation assisted in knowing the extent to which LWS may help reduce the UHI intensity and improve outdoor thermal comfort. It also helped in deciding on the efficiency of this strategy.

5.2. Conclusion

The main research question of this research was formulated as follows.

> *"How to design a Living Wall System that can be integrated into the built environment of Damascus and how efficient is the proposed design as an urban heat island mitigation strategy? "*

To answer it the sub-questions, need to be answered first.

- ***What is the Urban Heat Island phenomenon, and what are the associated consequences of this phenomenon?***

UHI is a climatic a climatic phenomenon noticed in urban areas where the ambient air temperature and surfaces temperatures are higher than surrounding rural areas. There are two types of heat islands: the surface and atmosphere heat islands. Both types occur day and night. However, the surface HI effect tends to be higher during the day while the sun is shining contrary to atmospheric HI.

Atmospheric HI is classified into two layers Urban Canopy layer (UCL) and Urban Boundary Layer (UBL). This study focuses on UCL as it occurs in the air layer between the ground and the tops of trees and roofs, and it is the layer where people's experience of the high temperature mainly occurs.

UHI has a negative effect on the energy consumption in the built environment because the increase in the ambient temperatures causes an increase in cooling demand.

Consequently, a significant increase in electricity consumption for cooling purposes. UHI can also worsen air quality for the following reasons, the accelerated rate of photochemical ground-level ozone production at higher temperatures and the increase in temperature-sensitive emissions of ozone precursors. Moreover, the increase in the intensity and duration of heatwaves due to the UHI effect aggravates the thermal discomfort of citizens, leading to a significant impact on human health and increasing the risk of thermal stress.

What are the key causes of the Urban Heat Island effect in Damascus?

Many factors contribute to the development of the UHI in Damascus. These causes can be classified into uncontrollable and controllable factors.

Uncontrollable factors include Climatic and Topographic characteristics. Damascus experiences a cold semi-arid climate which means it receives precipitation below potential evapotranspiration. Moreover, because of the city's location as a basin at the foothill of the Anti-Lebanon mountain range, the precipitations and wind flow from the Mediterranean Sea are mostly blocked, and the concentration of air pollutants is high.

Controllable causes include:

- Degradation of Al-Ghouta oasis, which separates the city from the dry land in the Syrian desert.
- Using low albedo material for urban surfaces such as concrete, glass, and steel, which absorb a large amount of incoming radiation during the day and release back to the environment during the night,
- Low SVF, high H/W ratio, consequently the heat is trapped in the urban canyons.
- The anthopogenic heat is due to transportation and high population density.

After analyzing the UHI effect in Damascus, it has been found that the intensity of UHI is higher at the city center northwest of the old city where the city's primary traffic nodes are located.

• How can Living Wall System mitigate the Urban Heat Island effect?

Three main factors are defined as the mechanisms through which LWS and VGS mitigate the UHI effect. These factors are the cooling effect of plants and substrate through evapotranspiration, thermal insulation, and shading.
In the evapotranspiration process, a large amount of solar radiation is converted into latent heat. As a result, it reduces the amount of long-wave radiation released back to the environment at night.

Regarding thermal insulation, the Vegetative layer and the growing media act as a thermal puffer which slows down the rate of heat transfer with the surrounding environment and improves the Thermal insulation of the wall.

The shading effect is important during hot summer when there is excessive solar radiation and a difference in temperature between exterior and interior façade surfaces. The vegetation helps in reducing the amount of solar radiation transmitted to the façade exterior wall.

• What are the types of Living wall systems currently available in the market?

There are three main types of living wall systems: LWS based on planter boxes, LWS based on panels, and LWS based on felt layers. The prices of studied LWSs are between 400- 800 euro per sqaure meter. Which considered to be relatively high. Moreover, the overall materials used have highly environmental impact.

Based on the evaluation of different LWSs, it has been observed that LWS based on Planter boxes is the best for Damascus.

• What are the challenges involved in Designing a Living wall system in Damascus?

For implementing LWS into the built environment, many challenges are involved. These challenges can be summarized into five, water consumption, cost, the environmental impact of the used materials, structural stability, and maintenance.

Based on these challenges, design criteria are defined. These criteria are linked to the system's main components to see how these criteria will affect the choice of each element. The first criterion is low water consumption which can be achieved by choosing the suitable plant species, growing medium with high water capacity, and using greywater treating system. The second one is Feasibility by reducing the system's cost, which can be partly fulfilled by using local materials and manufacturing technics. The third criterion is less environmental impact, which depends mainly on the selection of the material. The fourth criterion is structural stability to ensure safety and the serviceability of the system and, last but not least Low maintenance.

• How can Living Wall System be integrated into the built environment of Damascus?

This research can be used as a guideline for designing LWS in Damascus as the system's main requirements have been evaluated. But in general, these are the steps to follow:

- First, select drought-tolerant plants, suitable for Full Sun, semi-shade with little water consumption and low growth rate. This helps reduce water consumption, ensuring that the foliage will stay healthy without high maintenance demand. After evaluating different plant species, it has been found that Crassula ovate, Ipomoea pes-caprae, Hedera helix, Portulaca oleracea, Ophiopogon jaburan, Mentha piperita, and Aglaonema are perfect plants for LWS in Damascus.

- The second step is using a feasible artificial substrate with low weight and high water capacity. This can be achieved by mixing Growstones with peat.

- The third step is using local material and fabrication technics. This helps reduce the environmental impact of the system, the cost, and provide jobs opportunity. Giant reed is a good material for LWS. However, it needs to be well treated against moisture to increase the life expectancy of the system.

- The Fourth step: using self-standing hexagonal units. Because they are stable and have minimum deflection when creating them from woven reed fibers. Moreover, LWSs with hexagonal units are flexible, can adapt to different façade typologies, and have minimum deflection when creating them from woven reed fibers.

- The Fifth step: use a recirculating irrigation system with a timer and greywater treatment system to achieve low water consumption while ensuring the LWS is in good condition. Especially that LWS requires a lot of water and Damascus suffers from drought during summer.

- The Sixth steps: maintain the LWS to check if anything is broken or damaged to increase the life expectancy of the LWS and benefit the most from it.

• How efficient is the proposed strategy to mitigate the UHI effect on microclimate and improve pedestrian outdoor thermal comfort in the urban canyon?

fter evaluating different scenarios, It has been found that the higher the green coverage percentage, the more elevated the cooling impact of the LWS regardless the orientation of it. This impact is minimum during daytime and increases during the nighttime.

With 90% green coverage, a maximum reduction of 0.5°C in air temperature is achieved at night. Nighttime is important for air conditioning in the residential area in Damascus. This reduction could help reducing cooling energy consumption by 1,5 % to 2,5 % for each building. This is equal to 122.4 to 204 kWh and 95$ to 150$ yearly. This saving is significant when calculating for the whole urban canyon.

Moreover, 90% green coverage caused a maximum reduction of 0.7°C in Tmrt during the day. This helps to improve outdoor thermal comfort during the daytime, which is the period people spend their time outdoors.

Furthermore, 90% green coverage increases relative humidity by 1.67% compared to the base case, and the higher the relative humidity, the less the UHI is.

Regarding outdoor thermal comfort, 90% LWS helps in reducing PET values (between 0.3 -0.5°C compared to the base case) and improves outdoor thermal comfort.

However, the cooling effect is limited to the air layer around the LWS and reduces with the increase in distance from the wall, and it has no impact on the local climate in the middle of the shallow urban canyon. Therefore, using only LWSs on shallow canyons is not optimal as their cooling impact could not compensate for the solar gain. But at the same time, it has better performance than using HAM and It could be more beneficial in deep canyons.

Moreover, 90% green coverage means 1500 m^2 of LWS, 2982 L of water each irrigating time, around 24000$ for greywater treatment systems, in addition to the cost of the LWS. When comparing these values with the cooling impact achieved, it can be concluded that LWS is not a feasible strategy to be applied in Urban canyons with the same characteristics as the studied even though the designed LWS is relatively cheaper than ones in the market.

Therefore, it is wise to implement other strategies next to LWS for future work, such as green roofs and urban trees, which provide more shading. Then investigate the efficiency of these strategies. It is also essential to look into the energy performance of the buildings by taking into account the shading and insulation effect of LWS.

5.3. Limitation of research

This research has several limitations of which a few are mentioned below.

Simulation

- The climatic data used in the simulation is taken for the closest weather station, not for the studied urban canyon. This may affect the accuracy of the simulation result.
- The simulation uses simple forcing sitting, and the anthropogenic heat flux was not considered.
- The simulation focuses on a shallow E-W-oriented urban canyon that receives high solar radiation. Therefore, the results are valid for urban canyons with the same characteristics.

The impact of LWS on indoor climate and energy consumption

- The study did not consider the effect of LWS on indoor climate and energy consumption. Therefore, for future work, this needs to be investigated.

Experimental testing

- The mechanical properties of the Giant reed used in the structural analysis are not for the giant reed that grows in Damascus. Therefore, experimental testing for giant reed specimens from Damascus is also needed.

5.4. Reflection

The relationship between the theme of graduation studio and my graduation topic

The theme of the graduation studio is façade & product – urban façade
My graduation research titled “Living Wall System a strategy to mitigate the Urban Heat Island effect in Damascus” is related to façade& product design and climate design themes. The relationship with the façade design can be clearly seen from the design of LWS, which is considered a second skin for the building. In the designing phase, I focused on materialization, fabrication techniques, structural performance, and the technical aspect of the design, resulting in an innovative LWS design that meets the defined design criteria .

The relation with climate design is obvious from studying the cooling impact of LWS on microclimate and outdoor thermal comfort by simulating different scenarios and evaluating the results. Although LWS appeared not to be the most optimal UHI mitigation strategy as its effect is limited to the air layer in front of the wall, it could improve outdoor thermal comfort and reduce air temperature during the night, resulting in less energy consumption for cooling purposes. It also has different benefits such as enhance the quality of air, reducing noise pollution, and improve the aesthetic value of the façade.

The relationship between the project and the wider social context

My graduation project spots the light on the UHI problem in Damascus. This will help raise awareness and push the community and decision-makers to step up and take measurements and find solutions for this problem, especially that it, directly and indirectly, affects human health and energy consumption in the built environment.

Moreover, In Damascus, weaving reed is one of the traditional handicrafts. Therefore, using giant reed will add extra social and economic value to the design. It will provide job opportunities, preserve the cultural heritage and find a new application for the traditional handicrafts.

Learning from my work

At the beginning of my graduation project, I had a straightforward approach. After finishing the literature review phase and gathering information about living wall systems and Damascus’s urban heat island, I developed the approach to a more complex and detailed version. This helped me to have a clear view of my research and define the research’s main goal. But this was not an easy mission since few studies on UHI, and outdoor thermal comfort in Damascus were conducted. Consequently, I had to spend more time collecting the required data
.

Furthermore, there was a direct connection between the research and the design. The research phase contains understanding the UHI phenomenon in Damascus and its key causes, LWS and its cooling mechanism, the system requirements, and the LWSs currently available in the market. By analyzing and evaluating the output of the research phase, the design criteria were formulated and used to create a LWS design that is suitable for Damascus's built environment.

After designing, I evaluated the efficiency of LWS as a mitigation strategy, and I chose E-W oriented shallow urban canyon as the worst-case scenario. The Climatic Simulation in ENVI-met and data extracting was a time-consuming process. However, this was a good learning experience. Eventually, I was able to see some of the information learned in the literature review phase about the cooling impact of LWS in the simulation results. I also learned to have critical views when designing and evaluating.

One of the difficulties I faced was putting the results in context, and I am not sure I have 100% achieved that. I have also learned the importance of time management, which I am terrible at and had difficulties keeping up with deadlines. I also found it hard to stay motivated, especially during the lockdowns.

My mentors were extremely helpful and patient with me. They gave me useful feedback that broadened my horizon and helped develop the research and structure it in a more comprehended way. They also helped me in reaching good resources and software.

Eventually, the learning process has been practical and valuable for my personal and academic development. It was interesting to gain knowledge about UHI and LWS and find new applications for local traditional handicrafts.

Although there are some weak points in the research, I am delighted with the final product and looking forward to further developing my Mosaic Living Wall System.

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Figures

Tables

APPENDIX

Appendix .A:

Analysis of Living Wall Systen available in the Market

Analysis of current living wall system

	General information				Vegetation	Growing medium		Panel		Mounting system			Irrigation	
System	Type	Weight kg/m^2	Cost €/m^2	life expectancy	Plants per unit	Growing medium	Hydroponic	Material	Panel size cm	Material	Fixation	Insulation	Irrigation system	Water consumption l/day/m^2
Modulogreen	based on planter boxes	29-39 (dry)-69 (saturant)	500-600	30 years	16-32 plants wide range of plants	Soil mixture	no	ABS Plastic	90*90,4*17,8	Aluminium brackets Aluminium profile T80 *52	anchoring bolts Gasket EPDM	possible	close loop irrigation system	1
Flexipanel	based on rock wool	20-25 (dry) - 40-45 (saturant)	650	10 years	25 plants plants with short roots	Rockwool- soil	yes	Thermoplastic Polyolefin backing waterproof layer	62*52*16	Aluminium profile	anchoring bolts clips	possible	close loop system	1,5-2,5
Fytotextile	based on felt layers	25 (dry) - 41 (saturant)	800	10 years	42-45 plants with short roots	Rockwool - soil	no	FYT-RCF waterproof layer FYT-DRA irrigation distributor FYT-AIR evapotranspiration	100*100*13	aluminium profile	anchoring bolts	possible	close loop system	1,4
ANS	based on planter boxes	72 (saturant)	500-600	20 years	12 wide range of plants	Soil mixture	no	recycled Plastic Water proof layer	50*25*10	Steel frame	anchoring bolts	possible	close loop system	1,5
Vertiss plus	based on planter boxes	32 (dry) - 53 (saturant)	600-700	15years	16 wide range of plants	Organo-mineral medium	no	High Density Expanded Polypropylene	80*60*19	fixing rail galvanised steel	Stainless steel holder Stainless bolts	not possible	open system	2,5
LivePanel	based On rockwool	35-40 (saturant)	550	20 years	9 plants with short roots	Rockwool - soil	yes	Expanded Polypropylene pressed rock wool slabs	40*40*5,65	Aluminium profiles	anchoring bolts	possible	close loop system	3
Greenwave	based on planter boxes	120(saturant)	400	n.d	4-6 plants wide range of plants	Soil mixture	no	polypropylene (HDPP)	51,5 *600	Steel trail Steel brackets	clips anchoring bolts	possible	open system	n.d.
wall flore	based on rockwall	50	550	n.d.	20 plants with short roots	Rockwool	yes	galvanized steel wire -epoxy powder coating -HDPE film -Stone wool	100*60*30	Steel vertical trail	anchoring bolts	not possible	close loop system	n.d.

Appendix .B: structural calculation for the hexagonal units.

Calculating the equivalent density for the woven cross section:

$$p = p_1$$

where $p_{1=}\frac{m_a}{h}$ =>

$$p_1 = 1.03\ g/cm^3 = 1030\ Kg/m^3$$

m_a : the mass per unit area = 0.41 g/cm^2

h : the overall thickness of the woven cross section (4mm

Calculating the mass per unit area m_a

m_{dry} =6* mass of the rectangle + 9* mass of triangle

m_{dry} = 6* 70.08 + 9* 54 = 906.48 g

the basket contains 1265 g of Growstones, the substrate can hold up to 30% of its weight water which means the saturant weight of the substrate (1265 +379 = 1644)

$m_{Saturant}$ = 906.48 + 1644 = 2550.48 g

$$m_a = \frac{m_{dry}}{area} = \frac{906.48}{2226.85} = 0.41\ g/cm^2$$

From **(1)** =>

$$p_1 = 1.03\ g/cm^3 = 1030\ Kg/m^3$$

mass of one rectangle

Number of fibres in each rectangle	**40**
Fibre Thickness	**2 mm**
Fibre Width	**5 mm**
Fibre Length	**150 mm**
Fibre volume	**1.5 cm^3**
Density of giant reed fibre	**1.168 g/cm^3**
Mass of one fibre	**1.752 g**
Mass of one rectangle (mass one fibre *number of the fibres)	**70.08 g**

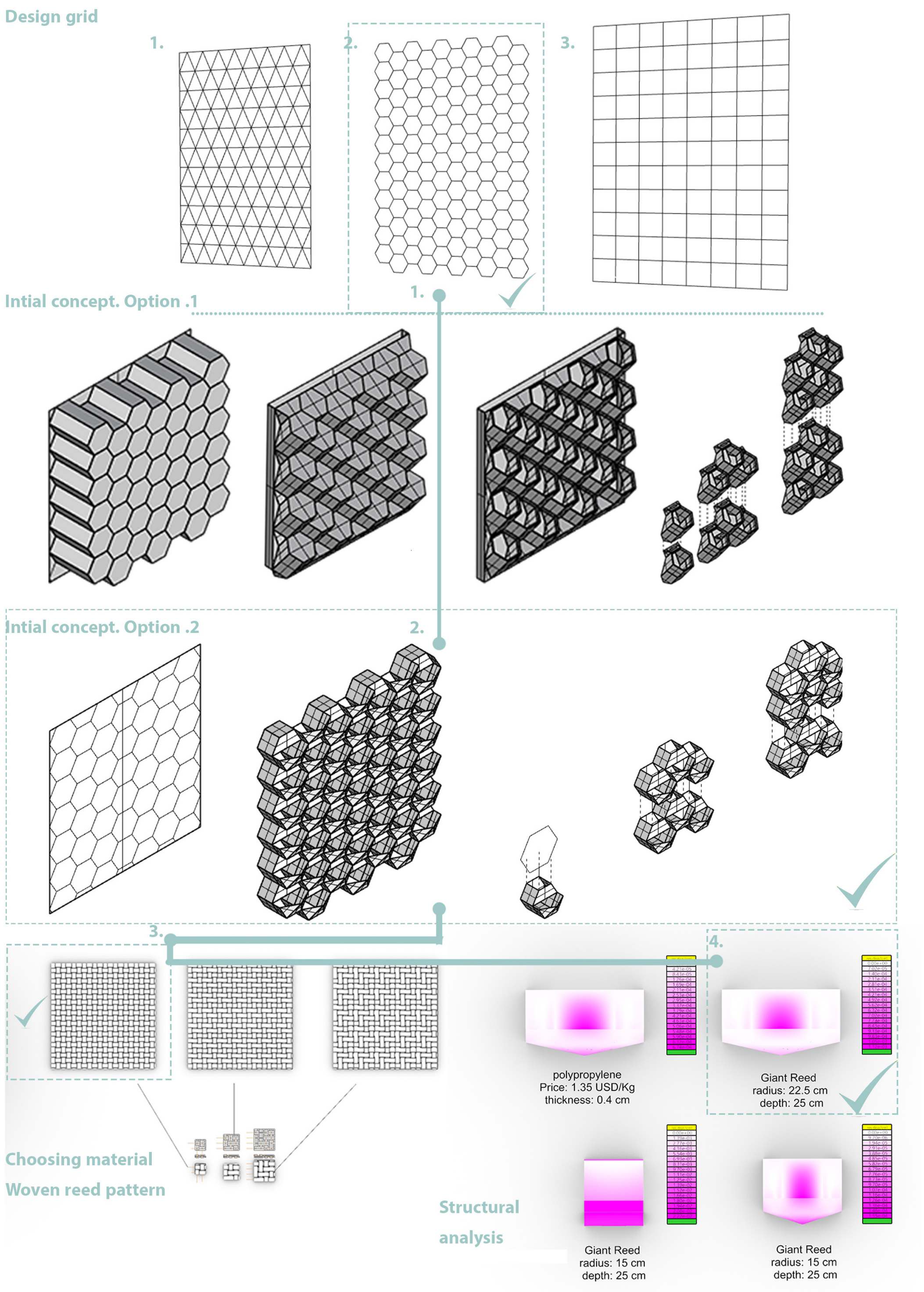
Mass of the one triangle

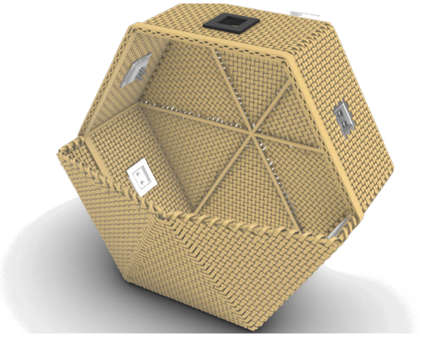
Number of fibres in each rectangle	**27**
Fibre thickness	**2 mm**
Fibre width	**50 mm**
Fibre length	**75 mm**
Mass of one fibre	**0.876 g**
Mass of triangle	**54 g**

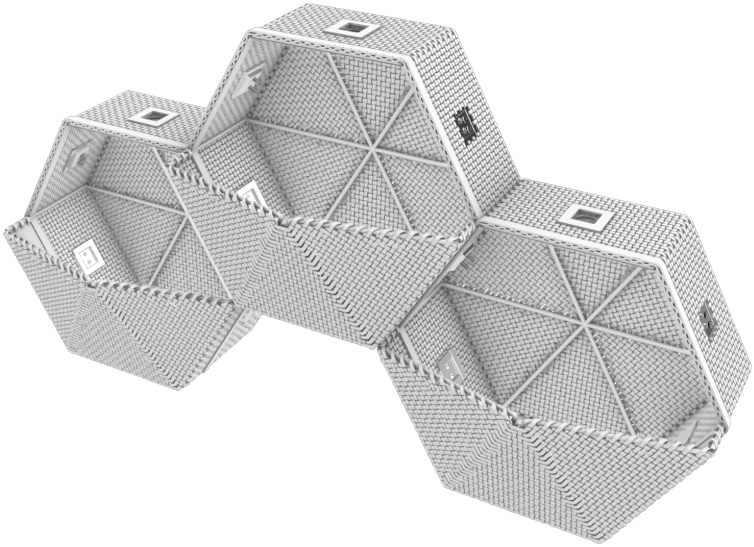
Load due to Self-weight of the basket without substrate = 0.906 * 9.81 = 8.88 $N \approx 9\ N$

Load due to the saturant Self-weight of the Growstone = 1.644* 9.81 = 16,12 $N \approx 16\ N$

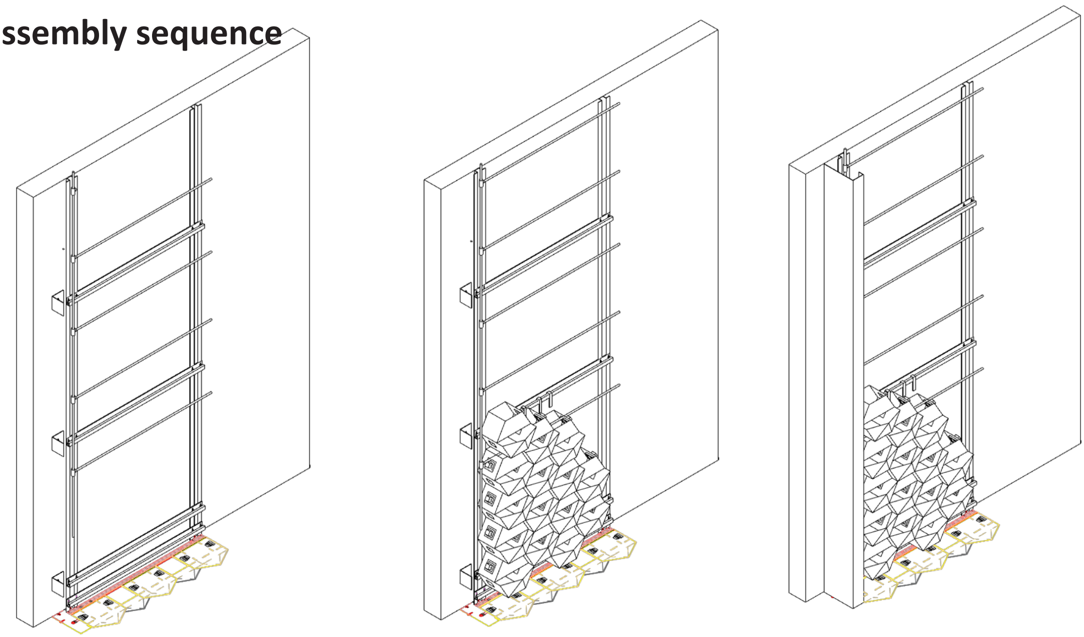
} Load cases f structural analysi


Design grid
1.
2.
3.
Intial concept. Option .1
1.
Intial concept. Option .2
2.
3.
4.
polypropylene
Price: 1.35 USD/Kg
thickness: 0.4 cm
Giant Reed
radius: 22.5 cm
depth: 25 cm
Choosing material
Woven reed pattern
Structural
analysis
Giant Reed
radius: 15 cm
depth: 25 cm
Giant Reed
radius: 15 cm
depth: 25 cm



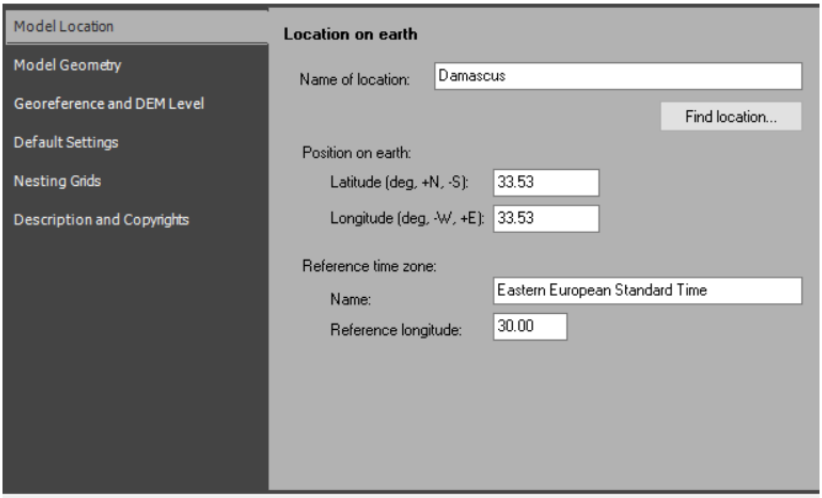


assembly sequence

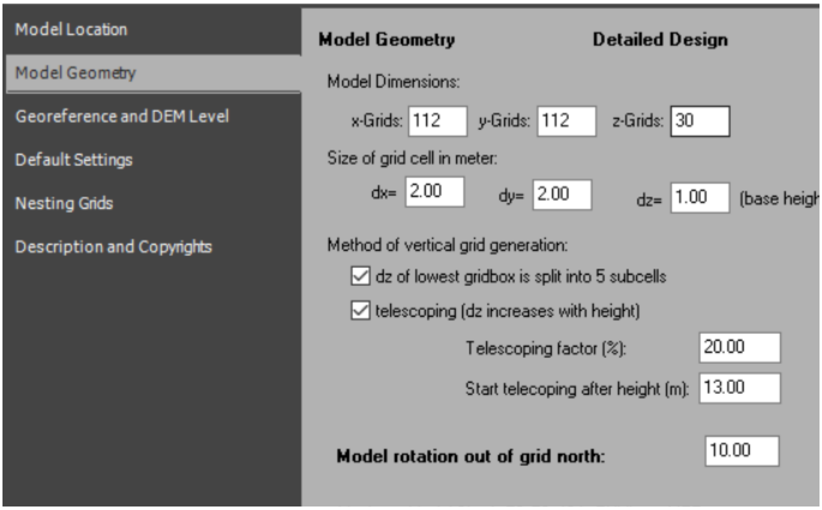


Appendix .E: Evaluation set up using ENVI-met

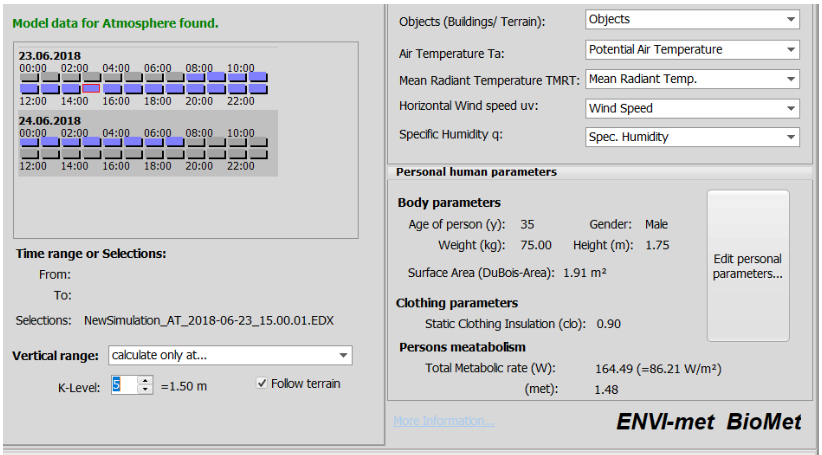
Location



grid size



Thermal comfort input



Appendix .F: Simulation results

simultaion PET values at R1, R2 and R3

R1

Date	Time	Base case	Scenario .1	Scenario .2	Scenario .3	Scenario .4
23.06.2018	08.00.01	45	44.341	44.712	45.299	44.888
23.06.2018	09.00.01	47.8	47.8	47.5	48.766	47.758
23.06.2018	10.00.01	49.2	49.2	48.5	50.6	49.4
23.06.2018	11.00.01	48.6	48.4	48.3	50.4	49.4
23.06.2018	12.00.01	49.081	48.8	48.8	50.614	49.804
23.06.2018	13.00.01	51.816	51.537	51.525	53.251	52.233
23.06.2018	14.00.01	54.021	53.991	53.978	55.502	54.479
23.06.2018	15.00.01	54.721	54.997	54.983	56.256	56.231
23.06.2018	16.00.01	53.363	54.023	54.015	54.972	54.949
23.06.2018	17.00.01	47.763	49.389	49.374	49.96	49.94
23.06.2018	18.00.01	35.901	34.6	34.6	34.706	34.6
23.06.2018	19.00.01	27.055	26.935	26.514	27.009	26.986
23.06.2018	20.00.01	25.79	25.539	25.217	25.759	25.735
23.06.2018	21.00.01	24.53	24.361	24.038	24.511	24.487
23.06.2018	22.00.01	23.399	23.118	22.897	23.386	23.363
23.06.2018	23.00.01	22.38	22.391	21.869	22.371	22.348
24.06.2018	00.00.01	21.376	21.181	20.858	21.371	21.347
24.06.2018	01.00.01	20.384	20.185	19.861	20.382	20.358
24.06.2018	02.00.01	19.398	19.196	18.872	19.396	19.374
24.06.2018	03.00.01	18.56	18.36	18.038	18.559	18.546
24.06.2018	04.00.01	17.601	17.493	17.169	17.606	17.583
24.06.2018	05.00.01	16.642	16.332	16.107	16.65	16.626
24.06.2018	06.00.01	20.218	19.136	19.092	19.361	19.335
24.06.2018	06.59.59	41.554	40.115	40.057	40.776	40.747

R2

Date	Time	Base case	Scenario .1	Scenario .2	Scenario .3	Scenario .4
23.06.2018	08.00.01	43.572	43.239	43.009	44.168	44.157
23.06.2018	09.00.01	46.4	46.127	46.003	47.583	47.574
23.06.2018	10.00.01	47.6	47.792	47.178	48.74	48.749
23.06.2018	11.00.01	47.6	47.745	47.133	49.141	49.135
23.06.2018	12.00.01	48.353	48.29	47.889	49.602	49.598
23.06.2018	13.00.01	51.294	51.205	50.785	52.35	52.343
23.06.2018	14.00.01	53.556	53.507	53.488	54.628	54.62
23.06.2018	15.00.01	54.336	54.384	54.565	55.432	55.424
23.06.2018	16.00.01	53.077	53.097	53.682	54.255	54.247
23.06.2018	17.00.01	47.687	47.924	48.905	49.209	49.204
23.06.2018	18.00.01	35.75	35.777	34.4	34.4	34.4
23.06.2018	19.00.01	26.92	26.99	26.482	26.826	26.817
23.06.2018	20.00.01	25.622	25.666	25.157	25.537	25.527
23.06.2018	21.00.01	24.334	24.365	23.855	24.251	24.242
23.06.2018	22.00.01	23.184	23.18	22.694	23.118	23.109
23.06.2018	23.00.01	22.129	22.143	21.633	22.066	22.056
24.06.2018	00.00.01	21.086	21.095	20.585	21.033	21.023
24.06.2018	01.00.01	20.059	20.064	19.554	20.011	20.002
24.06.2018	02.00.01	19.042	19.045	18.534	19	18.99
24.06.2018	03.00.01	18.159	18.16	17.649	18.117	18.107
24.06.2018	04.00.01	17.152	17.152	16.635	17.109	17.099
24.06.2018	05.00.01	16.149	16.147	15.636	16.115	16.105
24.06.2018	06.00.01	31.779	31.342	29.309	29.499	29.488
24.06.2018	06.59.59	40.144	40.077	38.736	39.265	39.251

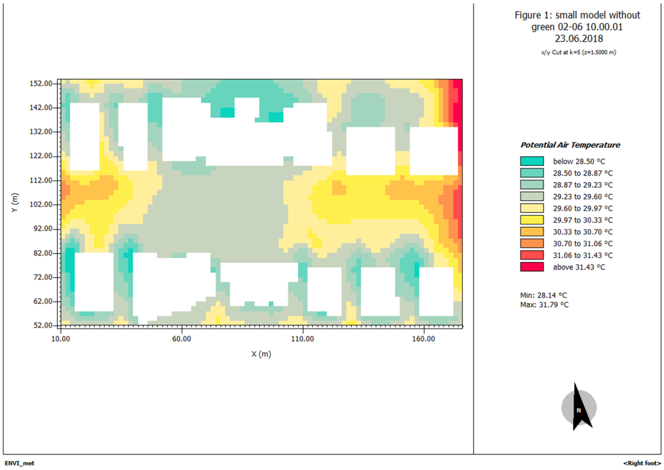
R3

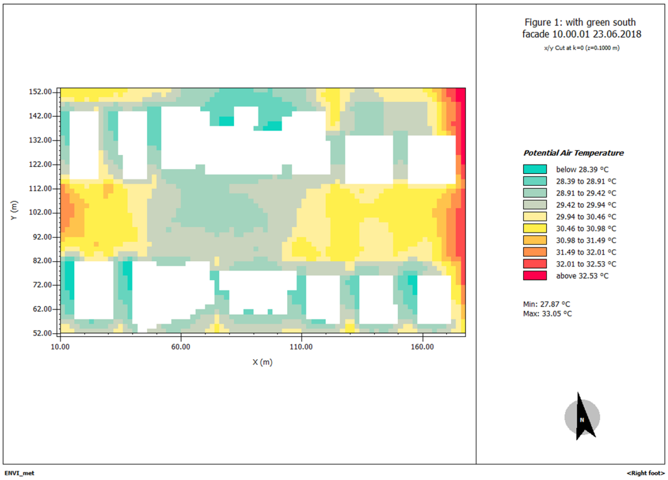
Date	Time	Base case	Scenario .1	Scenario .2	Scenario .3	Scenario .4
23.06.2018	08.00.01	44	43.559	43.544	44.6	44.6
23.06.2018	09.00.01	46.889	46.741	46.726	47.884	47.782
23.06.2018	10.00.01	48.2	48.4	48.3	49.6	49.3
23.06.2018	11.00.01	48.2	48.2	48	49.796	49.788
23.06.2018	12.00.01	48.871	48.562	48.557	50.15	50.143
23.06.2018	13.00.01	51.648	51.348	51.341	52.794	52.783
23.06.2018	14.00.01	53.843	53.787	53.679	54.998	54.986
23.06.2018	15.00.01	54.554	54.801	54.792	55.734	55.722
23.06.2018	16.00.01	53.211	53.842	53.836	54.466	54.455
23.06.2018	17.00.01	49.692	49.119	49.109	49.44	49.432
23.06.2018	18.00.01	34.715	34.478	34.4	34.4	34.4
23.06.2018	19.00.01	26.895	26.962	26.951	26.808	26.797
23.06.2018	20.00.01	25.611	25.648	25.637	25.531	25.519
23.06.2018	21.00.01	24.342	24.364	24.352	24.261	24.25
23.06.2018	22.00.01	23.211	23.22	23.21	23.145	23.133
23.06.2018	23.00.01	22.173	22.176	22.164	22.112	22.101
24.06.2018	00.00.01	21.15	21.147	21.129	21.087	21.076
24.06.2018	01.00.01	20.135	20.128	20.116	20.082	20.069
24.06.2018	02.00.01	19.133	19.123	19.111	19.083	19.071
24.06.2018	03.00.01	18.277	18.264	18.251	18.227	18.215
24.06.2018	04.00.01	17.29	17.274	17.261	17.244	17.232
24.06.2018	05.00.01	16.309	16.291	16.278	16.266	16.248
24.06.2018	06.00.01	32.34	29.829	29.802	30.015	30
24.06.2018	06.59.59	40.8	39.392	39.358	39.926	39.908

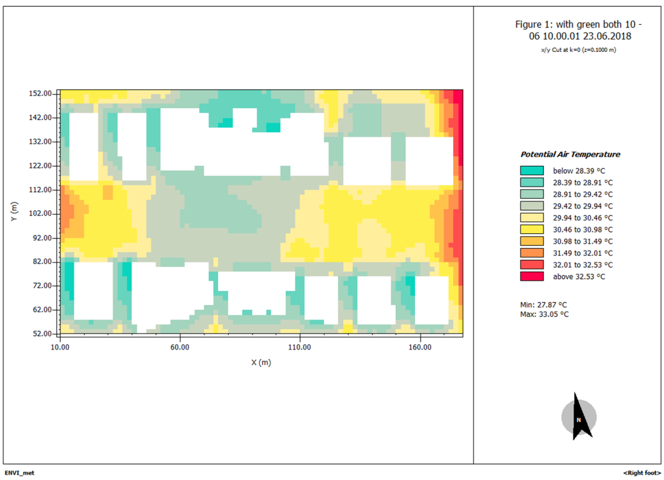
Simulation outouts fot T, Tmrt, W speed, Q.rel at R1,R2 and R3

	Base case			Scenario .1			Scenario .2			Scenario .3			Scenario .4		
receptors	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
	Tmrt 1			**Tmrt 2**			**Tmrt 3**			**Tmrt 4**			**Tmrt 5**		
10.00.01	63.73	63.77	66.74	63.68	63.72	66.72	63.37	63.41	66.72	67.38	67.43	70.41	67.36	67.41	70.39
14.00.01	74.25	52.81	76.78	73.24	52.8	76.75	73.55	52.72	76.71	76.59	56.66	79.24	76.4	56.44	79.16
20.00.01	23.95	23.95	23.3	23.91	23.91	23.33	23.72	23.73	23.26	24.06	24.05	23.18	23.84	23.84	23.11
22.00.01	21.88	21.88	20.95	21.78	21.78	20.94	21.57	21.57	20.87	21.96	21.96	20.86	21.74	21.74	20.78
		T1			**T2**			**T3**			**T4**			**T5**	
10.00.01	29.24	29.24	29.37	29.14	29.1	29.23	29.16	29.21	29.26	27.96	27.99	28.12	28.03	27.97	28.11
14.00.01	31.59	31.33	31.62	31.66	31.38	31.65	31.67	31.38	31.66	30.75	30.69	30.81	30.79	30.69	30.81
20.00.01	30.11	30.02	30.08	30.04	30.06	30.12	29.59	29.52	30.05	29.93	29.87	29.9	29.81	29.86	29.9
22.00.01	28.74	28.62	28.59	28.63	28.61	28.62	28.45	28.27	28.53	28.57	28.47	28.46	28.52	28.46	28.45
		wSpeed 1			**wSpeed 2**			**wSpeed 3**			**wSpeed 4**			**wSpeed 5**	
10.00.01	0.34	0.07	0.13	0.35	0.07	0.13	0.34	0.07	0.13	0.37	0.08	0.12	0.36	0.08	0.12
14.00.01	0.24	0.06	0.15	0.24	0.05	0.15	0.24	0.06	0.15	0.27	0.05	0.11	0.27	0.05	0.11
20.00.01	0.23	0.04	0.14	0.23	0.04	0.13	0.23	0.04	0.13	0.25	0.04	0.1	0.25	0.04	0.1
22.00.01	0.24	0.04	0.14	0.24	0.04	0.14	0.24	0.04	0.14	0.26	0.04	0.1	0.26	0.04	0.1
		q.rel 1			**q.rel 2**			**q.rel 3**			**q.rel 4**			**q.rel 5**	
10.00.01	52.86	53.5	52.91	53.88	53.9	53.3	54.13	54.76	53.68	57.08	57.76	57.03	57.57	57.76	57.02
14.00.01	48.82	49.77	48.89	48.84	49.69	48.86	48.87	50	48.96	51.17	51.57	51.13	51.19	51.57	51.15
20.00.01	54.51	54.85	54.67	54.9	54.74	54.55	55.11	55.83	54.86	55.02	55.28	55.16	55.53	55.31	55.19
22.00.01	57.01	57.42	57.5	57.62	57.32	57.41	57.96	59.09	57.9	57.53	57.88	57.9	58.26	57.92	57.93

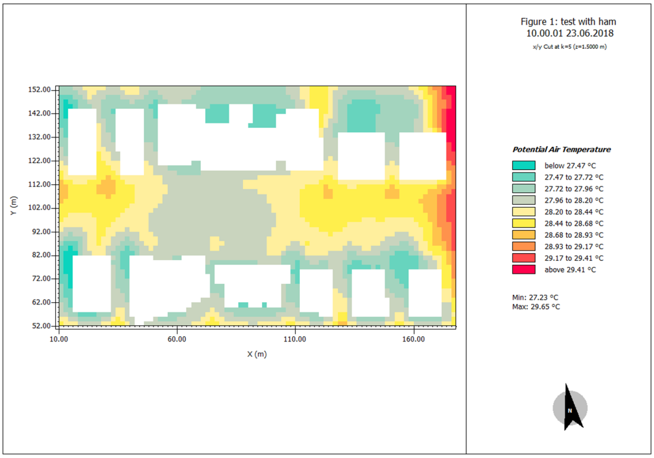
Air Temperature maps for all scenarios at 10 o'clock

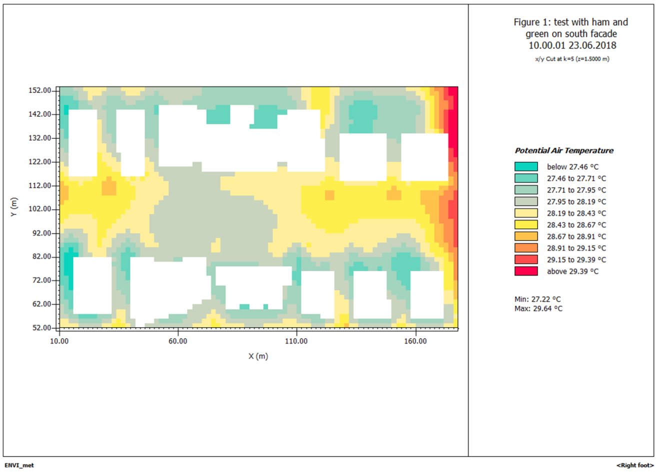




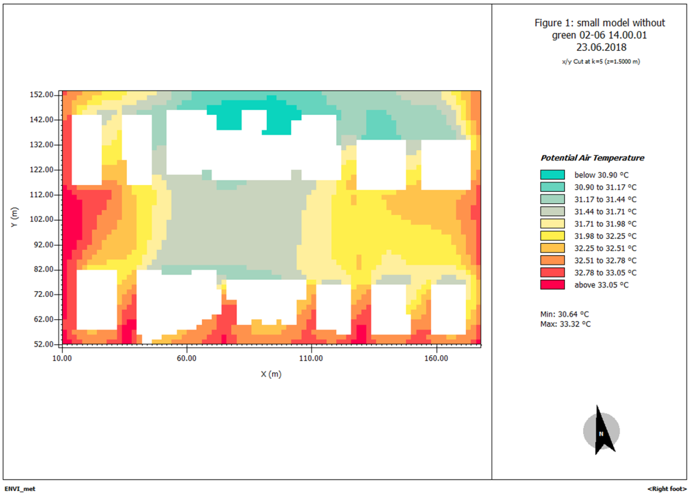


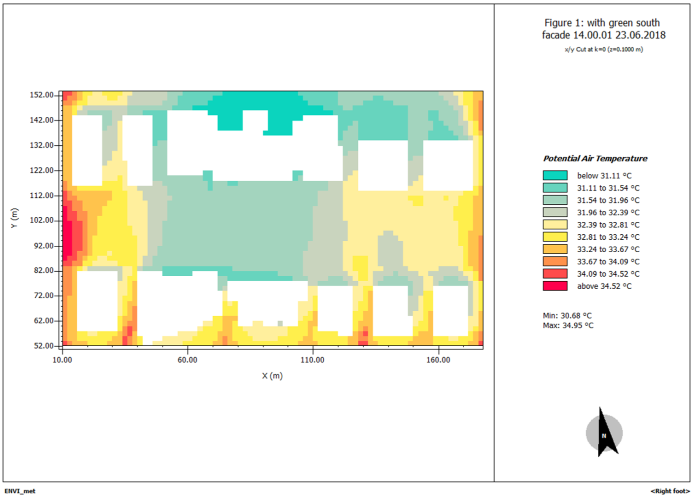
Air Temperature maps for all scenarios at 10, 14, 20 and 22 o'clock

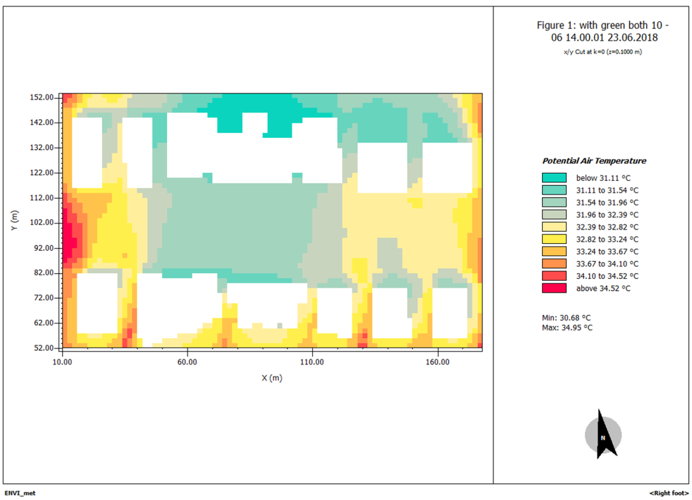




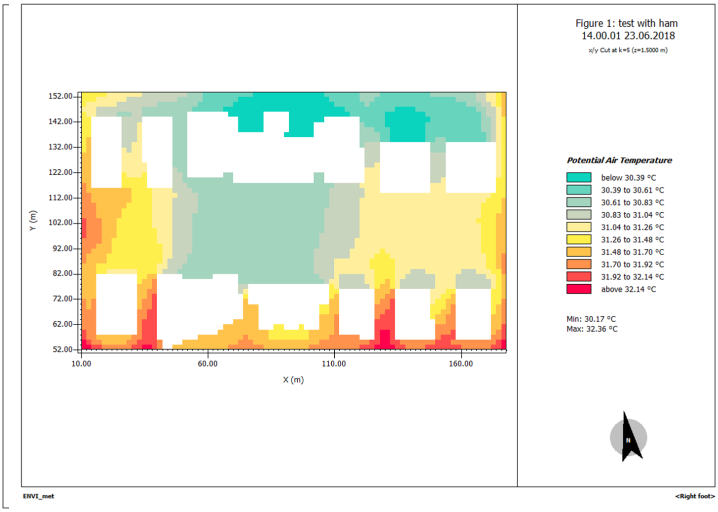
Air Temperature maps for all scenarios at 14 o'clock

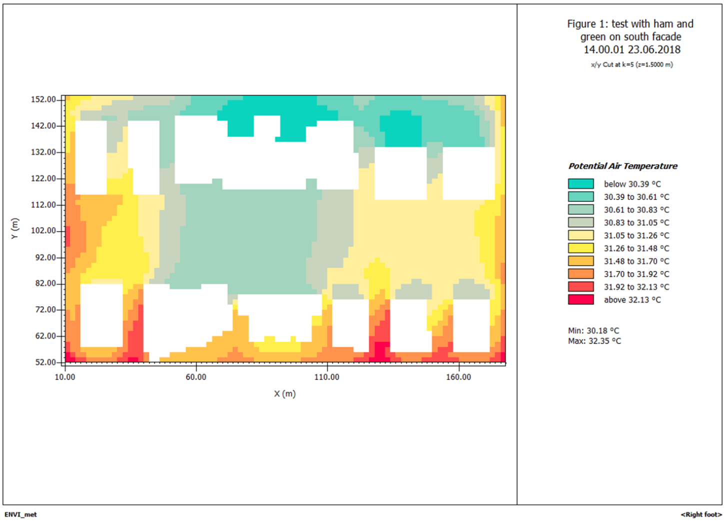




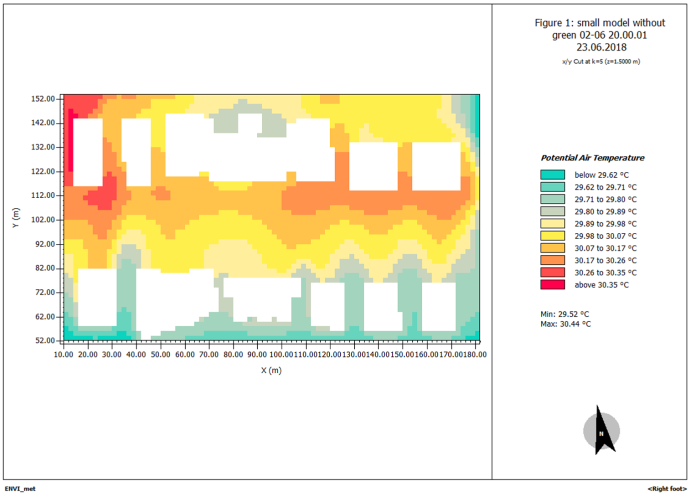


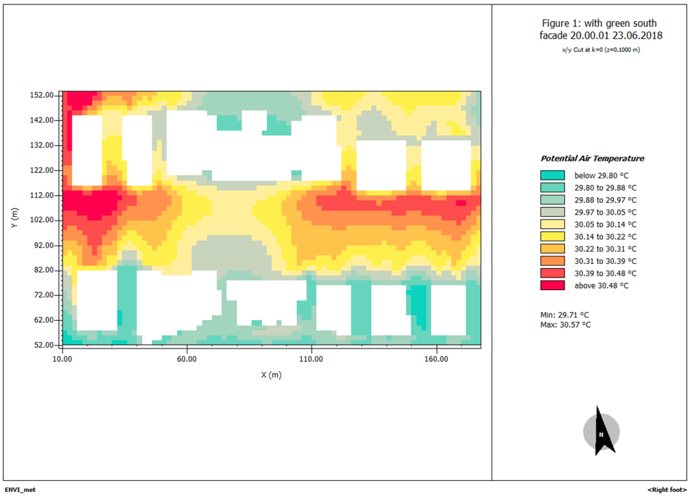
Air Temperature maps for all scenarios at 14 o'clock

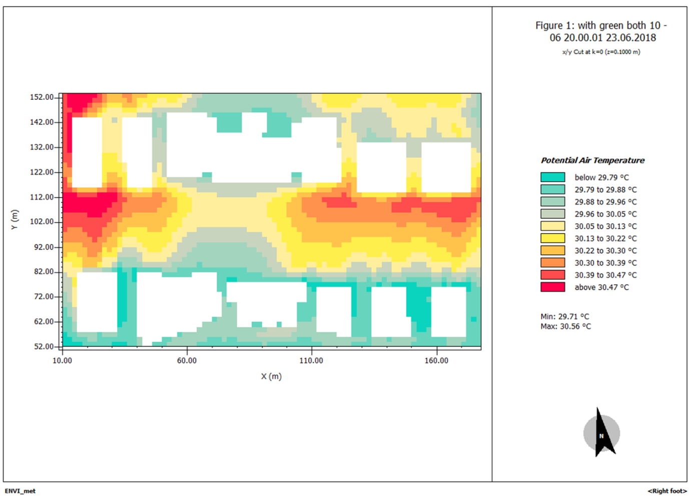




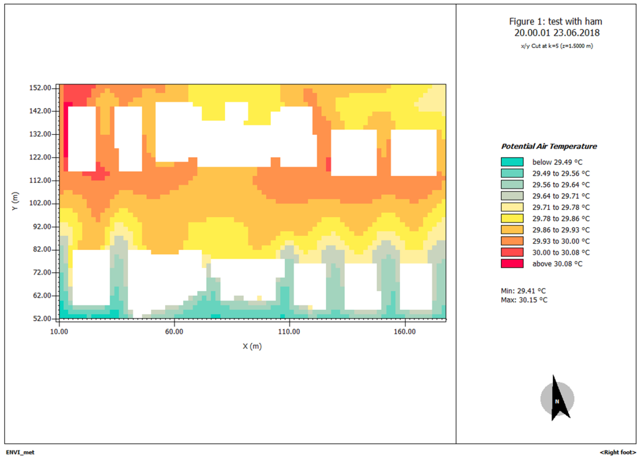
Air Temperature maps for all scenarios at 20 o'clock

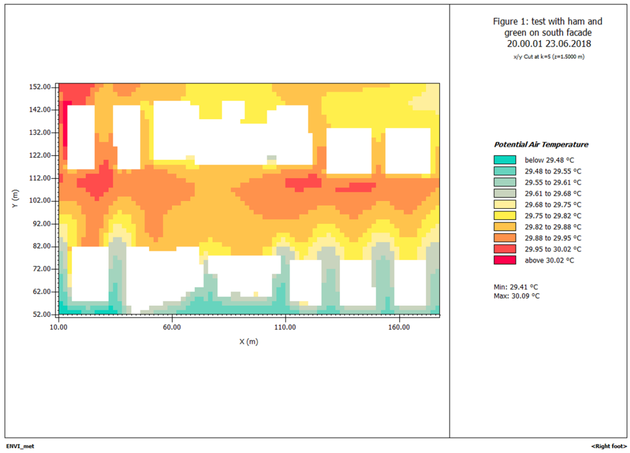




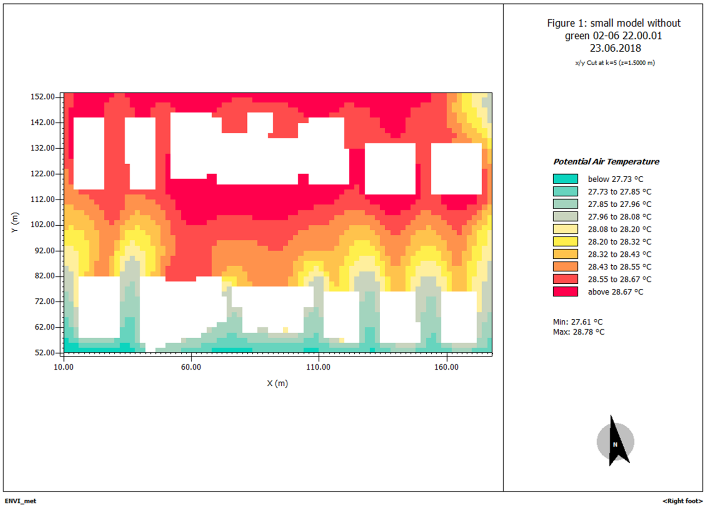


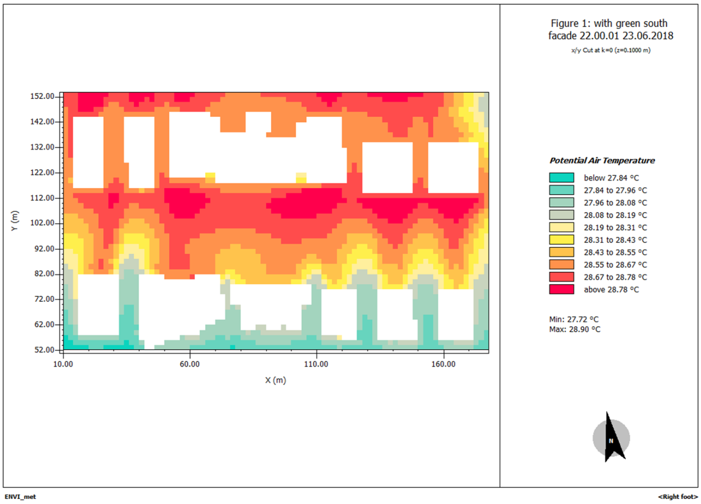
Air Temperature maps for all scenarios at 20 o’clock

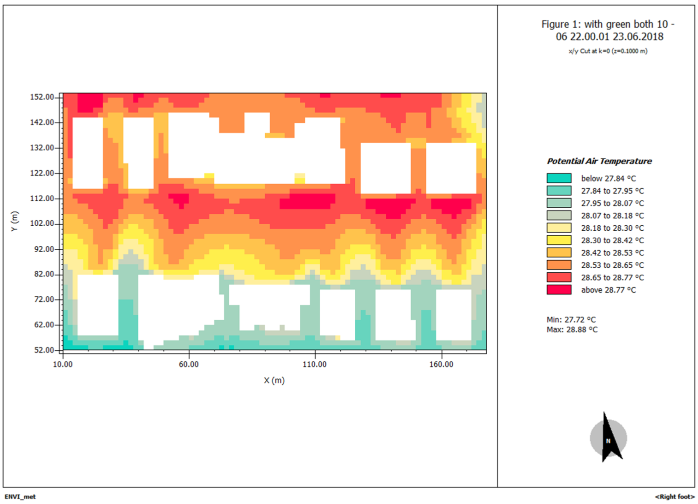




Air Temperature maps for all scenarios at 22 o'clock







Air Temperature maps for all scenarios at 22 o'clock