POLITECNICO DI MILANO

PhD program in
Architecture Built environment and Construction engineering

Heat Island Mitigation Strategies, with focus on the Urban Shading Devices. The case Study of Abu Dhabi Main Island, United Arab Emirates.

09 March 2017
Final Thesis

PhD student:
Lindita Bande
(29th cycle)

POLITECNICO DI MILANO
TUTOR: *Prof. Adalberto Del Bo*
SUPERVISOR: *Prof.ssa Paola Ronca*
SUPERVISOR: *Prof.ssa Tiziana Poli*
CO-ADVISOR: *Dr. Riccardo Paolini*

MASDAR INSTITUTE OF SCIENCE AND TECHNOLOGY
MAIN ADVISOR: *Prof. Afshin Afshari*
SUPERVISOR: *Prof. Khaled Al Awadi*

Via Ponzio 31
20133 Milano
TEL 02 2399.6014
FAX 02 23996020

PARTITA IVA 04376620151
CF 80057930150

Acknowledgement

This thesis was conducted partially at the ABC Department, Politecnico di Milano and partially at Masdar Institute of Science and Technology. I am deeply grateful to Prof. Adalberto Del Bo, Prof.ssa Paola Ronca, Prof. Afshin Afshari, Dr. Khaled Al Awadi.
I would like to express my gratitude to Dr. Riccardo Paolini and Prof.ssa Tiziana Poli for the numerous discussions. Further, I would like to thank Prof. Leslie Norfort and Dr. Prashanth Marpu for all their precious advices. My thanks also go to all my colleagues at POLIMI, MI, MIT: Adalberto Guerra Cabrera, Martin Miguel, Dina Al Masri, Joseph Yang.
Finally, I want to thank my family and my friends for their support.

Abstract

Cities in the Middle East and North Africa, like cities in other parts of the world, are experiencing an unprecedented wave of urbanization. As per the UN 2014 report, the world population in the urban areas will increase from 54% to 66% by 2050. The speed of growth brings out a great challenge for all those involved in the design, planning, construction, and management of the built environment in order to provide sustainable and livable cities for all people. The challenge of this development is how to control sustainability in all aspects of the city life. The challenges are also so diverse that sustaining cities will not be possible without external multidisciplinary interventions. The complex process of city transformation has to take into consideration problematic topics connected to a better quality of life for the citizens, green solutions for the reduction of the CO2 levels and in this research, also strategies of mitigating urban heat islands as a way of contributing in a direct and indirect way to a better quality of life. [1]

The cooling loads of buildings in Abu Dhabi can be reduced by following different strategies. Some of them are: educating the community on the benefits of energy saving, replacing non-efficient energy management systems with innovative ones, and indirectly by proposing strategies to mitigate the heat island. The speed of urban growth in Abu Dhabi brings about a great challenge to all the professionals involved in its design, planning and construction. The citizens are also indirectly involved in the expansion of the city. Abu Dhabi has a hot, arid climate with fresh winter and very hot and humid summer, therefore building in this city requires a deeper analysis and expertise. The downtown area developed without carefully considering factors contributing to the increase of the Urban Heat Island (UHI) levels. UHI is characterized by higher values of air temperature compared to rural areas. The relative humidity may increase at different times of the day creating short term urban moisture islands. The main contributors to this effect are: the radiation trapped in the urban canyon, the thermal properties of the buildings and the streets, the anthropogenic heat emitted from the traffic, AC waste heat rejection in the canyon etc. Among the different UHI mitigation strategies: such as cool roof, cool facades, innovative pavement and asphalt materials, shading trees etc., the urban shading devices combined with the one of the above strategies is an interesting and innovative approach. The aim of this research is to show that such proposed strategy not only improves the Physiological Equivalent Temperature (PET), but also improves the urban microclimate, therefore reducing the cooling load of the buildings.

The outdoor thermal comfort (in this research represented by PET) is an important parameter to measure the quality of life in a metropolitan city such as Abu Dhabi. The energy used in buildings worldwide can reach 40%. In UAE 80% of the annual electricity consumption goes to the buildings and 70% of the peak electricity demand can be traced back to cooling. The highest range of the cooling load is between the timeline of 12.00-14.00. [2][3][4][5]

Considering the above, the proposed mitigation strategies have a crucial role in the city development plan. Five main district typologies from the downtown area where the UHI effect is more significant are taken into consideration. Among these five areas, the focus of the Computational Fluid Dynamics (CFD) models are: the mid-rise/high rise district and the villa district. The particular selection of these two zones is due to the information gathered (building and environment properties), the site access, and the representative typology of the district (the largest number of districts in Abu Dhabi are falling into these categories). According to the area of focus (outdoor thermal comfort or building cooling load), there are different softwares used in this research. Mainly, CFD tools such as ENVI-met and others (numerical, python language) like Grasshopper (that uses Energy Plus for its simulations) are used. Having already had a coupled model that combines the environmental conditions with the building energy consumption, the methodology followed here is by using a decoupled model. Meaning, analyzing the outdoor surrounding environment separately and bringing the results as an input for the building cooling load calculation.

Making small interventions in each district can bring about a considerable improvement in the quality of life of the citizens, outdoor comfort and cooling load reduction. By implementing a proposed strategy that combines shading, vegetation and cool materials, the city can reach its goals toward the Abu Dhabi 2030 sustainability plan. [6]

Contents

Chapter 1: Introduction

1. Introduction

1.1 Background and motivation

In many cases, different cities have been subjected to re-qualifications and revitalizations. The re-qualification of different parts of the city suggests urban modifications of certain areas, construction of new community structures, readapting old structures, etc. The revitalization of a city has to do with interventions at a neighborhood scale such as modifying the landscape, the facades of the buildings, integrating the local community in improving the social life, etc. The background study below is one of many case studies that helps in defining this research project as a continuous work in improving cities in terms of outdoor thermal comfort, quality of life, and energy saving of the buildings as an indirect positive impact. The Urban Heat Island Effect is a phenomenon that contributes to increasing the cooling load. Improving the UHI mitigation strategies in an hot arid climate is a step closer to the UAE future sustainable plans.

The case of Multan City (figure 1) [7] was an inspiration and a reference point for this research. Evaluating the revitalization from a social, economic and environmental points of view has brought into light the various problems that such a rich cultural city has. Finding solutions with the integration of the local community makes this project achieve higher points in terms of sustainability. This project starts with a historical analysis of the city to highlight the value of the intervention. The city has a rich architectural background. The buildings have characteristic details that can be found only in this city. Its urban planning is very specific and different from the surrounding cities, defined by low-rise buildings. There are many religious buildings between the walls of this old city, which makes it very attractive to visitors from around the world. The main areas where the local life takes place are the bazaar, the jewelry shops, the ceramic industry, the textiles, etc. Parallel to this approach, Abu Dhabi was initially developed in the coastal area and from there it was expanded into the desert. The main local activities were pearl hunting and fishing. So we can say that culturally there is a parallelism between the two cities in a way, but then a very different way of developing.

Figure 1: Multan, the walled city. [227]

As part of the revitalization of Multan City, an analysis was done for the improvement of the outdoor thermal comfort and strategies of improving the cooling load of the buildings. As a result of this analysis, vegetation was discovered to be the best strategy to improve the outdoor comfort due to evapotranspiration of the plants and this could be achieved by creating a green dense canopy. The analysis was done with ENVI-met. Another proposal was to connect the green areas with green paths, again with the aim of improving the outdoor comfort. To this end, wind and solar stress, foliage maintenance, irrigation system and cost, and types of trees were carefully studied and proposed. Another approach of this research to improve the outdoor air temperatures is to add tents and create shades above the pathways as high as possible, but with a design that will not block the air movement, with very low solar absorbance, a very high solar reflectance index and a very low solar transmittance. This kind of tent should avoid the sealing of the street canyon. It’s also mentioned that by placing these tents near the buildings, it can improve the cooling load and decrease the temperatures below them by 10 degrees.[8]

On the other hand, a parallelism can be made for Abu Dhabi, but since the urban planning pattern is quite different, the appliance of the shading devices in different district typologies has a different impact. The streets of Abu Dhabi are wide and have a minimum 3 lines on each side. This points out the excessive anthropogenic heat released in the canyon. And as it will be shown in the coming chapters, the trees in such a hot, arid climate are comparable to the effect of the shading devices. These devices can reduce the temperatures and improve the microclimate of the canyon. [9]

The shading devices are an important mitigation strategy. With the development of CFD tools, there is plenty of space to test and to search for the best result. In this study, there was a double analysis with CFD software and Grasshopper to define the shape of the devices [10][11]. The SC Stream software was used to optimize the shading device used in one of the districts (mentioned in chapter 4). The wind speed value seemed to influence the UHI more than the nebulosity. UHI value was really affected by the wind when its speed exceeded 3 m/s, an observation consistent with previous studies.

Another important research related to this topic is the one done in Basel. In this study, the cooling and the heating loads were considered: the radiation exchange between neighboring buildings, the urban heat island (UHI) effect and the reduced convective heat transfer due to wind sheltering. This study was conducted for three different building types: a New, an Old and a Retrofitted Building. It was found that the space cooling demand for all building types was higher, and that the space heating demand was lower for buildings in a street canyon configuration than for the same stand-alone building. Neglecting the UHI effect leads to an important underestimation of the cooling demand. The local microclimate is crucial in defining the UHI effect and the cooling loads. [12][13]

Furthermore, there are different studies in real cases of the effect of UHI on the cooling load. An important input for such calculation is the weather file. Bueno developed a tool that gives us a weather file based on the rural conditions. In this case, it takes into consideration the UHI effect in increasing the temperatures by 2-3 degrees according to the geographical location. On the other side there are studies done in real cases. [14]

One of them was done in Tokyo. Basically, this research shows that the heating load in the pique time decreases due the UHI effect. Here is another approach of the effect of such a phenomenon. Previous researches showed that the urban neighborhood has an impact in the building cooling system. An analysis with CFD programs made it possible to calculate the best position to install the primary and secondary HVAC system in order to reduce the anthropogenic heat emitted in the canyon [15].

The four hours following sunset are essential in the UHI formation. In the study done in Nantes, the authors came out with the results that for such analysis, the number of sensors all over the city must be higher in order to have a better result. The size and the shape of the elementary areas defined for geographical analysis have been chosen arbitrarily. A comparative analysis using several territory partitioning methods might be performed in order to identify the one which gives the best results [16].

The uses of the sensors is crucial in evaluating the effect of the UHI in the urban areas. Another study is the one done in Hong Kong. This city endures a high air temperature from late May to early September. A hot period from mid-May to mid-September has been included into the summertime statistical calculation in this section. Based on the analysis of 25 clear days (0-2 Oktas) and 1064 partly cloudy days (3-7 Oktas) in the hot period (from mid-May to mid-September) from 2002 to 2012 (incomplete observation has been excluded), the results below were noted:

- Diurnal range of intra-urban and urban-rural thermal differences were smaller in partly cloudy days than that in clear days.
- Under clear sky condition, both intra-urban and urban-rural thermal differences increased during night and reached peak at early morning before sunrise.
- Under partly cloudy conditions, UHI intensity rose at a lower rate compared to clear sky conditions while intra-urban air temperature differences remained at a constant level from 20:00 to 6:00 next day morning.[17]

The CFD softwares have limitations in terms of the scale of the model that is being analyzed. The bigger models have the need for a larger computational scale that is time consuming. The more detailed the grid is the more the model will take time to give results and the different tests that need to be done will not make it possible for a full analysis to be done. This is also related to the detailing of a certain area, as sometimes, some sections of the canyon have to be reviewed closely.[18]

Furthermore, depending on the geometry of the district, CFD softwares such as COMSOL and ENVI-met can be used in the design phase of an urban planning project. The airflow between the buildings can be seen in the postprocessor. There is a risk of inaccurate results if the scale of the model is simplified more than the real conditions. The lack of details can modify the results of a real wind flow and therefore give moderate conclusions. The boundary conditions must also be defined properly based on real dimensions as, in certain CFD tools such as ENVI-met, there is a possibility of overestimation of the mean radiant temperature.[19][20]

The analysis at a district level has been a challenge due to the limitations of the different softwares. There have been improvements in certain CFD tools such as SCstream, however, factors like time consumption, the need for an initial knowledge, and cost limits the results and the analysis. The district study helps in understanding how the different building heights, their geometry, the street distance, and the several building typology interact with each other and therefore suggest the changes and possible spaces of improvement. A neighbor scale analysis helps in understanding how the outdoor thermal comfort can be improved by taking different measurements. In the Middle East’s specific hot arid climates, such analysis is limited. [21]

There are several studies done in the Middle Eastern region regarding the improvement of the microclimate, mainly through the landscape, however, there is no deep historical study of the ancient cities and the relation to the modern cities. The analysis of how the urban space evolved according to the society evolution and the market needs has place for improvement. The modern cities of the region such as Dubai, Doha, Abu Dhabi, Muscat, Kuwait, Manama etc., are still growing; therefore, there is a strong need of microclimate change study and site measurement campaign. Every urban development plan has an impact to the local climate and microclimate and has the potential to improve or decrease the air flow, air quality, air temperatures, relative humidity, mean radiant temperature, outdoor thermal comfort etc. [22][23]

The initial measurements of site conditions create a base of the model that is closer to the reality. Creating this background along with having strong computational skills and using the correct equations is crucial for the accuracy of results that will be obtained. The real case studies have a reduced scale. There are sporadic examples of projects in the Middle East that contribute to the improvement of the microclimate, [24] however, there is no official measurement campaign in the main cities of the gulf region in the last 20 years of their development. Measuring the air temperature, relative humidity, wind speed, the solar irradiance etc., with the aim of calibrating and validating the CFD models, as well as tracking the microclimate changes has not been done yet in the city of Abu Dhabi. These measurements can be done in several levels and in several different districts in order to have a full picture of the microclimate changes in the main island of Abu Dhabi. Such a campaign is also needed to monitor the impact of the anthropogenic heat released in the canyon from the AC units and the traffic. The site measurements are also needed to define the outdoor thermal comfort values. Part of this research is to conduct such campaign in order to create CFD models closer to the reality.

1.2 Scope and methodology

The Research Field concerns the urban planning in new cities and the strategies for the mitigation of the Urban Heat Island Effect. The interesting and new side of the research is the connection between the Urban Design Fixtures and the Mitigation of the UHI, all these being connected to the sustainability of the city in terms of energy saving and a higher quality of life. From one side there is an analysis on how the UHI affects the Cooling of the buildings and on the other side, an analysis on how to mitigate UHI with smart and sustainable solutions.

This topic is connected to several disciplines. First of all, in order to evaluate where the urban planning stands today, it is necessary to take an overview of the past steps. Since the case study is situated in the Middle East, the research takes another interesting path thanks to the different cultures, societies, architecture and construction technology. Analyzing the past in the different elements connected to the research topic can lighten up the evolution pathway and bring into perspective the positive, energy efficient solutions used for centuries.

Beside the first part that is theoretical, the research has a considerable amount of site monitoring as it is connected to the outdoor thermal comfort and energetic analysis as a way of measuring the effectiveness of such proposed solutions. Furthermore, a comparison between planned and applied project with a critical mindset will bring out important definitions to be taken into consideration in the future steps, such as assistance to a government entity for future urban areas.

Middle Eastern countries have emerging economies which are on their way to defining a modern identity. With such a fast development, countries such as UAE, Qatar, Oman, Bahrain, Kuwait, Yemen and more must be placed under a strict control system of construction in order to avoid a non-sustainable growth from economic, social and environmental points of view.

The Middle Eastern Cities have had a rapid development in terms of construction with few possibilities to make the necessary tests before applying. The case study taken into consideration will make a difference in this critical analysis. The Main Island of Abu Dhabi has had a growth that did not take into consideration many aspects contributing to the increase of the UHI levels.

There must be interventions in order to make the city more sustainable, such as: cool roof, innovative pavement materials, shading trees and urban shading fixtures, which are some of the main UHI mitigation strategies.

Technically, analyzing such proposals takes a long time, but with new softwares it can be possible to monitor the suggested intervention. The scope of this research is to analyze the impact of the proposed UHI mitigating strategies in decreasing the air temperature, improving the outdoor thermal comfort, and reducing the cooling load of the buildings. In this research, the most important part of the analysis is the comparison between the past and the present in order to show where and what can be improved so that the desired thermal comfort conditions are achieved. The aim is to start an analysis from the history of the Ancient Islamic Cities. Many lessons can be learned from the past in terms of the urban planning and architecture. The solutions that came out from the local experience and the adaptation to the difficult climate conditions made this city sustainable from the social, economic, and most importantly, environmental approach. Their similar characteristics in terms of street pattern and urban solutions bring out planning guidelines to the cities of tomorrow. The analysis of the urban forms and the urban development of the city is crucial to the understanding of the shapes and the type of the suggested strategy. In terms of the methodology, the steps will follow a timeline: the history of the development of the cities in the region, the development of Abu

Dhabi, the UHI phenomena, the proposed mitigation strategy, the CFD models, the Measurement campaign, the results and conclusions. The steps have a practical interaction and they fuse together at certain points. The design and proposal of mitigation strategies cannot be developed without a full picture of the past sustainable solutions in the region. The CFD models cannot be realistic without the site measurements.

1.3 Outline

This thesis consists of 7 chapters. In the chapter 2, there is an overview of the urban planning development in UAE. Chapter 3 covers the two types of proposed shading devices. The thesis main chapters are 4 and 5, where the models work and the validation process are discussed. In the chapter 6, the results of the research are shown. Chapter 7 covers the application field of the research and the calculation of the cost.

Chapter 2: UHI phenomena, mitigation strategies and local applications

2. UHI phenomena, mitigation strategies and local applications

2.1 UHI Phenomena

The Heat Island is a phenomenon created in the urban areas due to construction of the cities. The materials used for the streets, pavements, building facades, and rooftops absorb the heat from the direct solar radiation and release it during the night causing an increase in the air temperatures in some cases by more than 2°C. This depends also on the type of the city, the climate of the city, the traffic, etc. [25][26]

The urban canopy characteristic defines the level of the heat island effect. The connection between the height of the buildings and the width of the streets defines the amount of heat trapped into the canyon. There are several different strategies applied in the urban canyons that minimize this effect. The orientation of the urban canyon toward the wind direction also has an impact on mitigating the UHI effect. By analyzing all the factors that cause the UHI phenomena in a city, it can be possible to implement the right mitigation strategies. This is defined by the geographical position, the climate, and the socio-economic situation of the place.[27][28][29]

The UHI phenomena can be prevented at some levels of the urban planning phase of a neighborhood by selecting the optimized street size, amount of greens, building height and type of materials. The surface temperature can also show and be associated to the UHI Phenomena in the cities. Several studies show higher surface temperature in the urban areas than the rural ones. Several studies have been done on the spatial distribution of the UHI. Different cities have different configurations. Analyzing the different configurations of UHI helps the decision makers make the right approvals. [30][31]

The urban form and development defines the typologies of the strategies applied in a city. The design of the streets, the space dedicated to open parking and underground parking, and the building orientation are connected to the UHI phenomena and its intensity. According to a research conducted in Atlanta, Georgia, the single-family residential buildings have a bigger impact on the UHI phenomena than the high rise buildings in a high density area. [32]

Before proposing any UHI mitigation strategy, it is very important to understand the behavior of the urban canyon during different periods of the year. In the Mediterranean climate, the effect of the heat island in summer time has a direct effect on the outdoor thermal comfort and energy consumption of the buildings. A study done in Athens shows the different variations of the UHI during the summer season in several locations. A network of 25 fixed temperature sensors showed that the difference in temperature of the selected areas of the city reached 5°C. [33]

The UHI phenomenon has an important role in hot climates. It contributes to increasing the cooling load of the buildings and it decreases the outdoor thermal comfort values. The heat entrapped in the urban canyon increases the air temperatures, therefore increasing the need of cooling inside the buildings composing this canyon. The increase in air temperature in such climates where the air temperature in spring can reach 35°C increases the level of discomfort in the outdoor thermal comfort chart. [34] [35]

Phoenix, in Arizona has implemented an interesting policy that will help the city meet its targets of 2030 in reducing the UHI phenomenon. The hot arid climate of the city contributes to the creation of the UHI. The local institutions together with the local community cooperated in implementing the policies that were suggested and approved. The shape of the network in a certain urban area is connected to the wind flow and the natural ventilation of the city. The study of the wind direction and the different strategies to improve it, or in some cases, to stop it has an impact on the UHI phenomenon. In Phoenix, the rapid growth of the city increased the traffic therefore increasing the anthropogenic heat contributing to the UHI effect. [36][37]

The study of the strategies that can have a positive effect in mitigating the UHI is related to specific CFD modelling. For calibrated models, having a database with site conditions makes them more realistic and the tests done in the laboratory are closer to the reality. The site measurements are an initial support in order to have more reliable models and results. It is shown that the UHI intensity is connected to the geometry of the buildings since they contribute in regulating the long-wave radiative heat loss. The geometry of the canyon defines the relation between the size of the city and the UHI intensity. [38]

2.2 UHI mitigation strategies overview

There are several strategies applied in different cities with a different urban context and different urban climate. There are many ongoing studies in emerging countries trying to improve the micro-climate. The main applied strategies are: cool pavements, cool asphalt, cool façade, urban trees, green walls, green roofs etc. Their effects vary from one region to another depending on the local climate and development. [39][40]

Some other samples of how cool roofs, trees and shading can be used as strategies to mitigate the UHI are the ones applied in Phoenix, Arizona. With the aim of reducing the air temperature by 0.4-0.5 in an average neighborhood scale, the municipality of Phoenix requested an increase of the trees from 10% to 25% by 2030 and an implementation of the cool roofs. The results showed that the outdoor thermal comfort can be improved by several degrees. It would also decrease the air temperatures by 2°C under the shading. The type of the vegetation and the irrigation system are part of this research and they play an important role in the evapotranspiration process.[41][36]

Several studies were conducted to analyze the effect of the vegetation in reducing the UHI effect in the cities. The vegetation typology and index defines the magnitude of surface and air temperature reduction in the areas where they were applied. Due to the evapotranspiration process, the leaves of the trees cool down the air passing through them. They also create shades in the streets, reducing the area of the pavement and asphalt exposed to the short solar radiation. [42]

Alternative solutions such as the example of Sierpinski forest show that synthetic materials based on the natural design of the trees can help in reducing the surface temperature by at least 10 degrees compared to the air temperature, and in the full shade a difference of 20-30 degrees. The study shows the experiment in few common areas around the buildings in Japan. However the results are significant considering the effect of a 3D synthetic material. [43]

From the site experiments, the cool roof and the cool pavements reduce the surface temperature by 15-20 degrees, improving in this way not only the air temperature but also the outdoor thermal comfort. In this study, the urban shading device is an alternative proposal for the reduction of the thermal stress in a street canyon. From the developed model, it is shown that in this canyon the thermal stress is reduced by the application of canopy shading. [44]

The surface area temperature is reduced due to the shade created from the vegetation planted in the city. Different types of vegetation have different impacts in reducing the surface temperature.

Furthermore, the reduction of the surface and air temperatures because of the use of vegetation improves the outdoor thermal comfort and consequently improves the human health [45]

As a mitigation strategy, the vegetation can be applied at the ground level, on the vertical façade of the buildings, or on the rooftops. There are many studies analyzing the temperature decrease from the use of the vegetation on the rooftops. The climate is a crucial factor as its connected to the maintenance. In order for a strategy to be efficient and sustainable, the cost of maintenance is an important factor. Analyzing the different mitigation strategies brings out the limitations in each one in different locations and climate conditions, buildings and street properties. [46][46][47]

The Mediterranean region is quite problematic in terms of Heat Island Phenomena. From the several researches, the main strategies to intervene in such a climate are the cool surfaces and the shading trees. This kinds of solutions were historically applied in such climates but a deeper scientific analysis was done only in the last decades. The cool materials reflect back the biggest amount of direct solar radiation. There have been many trials in different climates which proved that the cool paints are quite efficient in facades and rooftops. [48][49] [50]

2.3 Regional applications

The UHI phenomenon is well known in different parts of the developed countries, but it is still in the initial steps at the emerging countries such as the Middle Eastern countries. The rapid urban growth has overpassed many lessons learned from the history of ~~the~~ urban planning.

There are efforts from local and central governments to improve the microclimate in young cities such as Abu Dhabi, Dubai, Doha, Bahrain etc. The main strategies proposed from the local legislation are the cool surfaces. Deeper studies must be done to analyze the effect of such a strategy in this kind of hot arid climate. There are several ongoing studies in the region such as in Egypt and Tel Aviv, with the scope of analyzing the urban canyon and how to improve the city urban conditions. The local climate makes this kind of intervention crucial and very important as it has a direct impact on the people's health and on the reduction of cooling load. [51][52]

The UHI phenomenon was also studied in Madinah, Saudi Arabia. The city is located in the gulf region and has similar climate conditions to Abu Dhabi. In the study, it was shown that the latest development of the city increased the UHI value. Several tests done in FLUEN (CFD software based on the Reynolds Averaged Navier Stokes approach) show that the orientation of the streets and the relation with the wind direction can improve the outdoor thermal comfort by decreasing the air temperature by 2°C. This CFD model can also define the air pollution, the wind comfort and thermal comfort.[34]

The landscape modification and distribution in different areas in the city of Doha were analyzed. The distance from the seaside impacts the wind flow of a certain area. The landscape combined with the wind flow can improve the outdoor thermal comfort in this hot, arid climate city and in similar cities around the region. It is adviced to maintain the first coastline of buildings at a certain height in order to let the wind flow go through the inner areas of the city. [22]

The hot, arid countries have very specific weather conditions with summer air temperatures that can reach 50°C, therefore the built environment has a strong impact on increasing the air temperatures within the city. In the UAE, Abu Dhabi is mainly concentrated in the main island while Dubai has a linear development. The building characteristic and the landscape vegetation are the main factors in mitigating the heat island effect in certain parts of the city. [23]

In the UAE, the local government has developed initiatives to improve the current neighborhoods with different rating systems and incentives. The Abu Dhabi 2030 is one of these initiatives and an Estidama rating system is applied in the latest developing plans of the city with the aim of having a sustainable city. The new areas expanding on the suburbs of the main island must have an Estidama proposal. The local authorities have released an awareness campaign in building a sustainable city since 2010. [53][54][55]

Estidama is a rating system created to improve the main factors of sustainability in the UAE: the environmental, economic, social and cultural factors. It influences the design, construction and operation processes. It involves the project owners, the developers, the design teams and the residents.

This rating system ~~is~~ was developed by the Urban Planning Council Abu Dhabi~~.~~ as part of the UPC and Development review. Since 2010, all projects submitted to the municipality for approval must have a report on the Estidama Rating system of the project. Part of the Pearl Rating System are:

- Pearl Community Rating System,
- Pearl Building Rating System,

- Pearl Villa Rating System,
- Estidama PRS Construction Rating site Audit Protocol,
- Temporary 1 Pearl Building and Villa Program.

The first point refers to a community of not less than 1000 residents. It can include a district of different types of building. It is mainly connected to the use of energy and water, waste minimization and local material use. It aims to improve the supply chain of sustainable and recycled materials and products.

Here are several manuals (Table 1) that help the design process, available in the UPC website. They are mainly used by the design companies in the early design stages. However, there are no specifications on cool materials or analysis of the UHI phenomenon. A deeper analysis and guidance in this phase would help the urban planners and architects define their design before starting the detailing and authority approval process. [56]

Table 1: Manuals of Urban Planning Development in Abu Dhabi

Authority	**Manual**	**Description**
Urban Planning Council	Abu Dhabi Urban Street Design Manual	Street retrofit, generic description on the material, no specifications.
Urban Planning Council/Estidama	Abu Dhabi Realm Design Manual	No description.
Abu Dhabi Municipality	Roadway Design Manual	Detailed description on the pavements design and characteristics. No cool pavements mentioned.
Urban Planning Council/AD 2030	Abu Dhabi Community Facility Planning Standards	Generic description on the design. No specifications on the materials.
Urban Planning Council/AD 2030	Neighborhood Planning	No specifications on the cool surfaces

Figure 2 shows the difference in the relative humidity between the rural and the urban data. As it can be seen, the relative humidity is higher in the suburb in the morning and evening hours, while during the hours 12.00-19.00 it goes lower than the urban.

Figure 3 shows the difference in temperature between the urban and the rural data. The rural temperature is lower during the morning and evening time and higher from 12.00-19.00. This was an expected result due to the heat trapped into the urban canyon.

Figure 4 shows the anthropogenic heat schedule during the weekdays and over the weekend in the city of Abu Dhabi. The study is based on average values of the five weekdays and the two weekend days. The peak values are mainly in the morning and evening time. The values refer to E3 district, downtown Abu Dhabi, and the reference of the study are the satellite data.

Figure 5 shows the UHI phenomena in the spring season. The average difference is 1.5 °C. The highest values are at 6.00am-7.00am as expected, and the lowest values are at 14.00 hour. The urban and rural measurements in pictures 2-5 refer to the year 2016. The network of sensors installed in Abu Dhabi is used also for the boundary conditions of ENVI-met as it will be shown in the coming chapters.

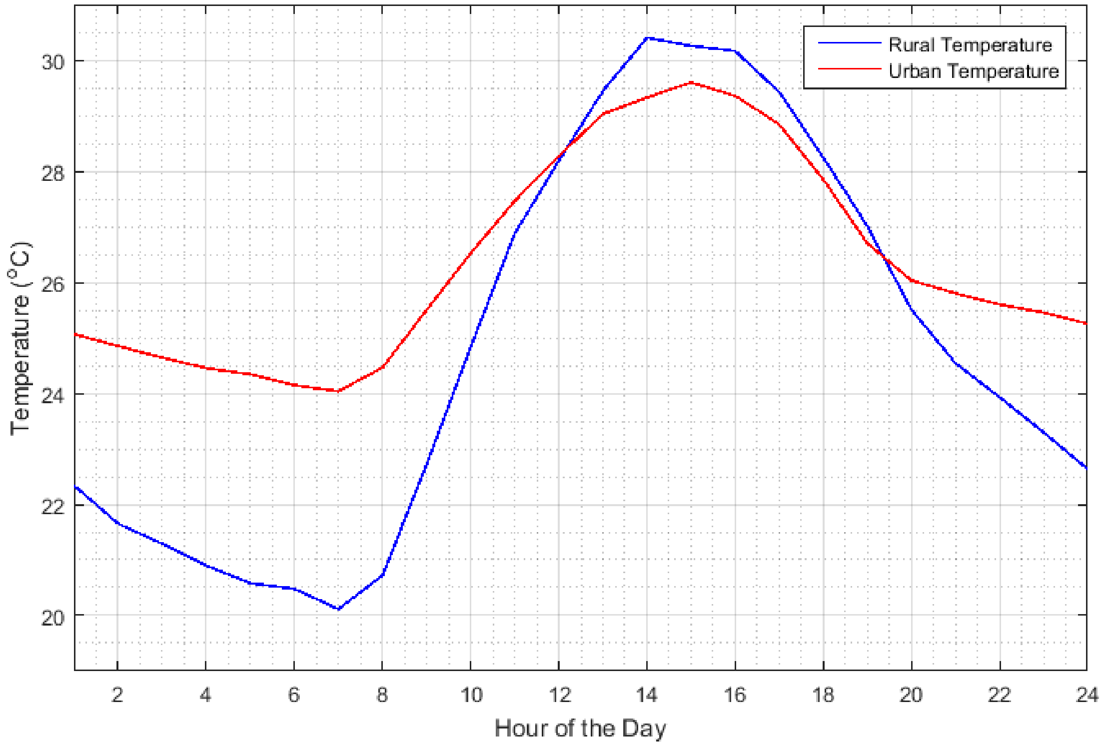


Figure 2: Temperature difference rural-urban, spring season. [228]

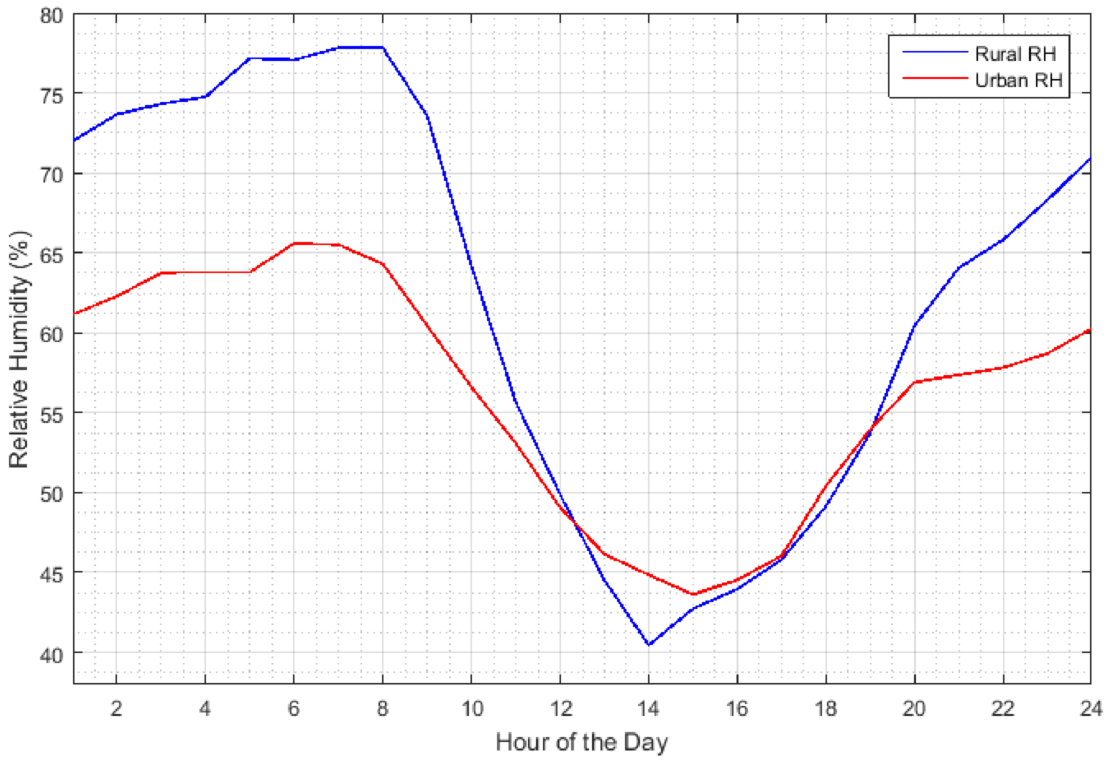


Figure 3: Relative humidity difference rural-urban, spring season. [228]

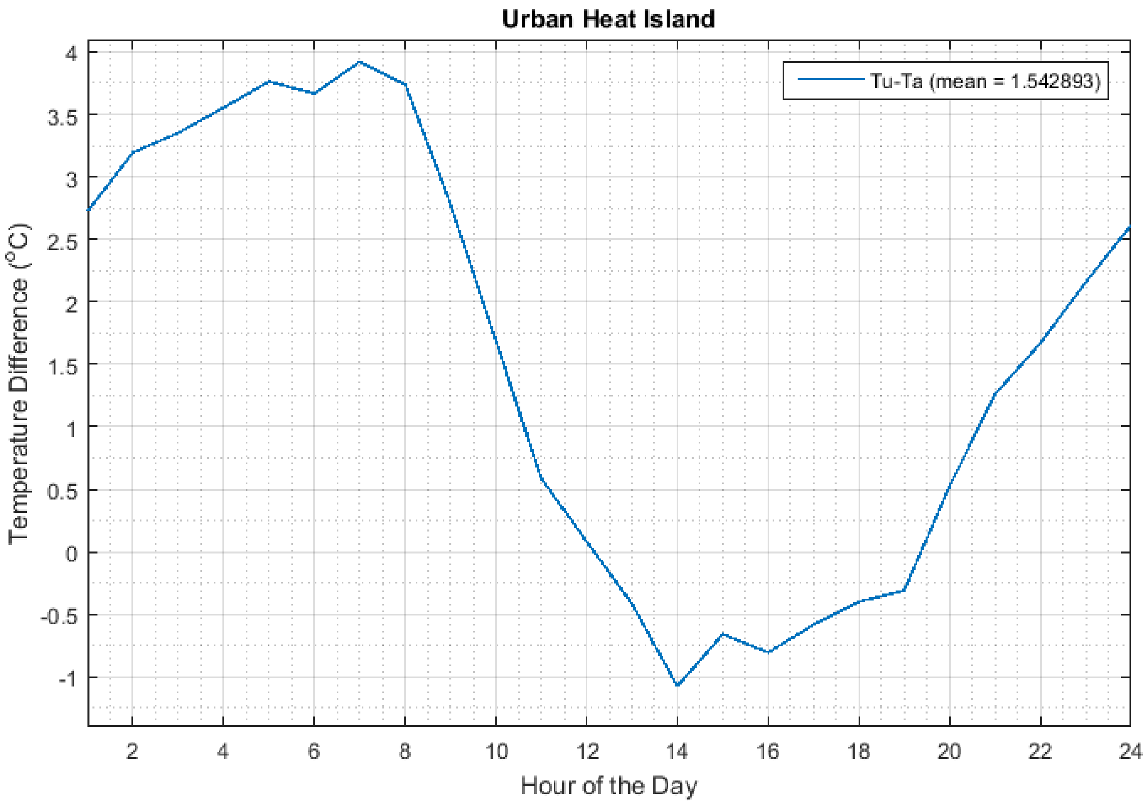


Figure 4: Heat Island phenomena in Abu Dhabi, spring season. [228]

Chapter 3: Urban Planning and Environmental Analysis

3. Urban Planning and Environmental Analysis

3.1 Introduction

The urban development of new cities is connected to the development of the society. The different building types and architecture are connected to a specific phase that the society is at a certain period of time. The street network, the different urban blocks, their types, their connection and the principles of a sustainable development are ongoing processes that tend to improve themselves. There are different approaches in studying the building types and the urban forms in different cities. This is connected to the history of development of the society, the geography, the climate conditions, the relation with the neighboring countries and the their influence into the local climate.[57][58][59]

The Middle Eastern cities are developing very fast. The biggest part of construction was made in the last 70-80 years. The public transportation has a crucial value in developing a sustainable city. Two-four cars per family is an excessive number when calculated against the parking lots coverage area in the city, the amount of asphalt area, the CO2 emissions, etc. Currently the local authorities are working on improving the public transportation.[54][60]

Several studies done at a mesoscale level analyzing the urban morphology, show a direct impact between H/W and the energy consumption in the buildings. This is related to the different behaviors of the canyon toward the solar radiation because of the orientation of the buildings and their volumes. The morphology of an urban area impacts mainly the outdoor thermal comfort and the health of the citizens.[61][62][63]

The design of the space between the buildings and the development of the public areas has a major impact in improving the outdoor thermal comfort and the microclimate. The use of local materials and the correct orientation of the proposed structure can potentially bring an improvement in the urban microclimate. The space between the buildings is connected to the sky view factor that is a quantitative factor in defining the different district morphologies. [64][65] [66]

The urban form evolution, the heights of the buildings, their orientation, and the distance between them are connected to the solar energy at an urban scale. In such climates as the one in UAE, the more dense the urban form, the more shaded the streets are and the more energy saving will be obtained. However, the development of the cities is connected to the global changes. [67][68][69]

The different urban analysis at a global scale show similarities in the urban forms and their impact on air pollutions related to the transportation systems and the construction speed. In the developing cities, the growing number of cars increase the air pollution compared to cities that have a defined structure. [70][71]

The careful planning of the residential blocks improves the life of the inhabitants. The careful calculation of the solar access, the natural ventilation and the orientation of the buildings can improve the health of the citizen in the indoor and outdoor area. The distance between the buildings must be sufficient enough to help the natural ventilation process. Having passive systems that can cool the building and reduce the energy spent in the air conditioning system is one of the main points to consider before starting the plan of a district. [72][73]

The urban planning is strictly connected to the climate conditions of the area where the development takes place. In hot, arid climates the distance between the buildings are quite different from cities in cold climates. The building orientation tends to avoid the sun and place the main areas toward the north, the opposite happens in the cold climate countries. The natural ventilation during the winter season can improve the indoor conditions, but during the humid days of summer, there are certain parameters to follow. In the desert areas, the building material selection must be done according to the country's conditions in order to have low maintenance costs. [74][75]

3.2 Urban Planning of Islamic Cities

The main points of this section are focused on the City Organization, Street Pattern, Identifying Buildings and Internal Open Recreative Areas.

City Organization

In order to understand the city organization the old city maps were studied. In the four cities, there is a similar urban distribution. The City organization understands the street pattern, the main identifying Buildings, open recreative areas etc.

In the case of Sanaa, the city starts from the central bazaar and expands toward the suburb. The center of the Islamic city is usually composed of the market place and the mosque. In other cases, they are separated but still in a walking distance from each other. In the case of Isfahan, the mosque and the bazaar are practically attached and from there the different neighborhoods started growing outwards. As can be seen in the case of Multan, the walled city, as well as in Fez, the walls that defended the city are the ones to determine the limits of the growth. This type of expansion, of course, is related to historical events as well as to the natural terrain conditions and to the concept of how much land a city should cover. In the case of Fez, one of the main attractions of the city is the leather elaboration circles. It's located in the edge of the North West part of the city, but it has an important economical role. [76][8]

Street Pattern

The Street pattern is connected to the way the city expanded and to the terrain conditions. Sanaa and the other three cities are characterized by narrow streets that are shaded during the day making the outdoor conditions more comfortable for the citizens. In some areas of the city the streets are parallel straight lines and in the border of the city they become curved due to the limits posed by the surrounding wall. In the case of Isfahan, the square shape of the central mosque defines the shape of the surrounding streets and then again they tend to curve to the limits of the city. Multan has more fragmented street pattern. They start from different spots that might be mosques or parks, and spread to the other centers. A similar street pattern is found in Fez. Of course the width of the streets is also related to the absence of cars and several historical traditions, but the main factor was to be protected from the sun. These four cities have similar weather conditions. This is a crucial factor that was used later on in the concept of Masdar City. An important point to be mentioned here is the H/W value that defines the shaded or the sun exposed areas. [77][78]

Identifying Buildings

As mentioned earlier, all of these factors are connected together. The street pattern is strongly connected to the identifying Buildings. In the case of Isfahan, the whole city is connected to the main Mosque. Also the bazaar has an important value as an identifying building that identifies this city. In this case, the bazaar is closed, as it is also in Istanbul. This is due not only to the climate conditions, but also to the city culture. The unique architecture that allows for natural light and ventilation gives this site a strong identifying characteristic. In the case of Multan, since it developed in the same time, it has more than one Identifying Building. It has several equally important Mosques. As for the city of Sanaa, the buildings themselves, with their special façade treatment are identifying buildings. In this case also, the bazaar is a distinguished center. In the case of Fez, the leather elaboration circles are a strong identifying site of the city. All the main streets of the city lead to this site. [79] [80]

Internal Open Recreative Areas

As for the recreational areas, such as parks or playgrounds, in this kind of cities, the concept is slightly different. In Isfahan and Multan, there are several external parks around the city. In Isfahan the central park within the territory of the main mosque is the main recreational center. On the other hand, Multan has smaller green areas, however they are important sites of the city that connect the streets to each other defining the street pattern. The city of Sanaa and Fez, are characterized by internal courts. This architectural characteristic is connected with the culture of the city and with the improvement of the natural ventilation. Small ponds and green areas where people gather and have recreational time characterizes the internal courts [81][82][83].

The city center organization, the buildings composing the core of the city and the street view of Sanaa, Isfahan, and Multan Walled City are shown in Table 2. The center of the city is very compact. The buildings of each center are different in style but they follow the same concept. They are close to each other and they create shades in the streets.

The building treatment, the facades, and the architectural details of the four cities under study from the region are shown in table 3. The buildings generally have 4-7 floors. Their façades are rich in details, showing a particular style connected to the tradition of each country. The architectural details most of the times have functional use, such as the mashrabiya window in Sanaa, or the structure of the tent above the shops in the ground floor in Multan Walled City.

Table 2: Urban Planning Analysis[84][85][86][77][87][88][76][89]

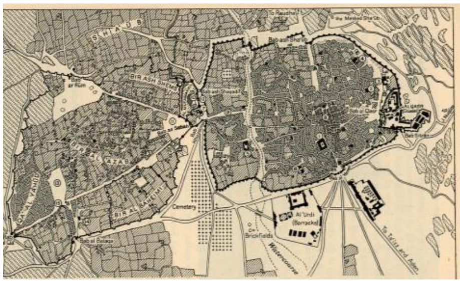
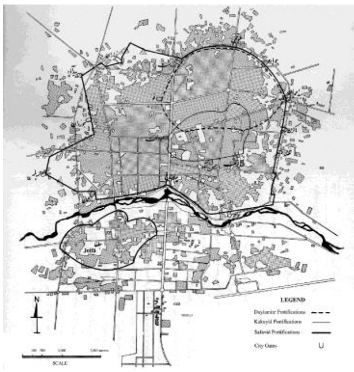
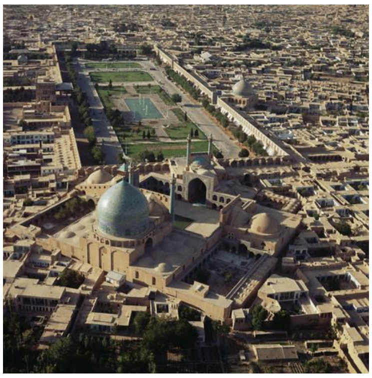
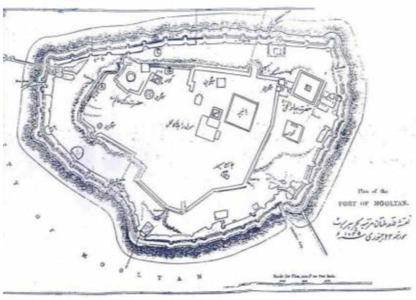
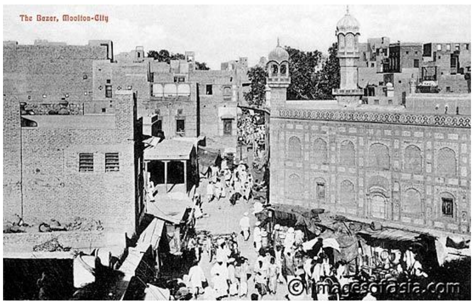
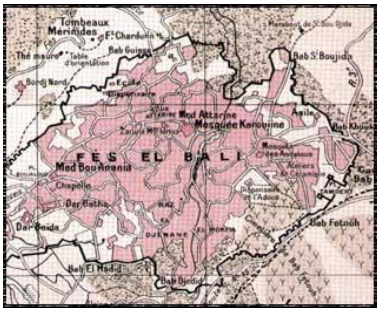
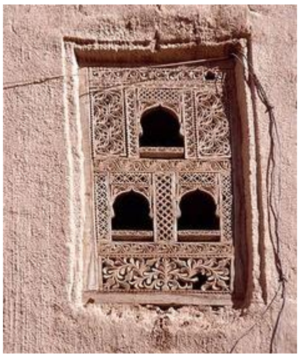
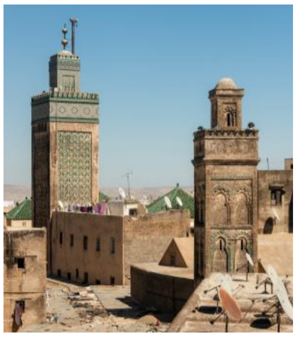
Urban Planning Analysis		
City Centre Map	City Centre Analysis	Street View
Sanaa, Yemen		
		
Isfahan, Iran		
		
Multan Walled City, Pakistan		
		
Fez, Morocco		
		

Table 3: Architectural Analysis[80][90][79][91] [92][93][94][95]

Architectural Analysis		
Building Characteristics	Façade Treatment	Architectural Details
Sanaa, Yemen		
		
Isfahan, Iran		
		
Multan Walled City, Pakistan		
		
Fez, Morocco		
		

3.3 Urban Planning in UAE

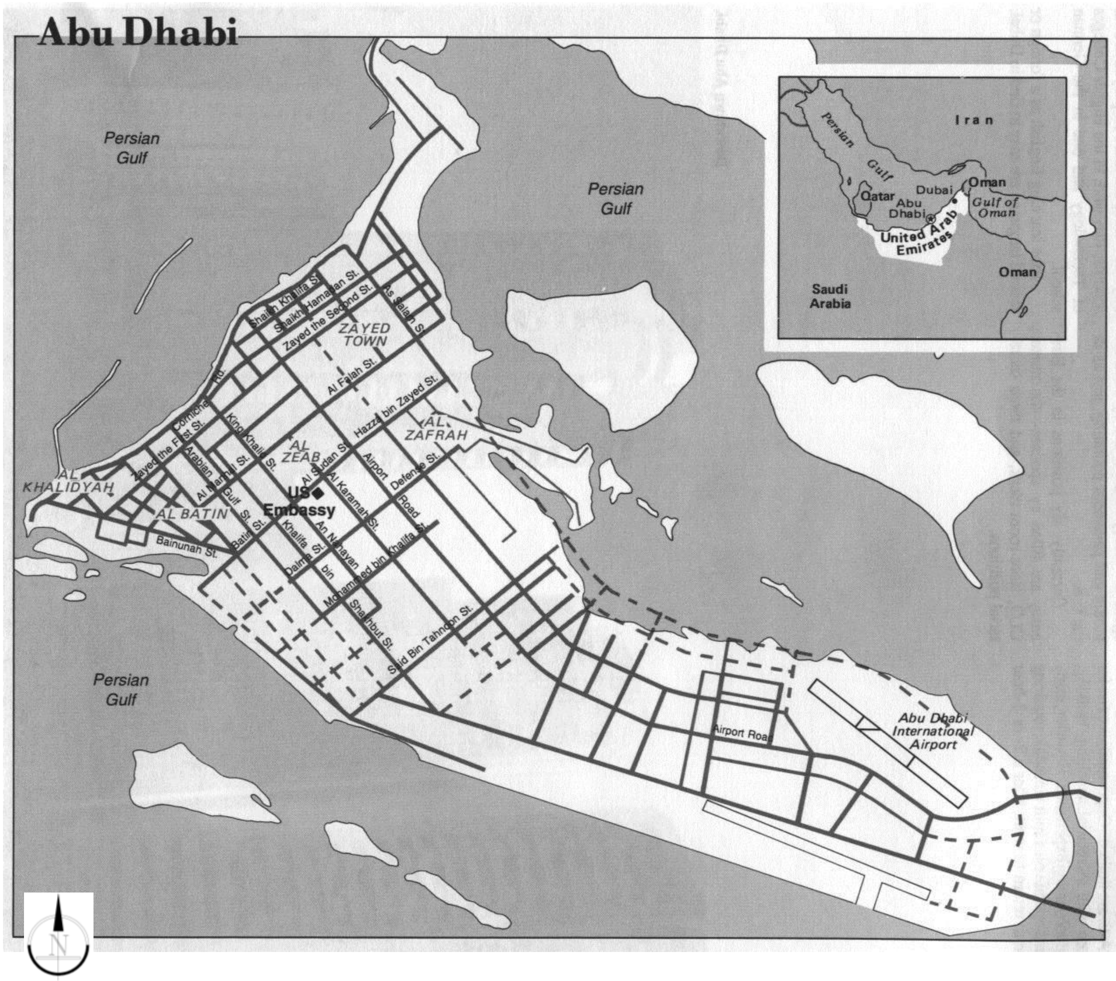


Figure 5: Abu Dhabi Map 1994 [4].

The city development

The first Masterplan that was proposed for the city of Abu Dhabi had a different concept from what is applied today. The plan was proposed by Mr. John Harris (Great Britain) in 1962, four years after the oil reserves were discovered. The plan was focused on organic development of the city with curved streets that were embracing the historic part of the Corniche area (Figure 5). However, this plan was not applied, but the concept of focusing the main lanes towards the historical area was maintained. In 1967 the USA-trained urban planner, Mr. Katsuhiko Takahashi (Japan) proposed a new Masterplan with linear roads and a main spine Airport Road, that were leading towards the historical area where the souk was located. This plan was based on a utility grid referring to the function as the main reason for such design. The main concern of the ruler of Abu Dhabi was the practical time to reach one point of the city from a certain location. This point was reflected in the Masterplan. Mr. Takahashi insisted on his concepts that were quite different from the ones developed in the region. Despite that, this plan is the basis of the street grid in Abu Dhabi today (Figure 6).

The proposed plan from Mr. Takahashi was carried out by Professor Abdulrahman Makhlouf (Egypt) in 1968, a city planner recommended from the United Nations to the ruler of Abu Dhabi. He kept the linear roads and redesigned the souk [96].

However the souk was demolished in 2005, and in place of the old structure, the Central Market was built by Fosters and Partners. Mr. Makhlouf developed the so called super blocks or districts based on the Emirati or the gulf traditional neighborhoods (Figure 7).

In each district there is a mosque where people gather to pray, there is a main lane where there are shops and restaurants, associated with the ‘’gossip lane’’ where women would gather in the evenings and talk about their day.

Each district is surrounded by high-rise commercial/residential buildings, and in the middle there are villas or low-rise buildings. This scheme associates with the distribution of the houses in the old neighborhoods where they are close to each other but far enough to have their privacy. Since the city was built in the years when cars was starting to be used in emirates, the streets between the blocks have six lanes. They isolate the blocks from each other. This division has a parallelism with the seven-house blocks divided from each other in the old Emirati neighborhoods.

The ruler of Abu Dhabi in the years when this master plan took place, Sheikh Zayed AL Nahyan, requested for the preservation of the mangrove and the keeping of the natural green areas. The new blocks were supposed to have internal parks, however, due to the rapid growth of the population all the internal areas in the districts are used as parking lots.

The Abu Dhabi 2030 plan reshapes the districts by diminishing the number of cars and improving the public transportation.

Figure 6: Boy and donkey inside the old Abu Dhabi Souk, approx. 1960, A 1950s Abu Dhabi family stands outside its traditional arish dwelling. [97]

The initial request was to prepare a city plan for 50,000 people, but the urban planner insisted on having one for 250,000 people with the possibility of expanding into Sadiyat and Reel Island. Today, the city has expanded into these areas and subsequent plans expand it even more towards the desert. Dr Makhlouf estimated that 40 percent of the population would be working in services, 30 percent in industry and shipping and the remainder as merchants.

The main architectural buildings of the city are: the Courthouse (Abdul Rahman Makhlouf 1977), the Cultural Foundation (TAC 1979), the Bus Terminal (Bulgarconsult A&E 1989), and the Municipality (Bulgarconsult A&E 1990). They represent a modernism move in the architecture of the city. The aim is to keep them as representative buildings of the modern architecture in UAE [7].

Figure 7: Qasr Al-Hosn Castle [99]

Located on Khalid bin Walid St. Abu Dhabi, Qasr al Hosn, the White Fort or old Fort, is the oldest Building in Abu Dhabi (Figure 7). The original structure was constructed in 1793 as the official residence of Abu Dhabi’s rulers, the Al Nahyan family. Today, two sectors are clearly distinguishable, the ancient fort, dating back to the time of Sheikh Saeed bin Tahnoon who ruled from 1845-1855, and a new section added in 1936 by Sheikh Shakhbut bin Sultan, brother of the late Sheikh Zayed bin Sultan Al Nahyan. Major renovations took place in 1983 and the whole Qasr Al Hosn Cultural Quarter is undergoing a large-scale redevelopment.

The United Arab Emirates covers a land area of approximately 83,000 km2, of which the Emirate of Abu Dhabi makes up about 85%. Abu Dhabi is the largest of the seven Emirates that comprise the United Arab Emirates, a nation founded by the late Sheikh Zayed bin Sultan al Nahyan in 1971. Abu Dhabi is the capital of the UAE and the national seat of the Government. Since 1971, Abu Dhabi has evolved from having no sealed roads and only a small number of permanent buildings to being one of the most important modern economic centers, both regionally and globally. This rapid growth is attributed to the wise vision of the late Sheikh Zayed bin Sultan Al Nahyan who prudently invested the Emirate’s oil and gas profits for the benefit and development of the country and its people.

The first city core of Abu Dhabi was on the main island, close to the port which was also an important economic part. As the years passed by, due to economic growth, the city started to develop within the island and then towards the desert. On the map of 1968, 1972, and 1978, this growth can be seen within the island. Starting from 1980, the city started to expand towards the desert with an initial industrial area. In 1990 and then 2015, the city went further into the southeast direction. Abu Dhabi Main Island is organized into parallel streets, creating rectangular blocks. The center of the city can be considered to be the oldest building, Qasn Al Hosn. Later on, other central areas were developed such as Al Wahda area (Table 4-5).

This Proportion creates a low H/W value, leaving the streets and the pavements exposed to the sun all day. Some of them are the malls. Due to the difficult climate conditions in the summer, the closed shopping places became recognized sites of social interaction. This was also due to the requirements of the population of Abu Dhabi.

Regarding the recreational areas such as external parks and play areas, the main island of Abu Dhabi has a lot to offer, but when scaled down to the district level, there is still place for improvement. This analysis will take place in the next paragraph. Regarding the building volumes and characteristics, the main island has large buildings due to its scale. However, several districts can be categorized, as their structures are similar to many others.

Downtown Abu Dhabi, there are many elements that can be identified depending on the period the buildings were built. An example is the structure of the main bus station that is visible to the eye. Another one is the round windows in some of the older buildings. Even though their construction time is less than 50 years, they are part of the history of the city, marking a certain decade and its architectural trend within the city. The table below shows how the city expanded from Corniche part, in the end of the main Island, towards the direction of Al Ain and Dubai.

Table 4: Abu Dhabi Urban Planning Development [98] [99][100][101].

Abu Dhabi Urban Planning Development	
Abu Dhabi 1955	Masterplan Presentation Abu Dhabi 1956
	
Abu Dhabi 1970	Abu Dhabi 1971
	

The city expansion

In an era of globalization, considering the ecosystem around a city is crucial. Planning according to the local standards and respecting the regional climate should make the city sustainable. [102][103][104]

Sustainability is strongly dependent on the decision-making process of a city council or respective institutions. In Abu Dhabi, beside the UPC-Urban Planning Council and the ADM- Abu Dhabi Municipality there is also the Environment Agency that monitors the different projects approvals and executions (Figure 8-9). [102][54][105]

Masdar City is a good example of how the decision making process can create sustainable neighborhoods. It is located in the suburbs of Abu Dhabi. The architecture is based on the old Arabic Cities. The buildings are close to each other in order to create shading in the streets and improve the life of the citizens. The façade of the buildings is based on the mashrabiya design and local material selection. It is a real case study for the future expansion of the city, specified in the Abu Dhabi 2030 Plan. [106]

The urban planning in Europe has developed over many centuries. The different ages of the city expansions are visible because of the building architecture and the typology. Abu Dhabi developed over a very short period as mentioned above. Due to this rapid construction, the authorities try to implement new technologies and softwares into the decision making process such as BIM. It Is used generally in Dubai, but Abu Dhabi is also adapting it. [107][108][104][109]

The Heat Island phenomenon connected to urban development plays a crucial role not only in the reduction of the air temperature but also in the cooling load of the buildings and the health of the citizens. The more the area near the cities is urbanized the more the UHI phenomenon is present and visible. There will be a dedicated topic on this subject in the following chapter. Such phenomena influence not only the life of the citizens, but also the cooling load of the buildings. [37]

In the development of Abu Dhabi, the authorities pay a great attention to the use of the different materials such as the concrete, glass, insulation, street tiles etc., in order to reduce the negative effects the characteristics of the materials might bring in the development of the city. [110][111][112]

Table 5: Abu Dhabi Urban Planning Analysis [113]

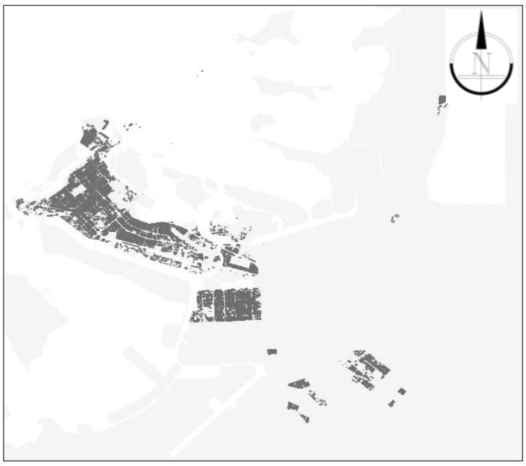
Urban Planning Analysis	
1968	1972
	
1978	1980
	
1990	2005
	

Figure 8: Abu Dhabi City Urban Plan 2015. [113]

Figure 9: Abu Dhabi City Map 2016.

The local standards

Some of the standards and Policies related to Urban Heat Island Effect and Mitigation Strategies in UAE are: Leed Approach, Estidama Approach, Abu Dhabi Municipality Guidelines, and Urban Planning Council Policies.

Abu Dhabi's Plan 2030 establishes a clear vision for sustainability as the foundation of any new development occurring in the Emirate and capital city of Abu Dhabi. This commitment is a reflection of the values and ideals of our nation. The tenets of sustainable living in the Middle East are the guiding forces behind Estidama. More than just a sustainability program, Estidama is the symbol of an inspired vision for governance and community development.

It promotes a new mindset for building a forward thinking global capital. To establish a distinctive overarching framework for measuring sustainability performance beyond the usual planning and construction phases, UPC has worked with the team, guiding Estidama to ensure that sustainability is continually addressed through four pre-defined angles: environmental, economic, social and cultural.

The purpose of Estidama is to create a new sustainability framework that will direct the current course while allowing adaptation as new understandings evolve. By promoting a new sense of responsibility with Estidama, UPC is going beyond other sustainable development initiatives around the world, by creating new tools, resources and procedures crucial to the 2030 vision. [55]

3.4 PET

Physiological equivalent temperature (PET) is an index that measures the thermal comfort of a human body. It is defined to be as a standardized person with a work metabolism of 80W of light activity, in additional to basic metabolism and 0.9 clo of heat resistance because of clothing. The different levels of PET vary according to the levels of temperature into: very cold, cold, cool, slightly cool, comfortable, slightly warm, warm, and hot. [114][35]

There are several studies done on the outdoor thermal comfort and the conditions that improve it. The urban design and the attention paid to the internal spaces is connected to such parameter. The impact of the building environment is different in different climates. There are several softwares developed to improve such parameters such as RAYman, which is mainly used in this research to process the air temperature, wind speed, relative humidity, and mean radiant temperature measured in the real site downtown Abu Dhabi. (table 6) [115][35]

Other softwares used in calculating and simulating the PET are : ENVI-met, Fluent etc. Despite the defects that the software has in calculating the mean radiant temperature, the results of the PET before and after an intervention are close to the real measured data. Several different studies show the effect of the vegetation and shading. The PET can be decreased by several degrees in hot arid climate. The wind analysis is also an important factor in these CFD softwares and impacts the PET results.[34] [116]

As regards a research conducted in Shanghai, an increase of 0.4 in the ground surface albedo generally reduces the thermal comfort by 5-7°C in PET. The tree canopy can reduce daytime PET by up to 15°C if dense. The measurements are done in two different residential areas and the models are developed with ENVI-met. The effect of the vegetation has a bigger impact on reducing the PET than the cool surfaces.[117]

The Green areas impact on the improvement of the outdoor thermal comfort is analyzed in the city of Hong Kong. From the measurements taken, it is shown that the green roofs can reduce the air temperatures of the district by 0.4-0.7 °C. This improves the outdoor thermal comfort and also reduces the energy use of the buildings analyzed in this research.[118]

Several studies focused on human behavior towards outdoor thermal conditions. The perception of different people and their physiognomy is the one to define the personal outdoor thermal comfort.

In a research done in Athens during summer, the use of architectural solutions to improve the OTC by an average of 6% was shown. Another research done in Algeria during the summer season showed that the PET under the trees in a canopy are several degrees lower than the same scenario without trees. The air temperature could be reduced by 1.5°C. [119][120]
A study done in Fez, Morocco showed that the air temperature in the narrow streets of the city have a difference of 6-10K from the shallow areas. This showed that during the summer the narrow areas of the city were more comfortable for the inhabitants to walk in. (table 6)[121]

Table 6: Physiological equivalent temperature (PET) ranges. Internal heat production 80W, heat transfer resistance of the clothing 0.9 clo. [35]

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

3.5 The temperature step

The outdoor thermal comfort is a parameter connected to the human health. Several studies have been done on the impact that different outdoor measurements have on reducing the PET values. However, few studies have been done on the impact that the difference of temperature from one environment to the other might cause to the human health. The temperature steps have a higher importance in extreme climates such as the summer in Abu Dhabi.

During this period the human body makes changes to accommodate the new thermal conditions. This adaptation phase causes body stress that has side effects on long term human health [122][123]and sometimes the multiple temperature steps might cause hypertension. [44]

In A study done in Shanghai, the large difference between the indoor and outdoor air temperatures is connected to high risks of discomfort in the nervous system, digestive system, respiratory system, skin and mucous membranes. [124]

Xiong et al. (2015) studied different potential indicators connected to the effect of the temperature steps on human health and thermal comfort. These parameters, psychological and physiological (oral and skin temperatures, blood oxygen saturation, respiration rate, hear rate, heart rate variability) change due to the temperature step. They have variations depending on the intensity of this change. According to this study, the down-steps might be more serious than the up-steps. [125]

The focus is on the thermal perception and skin temperature in different transient thermal environments. According to the study, about 45 minutes is needed for the skin temperature to become steady after down-steps. The human body has psychological and physiological adaptations to the environment. The thermal sensations are subject to asymmetry and are significantly larger after up steps. The main parameters considered in this study are the thermal perception and the skin temperature. Other studies show that the skin temperature and its variations have an impact on the thermal sensation. The self-reported health symptoms and fatigue after step changes are not studied as the thermal comfort, however the authors concluded that perspiration, eyestrain, dizziness, accelerated respiration and heart rate are sensitive self-reported symptoms to the temperature step changes. The human subjective perception is also influenced by the temperature step. The human response is asymmetric on the temperature steps of equal magnitude. According to this study, it takes longer for the skin temperature to reach stability after a higher magnitude of steps, although it's not precise to use it directly for the prediction of thermal perception (Figure 10). [126]

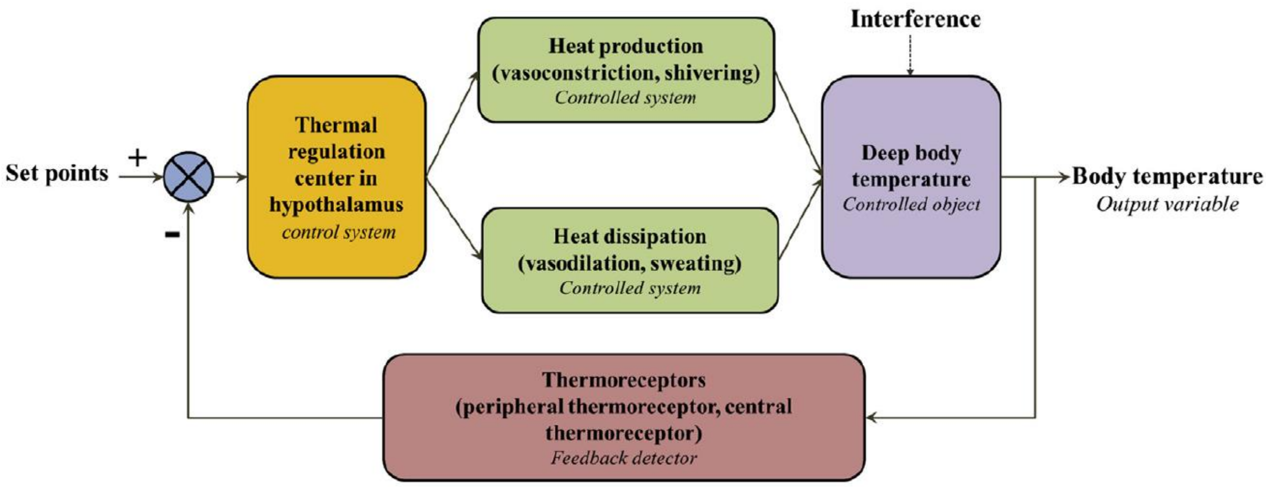


Figure 10: The temperature step effect on the human health. [122]

3.6 Five Districts Analysis.

Five Districts Downtown Abu Dhabi.

The districts downtown Abu Dhabi are parts of a larger district, but the comparison is done partially on the smaller scale and partially on the larger scale. Each district can be seen as a scaled down city. Some of the main characteristics of a city are integrated in the districts as smaller representative units. While in the two districts from the main island, the center can be considered to be the Mosque, there are no internal parks that can serve as centers for outdoor life. However, in the first case, the street pattern is linear as well as in the other two cases.

The building characteristics vary from one district to the other. Some of the buildings in the districts downtown Abu Dhabi, even those built at almost the same time, refer to the architecture of old Emirati Neighborhoods. The façade of each building as showed in the views below is highly energy efficient, contributing to the decrease of the cooling load. On the other side, each element such as the mashrabiya, the proportions of the floors and the connection between the buildings gives to this block an identifying characteristic. The facades of the buildings in the other districts downtown as showed in the side view are quite simple, without any identifying elements. Some of the units change their use after being constructed, making the district change its initial purpose of mixed use. In the other two districts, some treatments of some balconies, few arcades and the rest of the treatment is very basic.

Figure 11 shows the location of the five districts taken into study.The villa district and the mod-rise building district are located in the sides of the second half of the main island. The villa district is affected by the wind coming from the east and the mid-rise building district is affected from the wind coming from the west side of the island. The three remaining districts are located downtown where the built ups area is more dense. The table 7 analyzes the district areas, pavement, green, shading quantity etc. Meanwhile table 8 quantifies the facades of the buildings. Table 9 makes an analysis of the space in each district by pointing out the road system. Table 10 has pictures of each district from the district center and the street view showing the distance between the buildings. Table 11 has the cross section of each district showing the difference of height and the canyon section. Table 12 has images from the site of the five districts focusing on the building typology and the architectural details. These images are quite different in terms of cultural identity to the ones shown in the second chapter from different cities around the region.

Figure 11: District location.

Table 7: Five districts characteristic.

Description	District 1	District 2	District 3	District 4	District 5
Typology	Villas	High Rise Buildings	Medium and High Rise Buildings	Medium Rise Buildings.	Villas and High Rise Buildings.
No. of Buildings	68	48	70.00	81	69
Max Floor No.	4	49	20.00	5	22
Min Floor No.	1	9	5.00	3	3
Max. Border Dimensions (m)	414x289	464x328	582x331	401x341	406x414
Total Area (m^2)	120.000	151.000	193.000	136.000	162.000
Building Area (m^2)	28.000	27.000	46.000	31.000	27.000
Building Area in %	23	18	24	23	17
Asphalt Area (m^2)	27.000	85.000	93.000	52.000	95.000
Asphalt Area in %	23	56	48	38	59
Paved Area (m^2)	63.000	38.000	53.000	52.000	39.000
Paved Area in %	53	25	27	38	24
Green Area (m^2)	3963	NA	NA	1783	NA
Green Area in %	3.31	NA	NA	1.30	NA
Existing Shaded Area (m^2)	NA	NA	NA	NA	NA
Proposed Shaded Area (m^2)	NA	NA	NA	NA	NA
Existing No of Trees	151	NA	24.00	54	79
Proposed No of Trees	NA	NA	NA	NA	NA

Table 8: Five districts characteristic 2

Description	District 1	District 2	District 3	District 4
Typology	Villas	High Rise Build-ings	Medium and High Rise Buildings	Medium Rise Buildings.
Area of the façade (m^2)	219.000	332.000	219.000	118.000
Total perimeter (m)	4.000	4.000	4.000	8.000
Average H (m)	44	70	44	14
Average A (build area, m2)	415	568	666	394
W (m)	22	32	27	21

Table 9: Five districts street pattern.

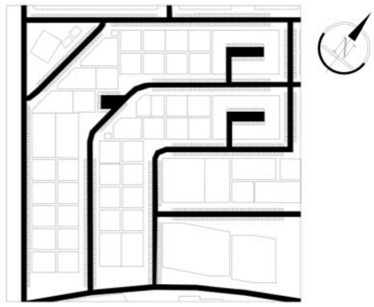
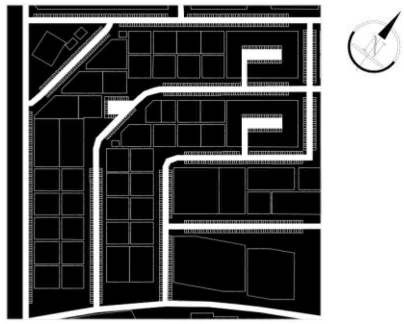
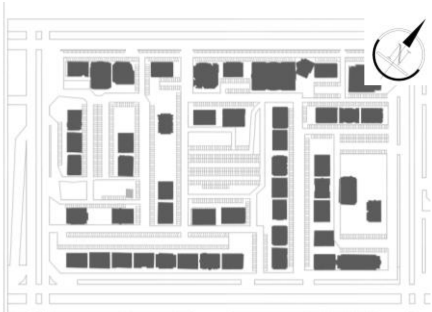
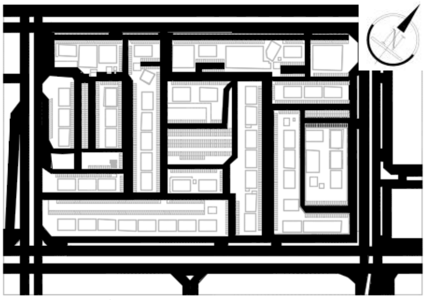
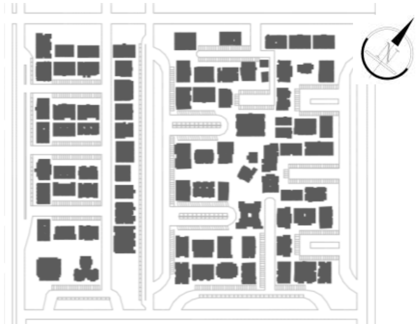
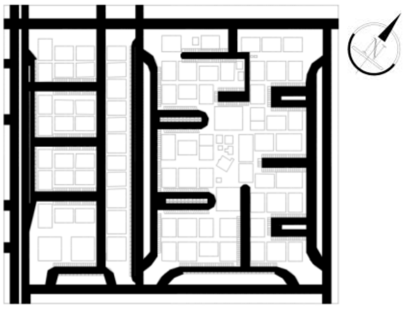
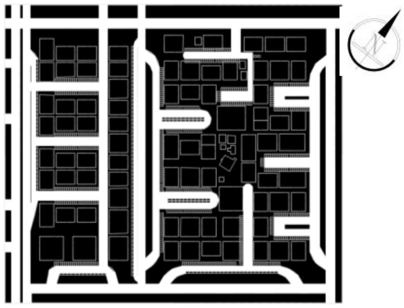
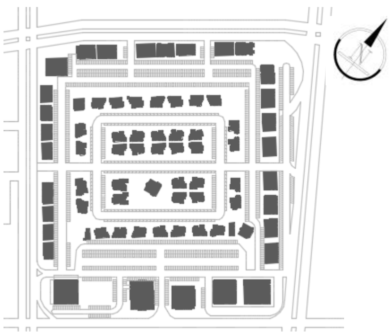
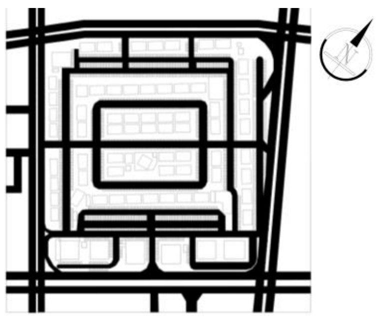
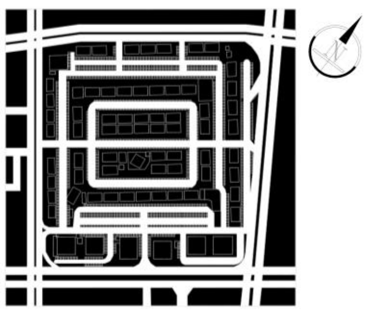
<table>
<tr><td colspan="3">URBAN PLANNING ANALYSIS-E3 (scale 1: 500)</td></tr>
<tr><td>The building footprint</td><td>The street pattern A</td><td>The street pattern B</td></tr>
<tr><td colspan="3">District 1 - Villas</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">District 2 – High Rise Buildings</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">District 4 – Mid-Rise Buildings</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">District 5 – High Rise Buildings and Villas</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

Table 10: Site observation, five districts.

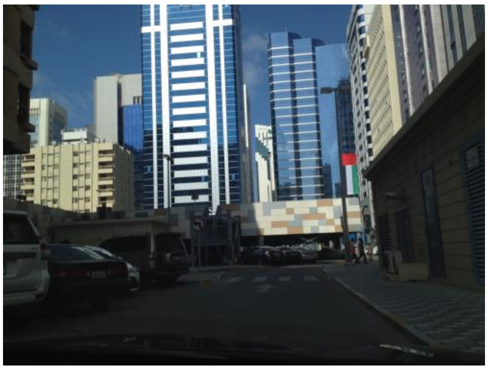
Urban Planning Analysis	
The district center	Street view
District 1 - Villas	
	
District 2 – High Rise Buildings	
	
District 4 – Mid-Rise Buildings	
	
District 5 – High Rise Buildings and Villas	
	

Table 11: Five districts Cross Section.

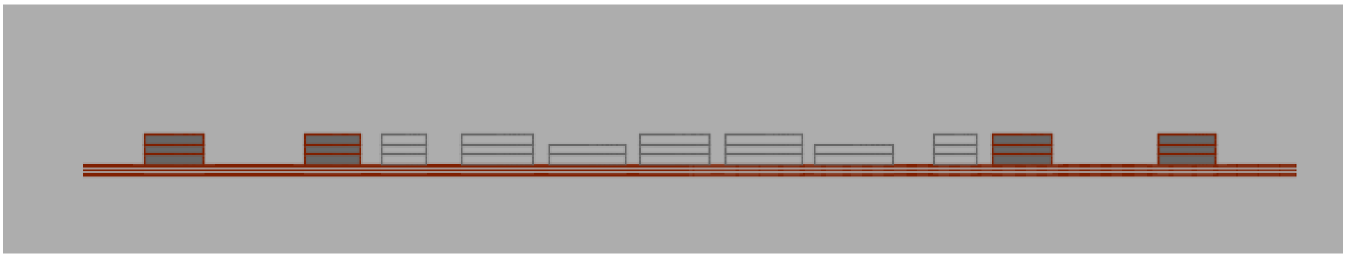
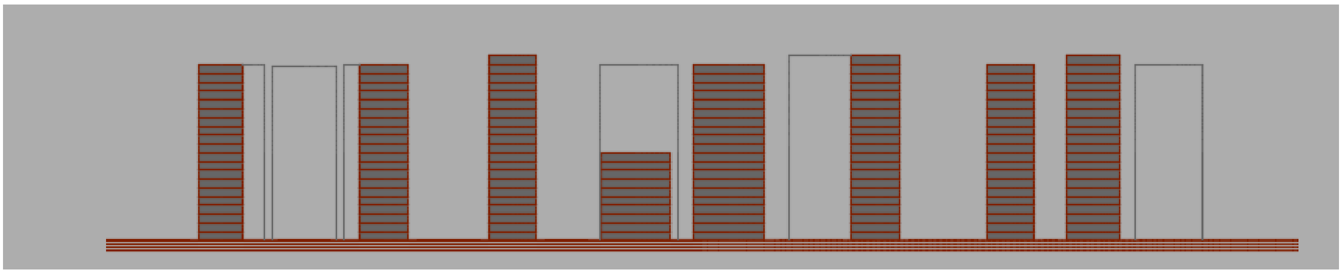
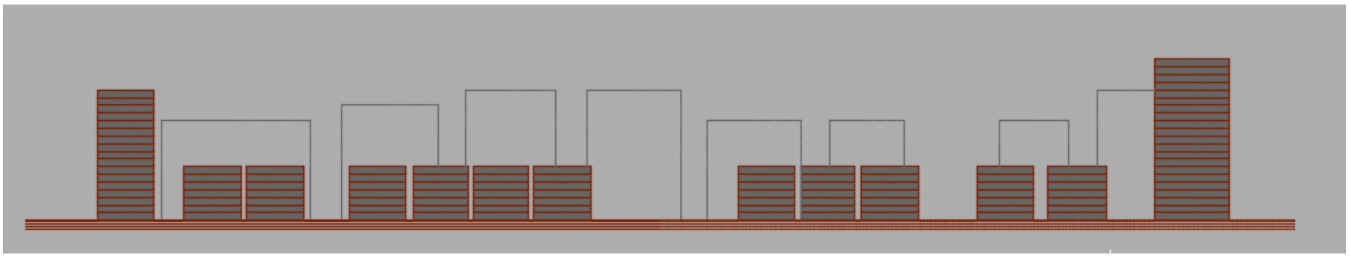
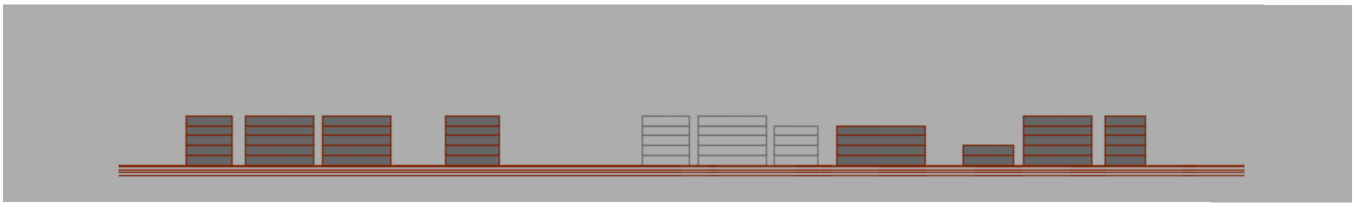
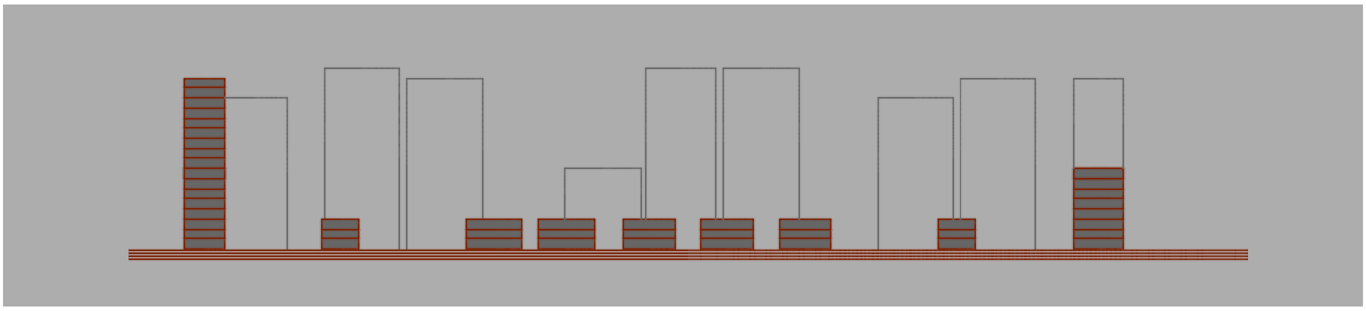
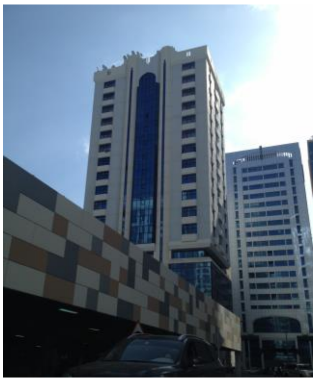
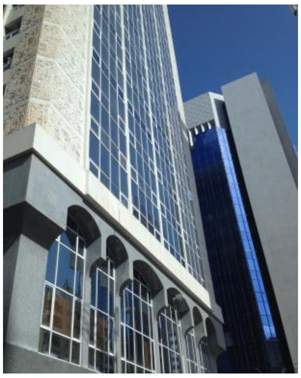
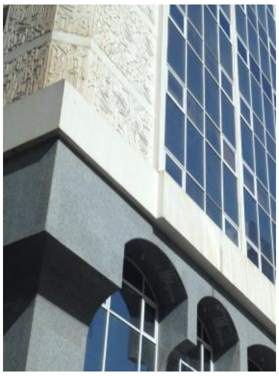
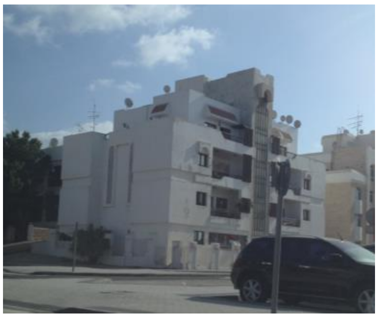
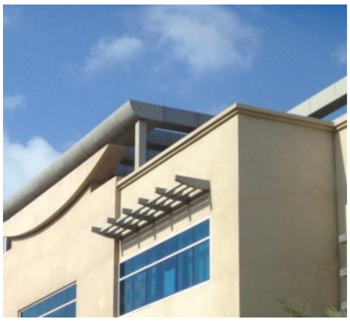
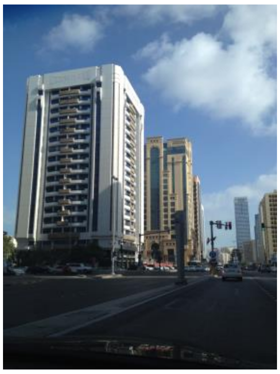
District Section (scale 1:500)
District 1 - Villas

District 2 – High Rise Buildings

District 3 – High Rise and Mid-Rise Buildings

District 4 – Mid-Rise Buildings

District 5 – High Rise Buildings and Villas


Table 12: Five Districts architectural Analysis thru images.

ARCHITECTURAL ANALYSIS		
BUILDING CHARACTERISTIC	FAÇADE TREATEMENT	ARCHITECTURAL DETAILS
District 1 - Villas		
		
District 2 – High Rise Buildings		
		
District 4 – Mid-Rise Buildings		
		
District 5 – High Rise Buildings and Villas		
		

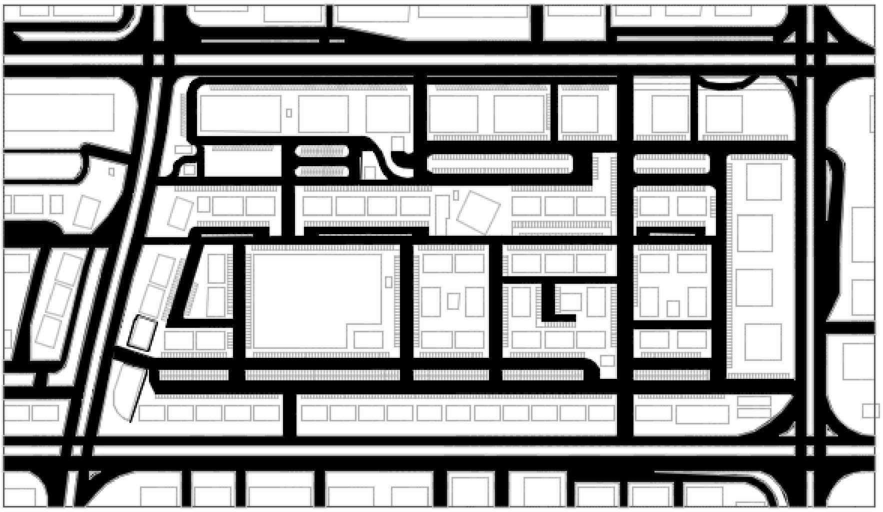


Figure 12: Street network analysis.

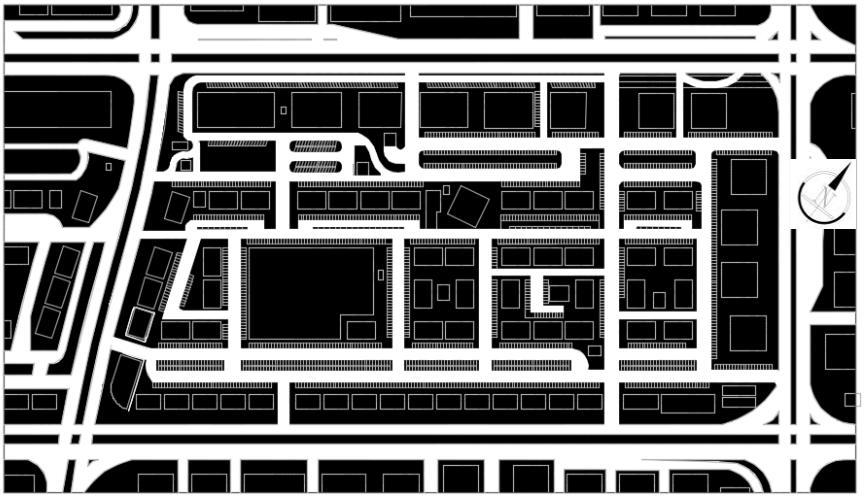


Figure 13: Building footprint analysis.

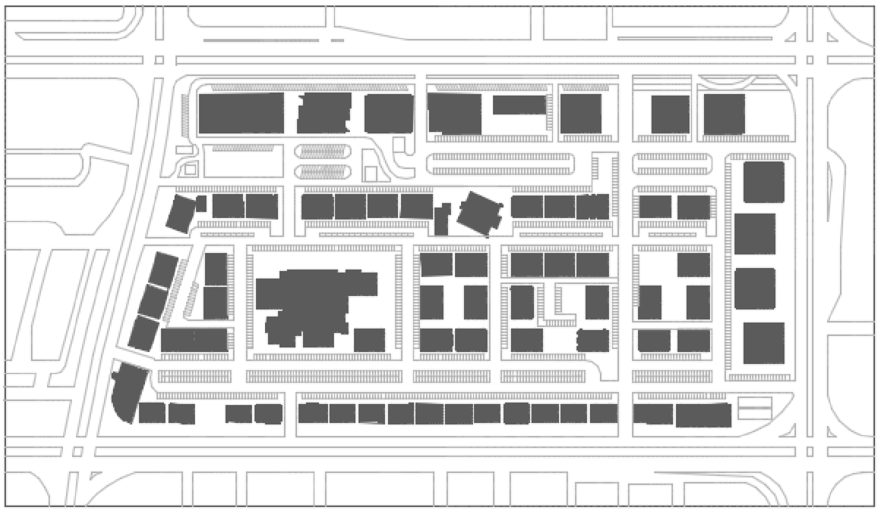


Figure 14: Street network analysis.

Table 13: Current and Improved District Conditions

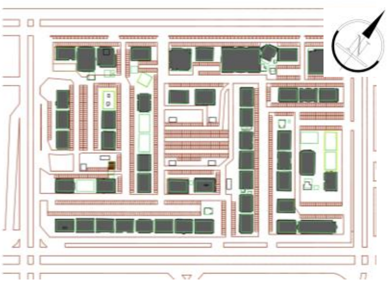
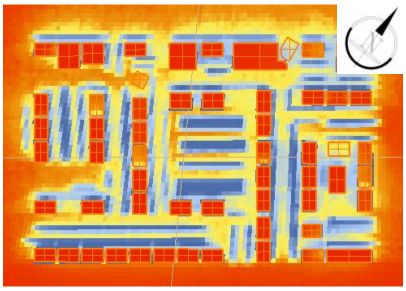
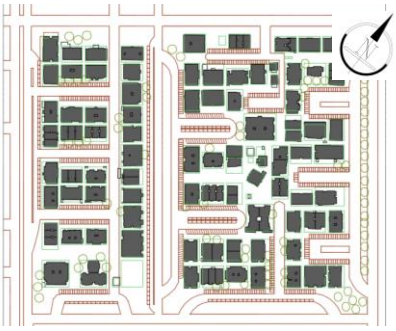
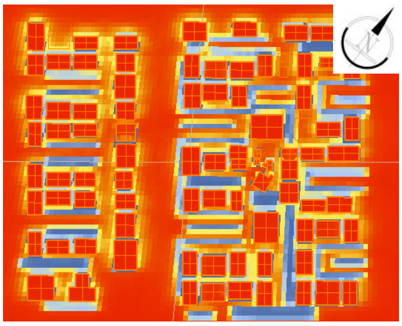
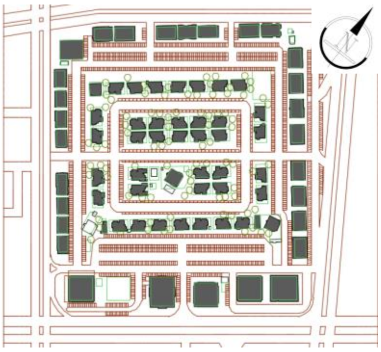
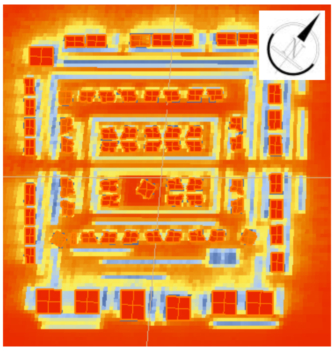
Current and Improved Conditions Plan		
Current Conditions	Proposed Intervention	Solar Radiation Analysis (scale: 218-2188 kWh/m2)
District 1 - Villas		
		
District 2 – High Rise Buildings		
		
District 4 – Mid-Rise Buildings		
		
District 5 – High Rise Buildings and Villas		
		

Table 14: Architectural Analysis E3

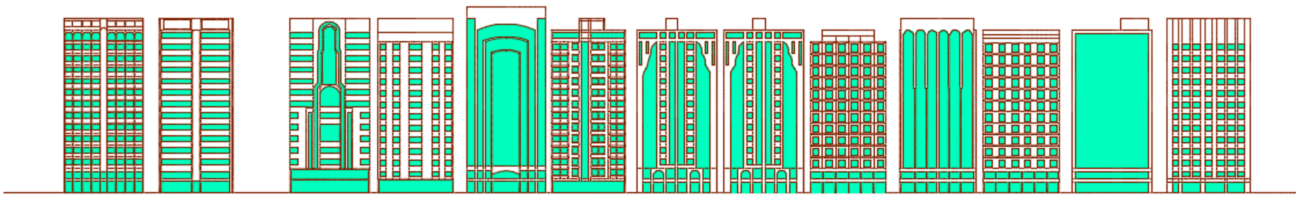
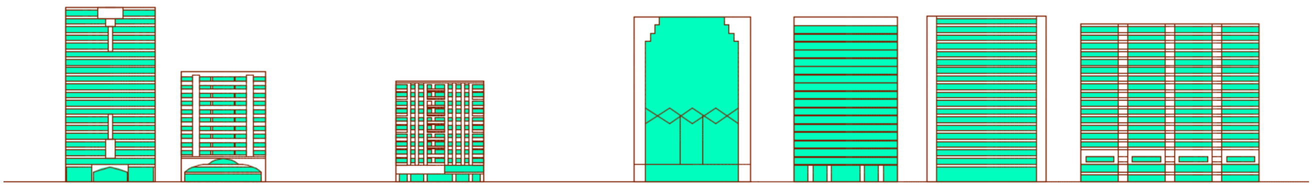
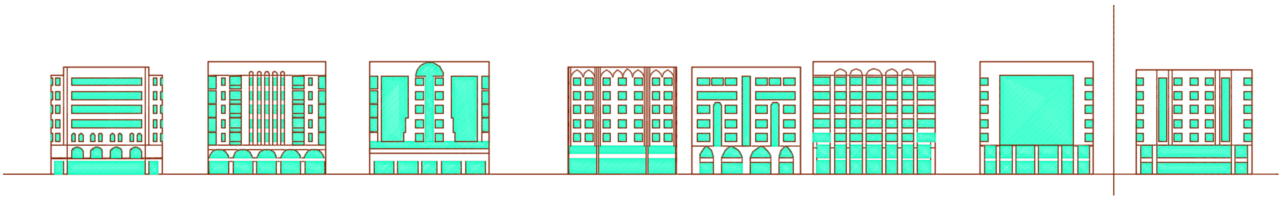
<table>
<tr><td colspan="3">Architectural Analysis</td></tr>
<tr><td colspan="3">South District Main Facade</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">North District Main Facade</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">South District Internal Facade</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Building Characteristics</td><td>Façade Treatment</td><td>Architectural Details</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

Figure 12-14 shows a detailed plan of the space between the buildings and the street network in black and white to understand the differences better. Table 13 shows the current and the improved conditions of the five different districts. It also shows the solar radiation in these districts. It is an analysis that is done to understand the areas that need to have shading and trees. Table 14 has façade section of the district E3 from the main orientations. It shows the glass surface and the building height.

Building Typology

The history of the use of prefabricated elements in residential buildings is very long and is spread all over Europe, USA and Asia. The prefabricated buildings can be connected to the architectural evolution the industrial design development. Forty decades ago, the world felt the effects of the first oil crisis. Since this time, there was a growing concern about energy efficiency questions, climatic changes and environmental problem issue. The buildings in Abu Dhabi have different energy performance depending on the year of the construction and the materials uses for the construction (figure 15).

Construction techniques are evolving with development of new materials. Prefabricated panels are being increasingly used in residential buildings. There are a various reasons connected to this. The sustainability in terms of wastage and management, and the energy efficiency improvements in the production and mounting phase make the use of prefabricated panels to increase in the emerging countries.In the UAE construction market the life cycle of the materials is analyzed under the credentials of Estidama. This rating system supervised from the UPC (Urban Planning Council) is contribuiting into the recycling process of the buildings that are being demolished downtown Abu Dhabi.[127]

Construction waste is considered to be one of the main factors affecting the environment. Construction waste is defined as the by-product generated and removed from construction, renovation and demolition workplaces or sites of building and civil engineering structures. With the increasing demands in implementing major infrastructural projects, together with many commercial building and housing redevelopment programmes, a large amount of construction waste is being produced. Existing works have proposed various waste management approaches. By the use of the prefabricated panels, this waste is reduced significantly. The new technologies of production and mounting make these panels to be energy efficient and sustainable from the management point of view. It is not only the trend or modernism, but also the requalification of a technology that vanished for many years

Figure 15: Year of Building Construction.[106]

3.7 Urban Microclimate

Urban planning is strictly related to the urban microclimate. The solar radiation, the wind flow, and the relative humidity can be modified depending on the typology of the buildings, their dimensions, orientation, location and relation with the circulation and traffic, the landscape between the buildings etc. The local climate can be modified by such interventions and the anthropogenic heat released into the canyons of the different districts of the city.[128][129][130]

Since the first draft of an urban plan, the main points of reference are the north and south, and the wind rose. This is in order to improve the relation of the citizens to orientation of the sun and the wind flow to improve the natural ventilation. The size of the city and the density of the buildings have different impacts on the microclimate. In megacities, this relationship between the build environment, internal parks, and traffic has a bigger impact on the microclimate changes. [24][131][132]

There are several studies analyzing the orientation of the buildings in a certain urban environment in order to study the impact that they have on the microclimate. Simulations of this relationship with CFD softwares include all the parameters that are considered in the real conditions. [133][134][135]

The modification of the microclimate can be detected also from the satellite images. The change of the air temperatures and wind speed can be detected on high resolution maps. Several tools are used to estimate these changes and predict the impact of different UHI mitigation strategies on microclimate changes**.**[136][137]

Abu Dhabi Climate

A short introduction to the climate of Abu Dhabi:

The Emirate has hyper-arid climatic conditions, with hot and dry summers, and mild to warm winters with meager, sporadic rains. The climate plays a central role in determining the evolution and changes of the land surface. The topography of the Emirate is dominated by large sand dunes that in certain places exceed 250m and are among the largest in the world, interspersed with sparsely vegetated interdunal plains. Geologically, the Emirate of Abu Dhabi and adjacent areas have been relatively stable over, with the oldest exposed rocks in the emirate occurring in Jebel Dhanna. As a result of a rapidly expanding population and a consequent increase in the consumption of natural resources, the Emirate is facing environmental degradation. Soil, a vital part of the environment, has a key role in different interactions, linking the atmosphere, water resources and land use. Protecting the activity of the soil to support agriculture, forestry, wildlife and other uses is an important part of a wider effort to conserve the environment and to promote the national economy.

A Dry Bulb (Db) Temperature

The temperature of Abu Dhabi Emirate noticeably fluctuates during the year. The monthly mean Db temperatures have lowest values of 18-19°C in January and February and then rapidly rise between March to May. The rise in temperature continues in May and June, but at a slower rate, to reach the peaks of 34-38°C in July and August. The temperature then declines to 20.5-21.6°C in December. This distribution in temperature roughly exhibits the seasonal changes; it presents December until mid March as the cold period (winter season) and the second half of June through September as the hot period (summer season). It also presents the two periods in between the winter and summer, as the transitional periods of spring and autumn respectively. The diurnal range is smaller during the winter (9.6 to 12.5) and summer (11.0 to 14.9) while it reaches its peaks of 13 to 17.6 and 12.2 to 15.0 during the transitional periods of spring and autumn respectively. The highest peak occurs in May because of the occasional outbreak of the “The summer 40 days Shamal” cool flow. Comparing these values of the diurnal range with the annual range of the daily mean temperature of 0.2- 7.4°C leads to one of the hallmarks of the temperature regime in the tropics: in the tropics, the diurnal range is great and the seasonality is reduced with no well-identified four seasons. The noticeable fluctuations in the temperature can be attributed to the outbreaks of the cool northwesterly ('Shamal') wind that is often interspersed with warmer southeasterly ('Alkaus') wind, especially in winter. But in the non-winter months, the contribution is mainly confined to the local land-sea circulation and to the nature of the land surface. The land-sea breeze strongly impacts the temperature regime of the area. The afternoon northwesterly sea breeze being cooler, ceases the rapid rise of temperature, generally for places along the coastal fringe. Days with the highest record of temperature along the coastal fringe are those when the sea breeze delays, leaving the very hot land breeze from the Empty Quarter, 1-2 hours after 9 GMT. This very short delay is enough for the southeasterly land breeze to cause an abrupt temperature jump. In the interior area, out of the sea breeze horizontal extent, the static weather systems and the intense surface heating of the sandy desert keep summer-time maximum temperature most often above 45°C as can be noted in figure 16 below. This figure presents the monthly statistics of the extreme temperature. In this figure, the maximum temperature exceeds 45°C between April and September, and reaches near 50°C in June, July and August in the southwest area. The extreme minimum temperatures occur during winter nights after the weakening of the cold Shamal wind.

Values of extreme minimum temperatures below 0°C are not strange, especially in the interior of the southwest area, within the Empty Quarter, as the clear skies, combined with higher reflectivity of the sandy surface increases the nocturnal cooling (figure 16).

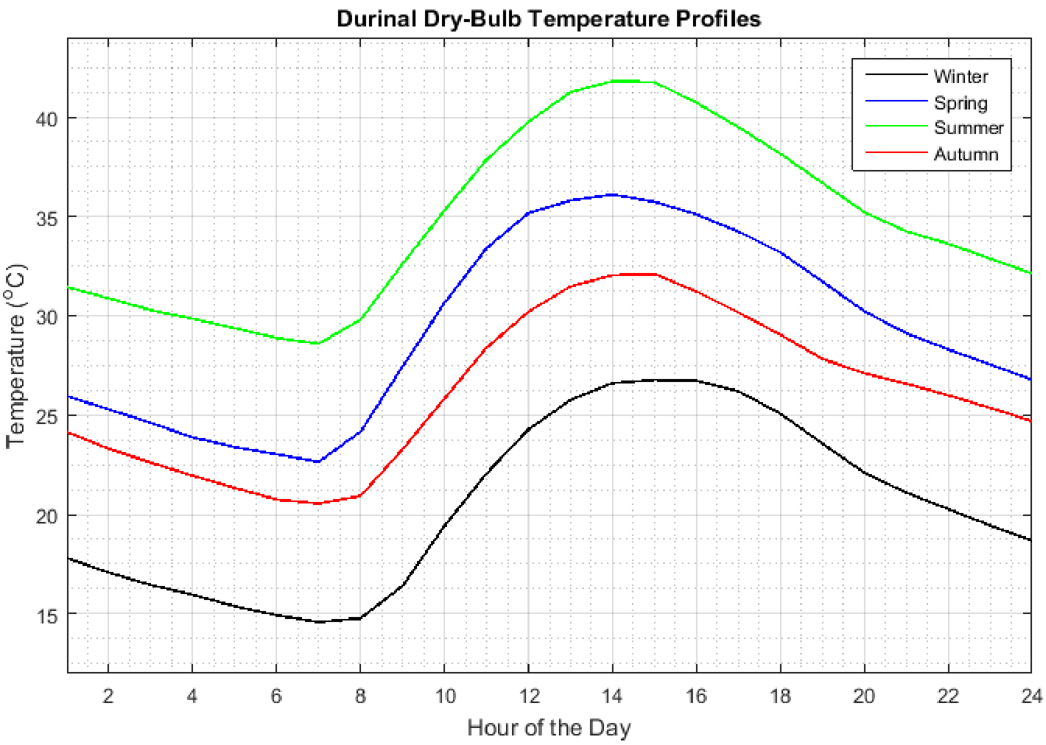


Figure 16: Diurnal Dry-Bulb Temperature Profiles for the characteristic equinox and solstice days (for 2015: 20 March, 21 June, 23 September, 22 December).

Relative Humidity

The daily mean of the relative humidity behaves similarly during most days of the year. The humidity gradually increases a few hours after midday to reach values of 70-80%. It then declines to 35-50% by midday hours. The values during winter are 10% higher than those during summer. Along the coastal strip, the values are higher than the inland area by 10-20% depending on the intensity and depth of the afternoon sea breeze. An increase in humidity increases the feel of the temperature (called Effective Temperature). Generally, the most intolerable weather condition periods are those when the humidity is above 70% and temperature above 35°C (figure 17).

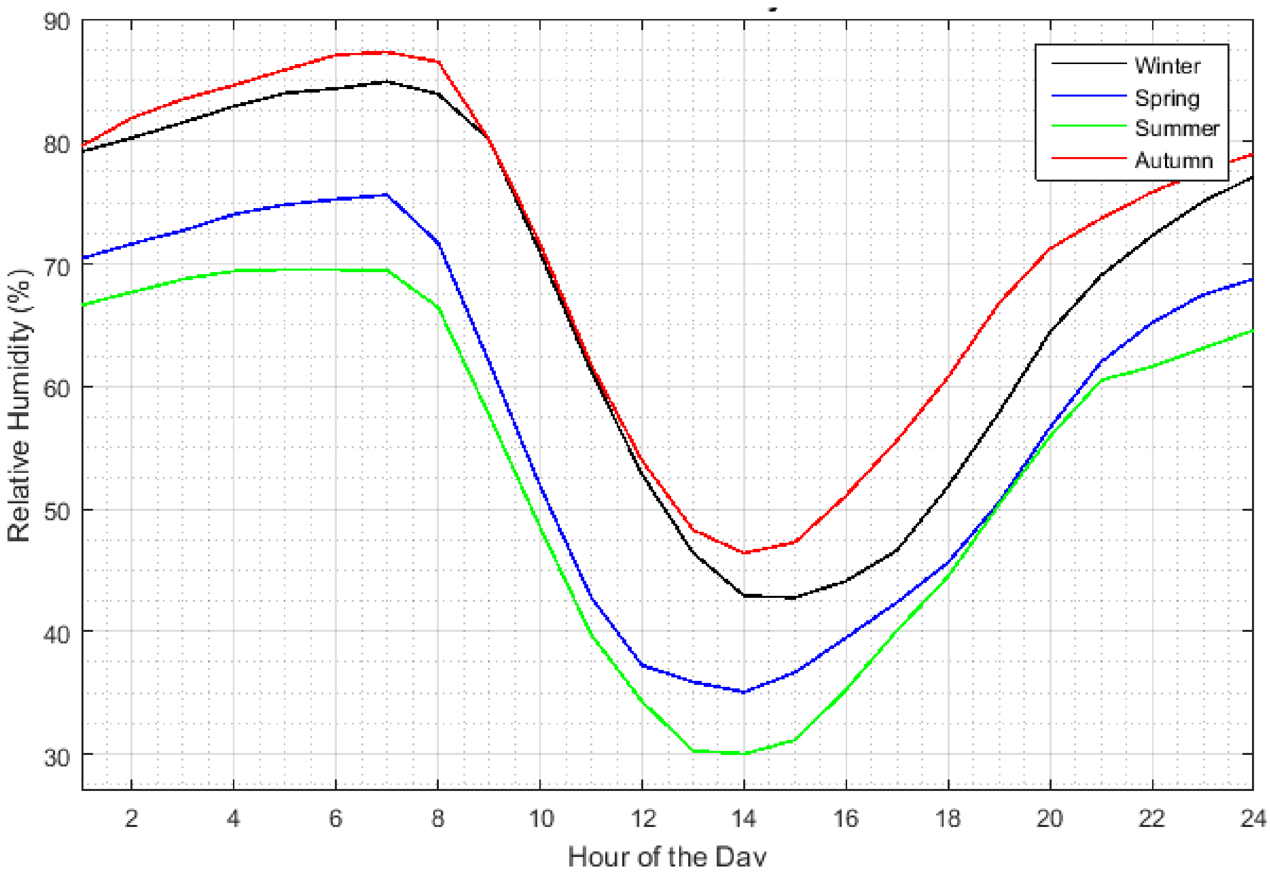


Figure 17: Diurnal Relative-Humidity Profiles for the characteristic equinox and solstice days (for 2015: 20 March, 21 June, 23 September, 22 December).

Sunshine and Solar Radiation

In the UAE, the longest day is the 21st of June and the shortest is 21st of December. On the 21st of April and 22nd of September, the day and nights are equal. The monthly mean of the daily sunshine hours slightly differs from the astronomical day length (the time between sunrise and sunset), because the sky is mostly cloud free and its effect on sunshine is very slight. The monthly mean of the daily sunshine hours is similar all over the Emirate, and ranges between 8.4 hours in winter, to 11.6 hrs in summer. These values accumulate total sunshine hours of about 3,600 hours per year, which is among the highest in the world. Referring to the climatic atlases published by the WMO, the Arabian Peninsula and the African desert are the two areas that receive the highest amount of the incoming solar radiation.

Wind speed and direction

The several wind regimes that dominate the area are briefly discussed below. The statistical description of the wind direction and speed is given in Figure 18. The selected stations were ADIA to represent a coastal area, Al Ain as inland area, and Abubukhoush (ABK) offshore oilfield in the west, for comparison. From these three wind roses, it is clear that NNW flow is the most prevailing direction. The NNW represents about 47% for ABK, 36% for ADIA and 30% for Al Ain. Also Wind from quadrant two, around the South is remarkably noted in Al Ain as a direct effect of both the Alkaus and the Southwest monsoons. The contribution from South-Southeast breeze is, of course, very small in Abulbukhoush, whilst fairly contributing in ADIA. In general, the most prevailing wind direction is from the northwest (figure 19-20).

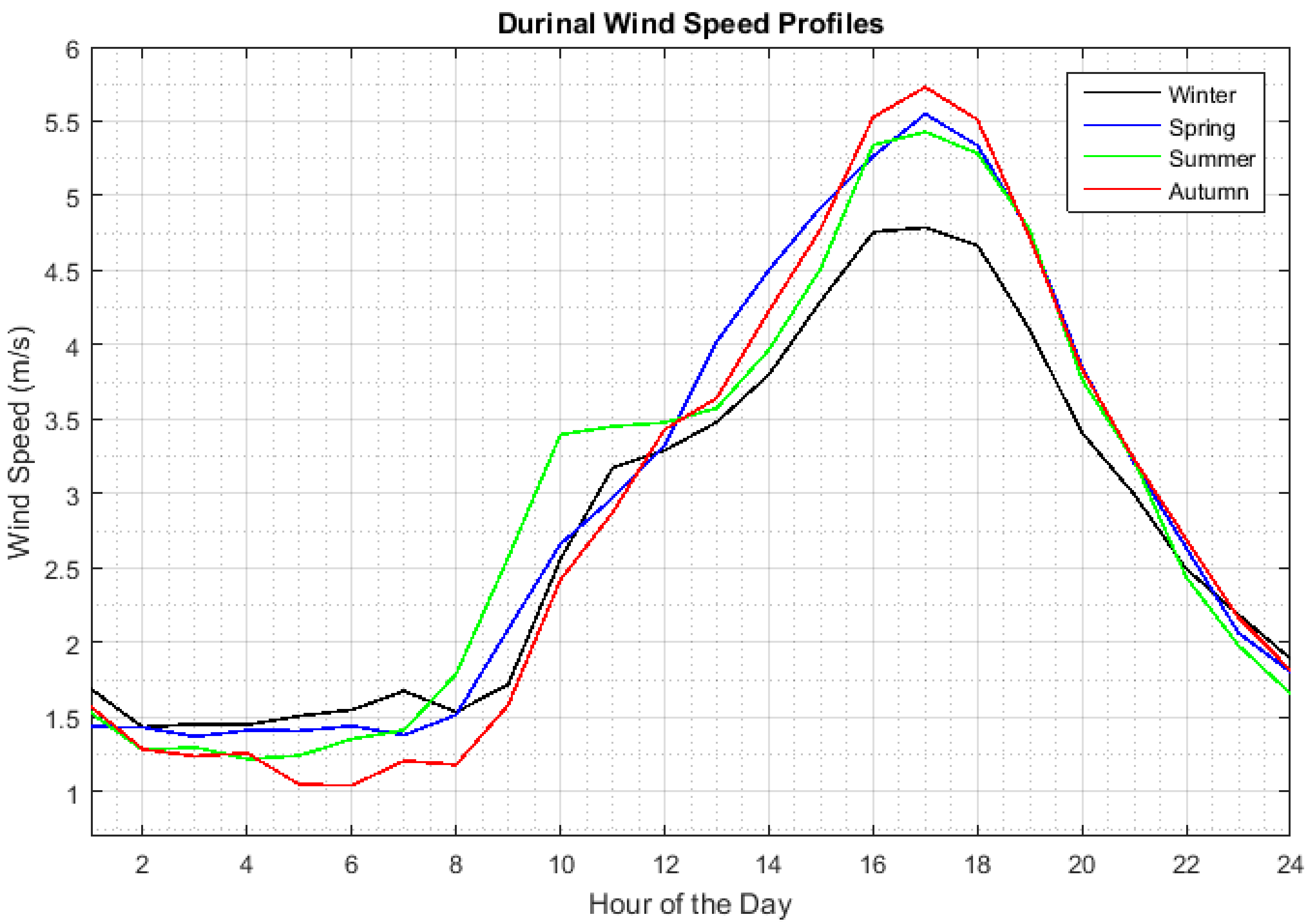


Figure 18: Diurnal Wind Speed Profiles for the characteristic equinox and solstice days (for 2015: 20 March, 21 June, 23 September, 22 December).

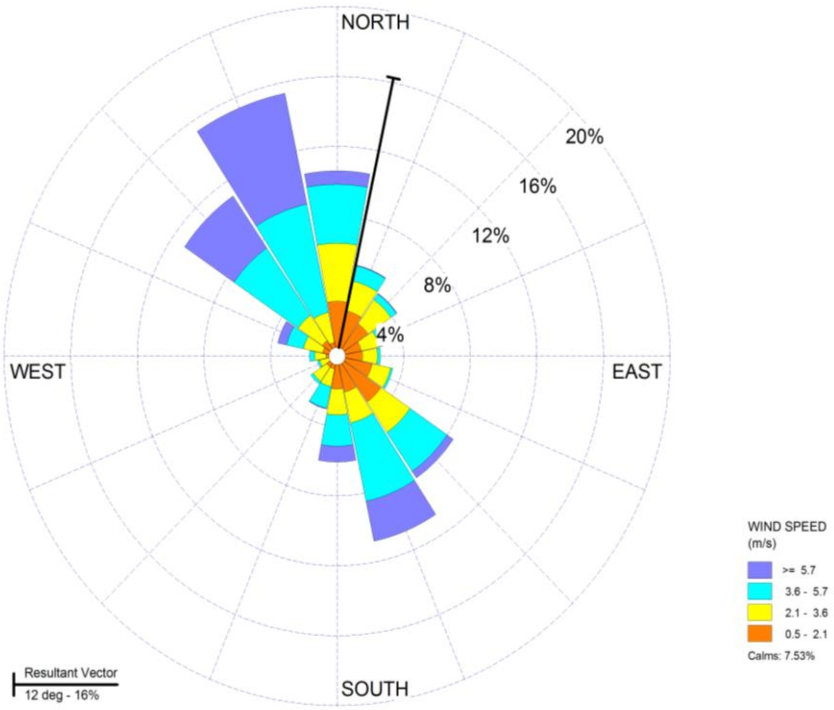


Figure 19: Summer season wind rose, 21 December- 21 March.

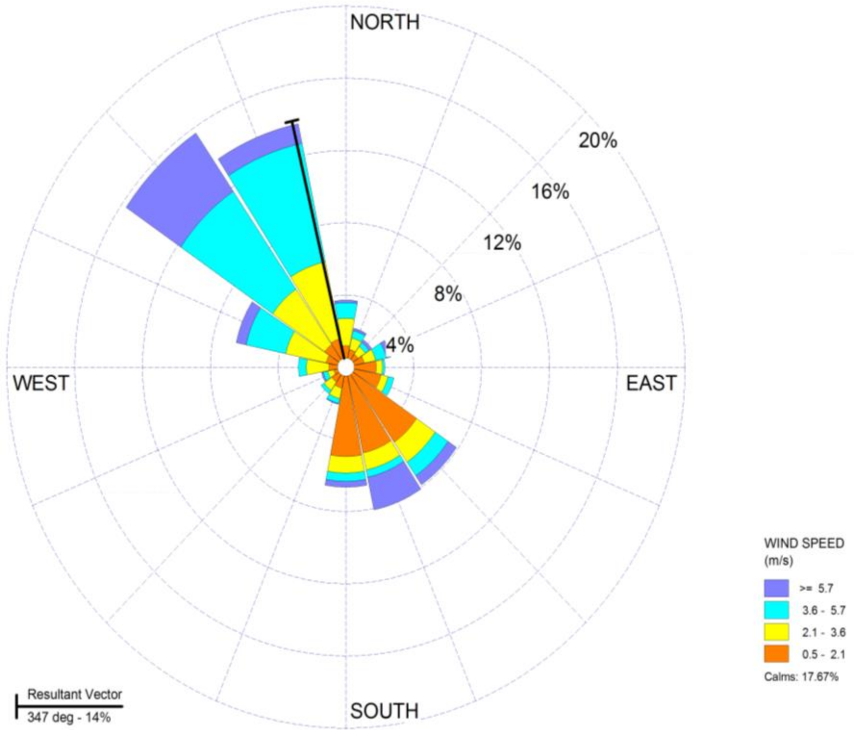


Figure 20: Winter season wind rose, 21 July – 21 September

Chapter 4: The case study

4. The case study

4.1 General Description

In the previous paragraphs, the existing conditions in the districts in the study were described. The scope of this section is to show a hypothetical improvement or it can be called a neighbourhood retrofit proposal by changing some parameters and factors that can make these areas more sustainable. The main elements of the study are the shading device. The two main shading devices analyzed here are the ‘cool’ and the ‘green’ shading devices. The first phase of the analysis is done in an architectural software Auto-CAD, then the second phase, that is, and ENVI-met modelling (a CFD software that will be analyzed in chapter 7)

Figure 21 shows the two selected districts that are selected among five considered initially. The villa district is located in the north-east of the island and is closer to the Mangrove area (a natural green belt protected under the national environmental law). The second district (high-rise and mid-rise building) is located in the downtown area and as a major orientation toward the north-west. The area where this district is located is surrounded by similar district typologies.

The current conditions of the E3 district (high-rise and mid-rise buildings) are shown in figure 22. The buildings are marked in grey and the parking lots are marked with brown stripes. The blank area represents the paved surface. Figure 23 shows the proposed shading devices over the parking lot. They are represented by beige and brown stripes. In the northern part of the district, there is a mix of shading devices and vegetation. However, in the ENVI-met model, all the shading devices are represented by one typology and texture. A detailed description of the models and their texture will be found in Chapter 7.

Figures 24-25 show the current and the improved conditions of the villa district. This district has a large distance between the buildings, allowing the shading devices to be larger; therefore, they will need a stronger structure that will impact the cost (described in the Annexe). The shading devices in figure 25 are represented by large brown stripes.

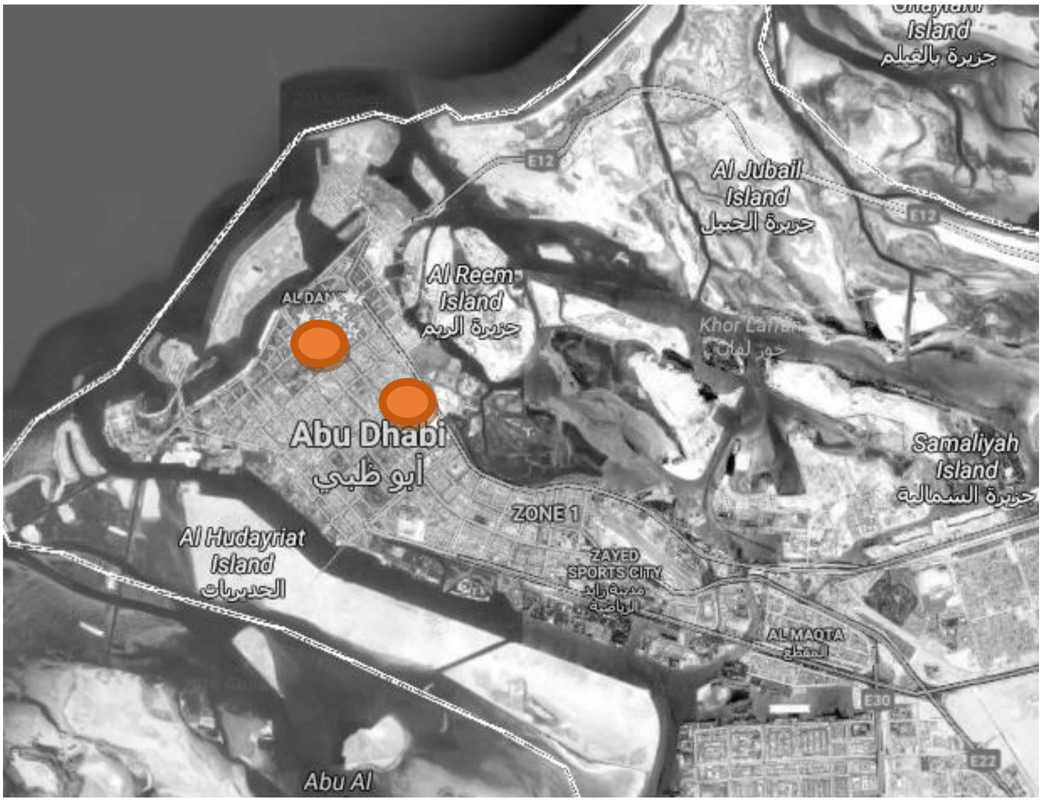


Figure 21: District location.

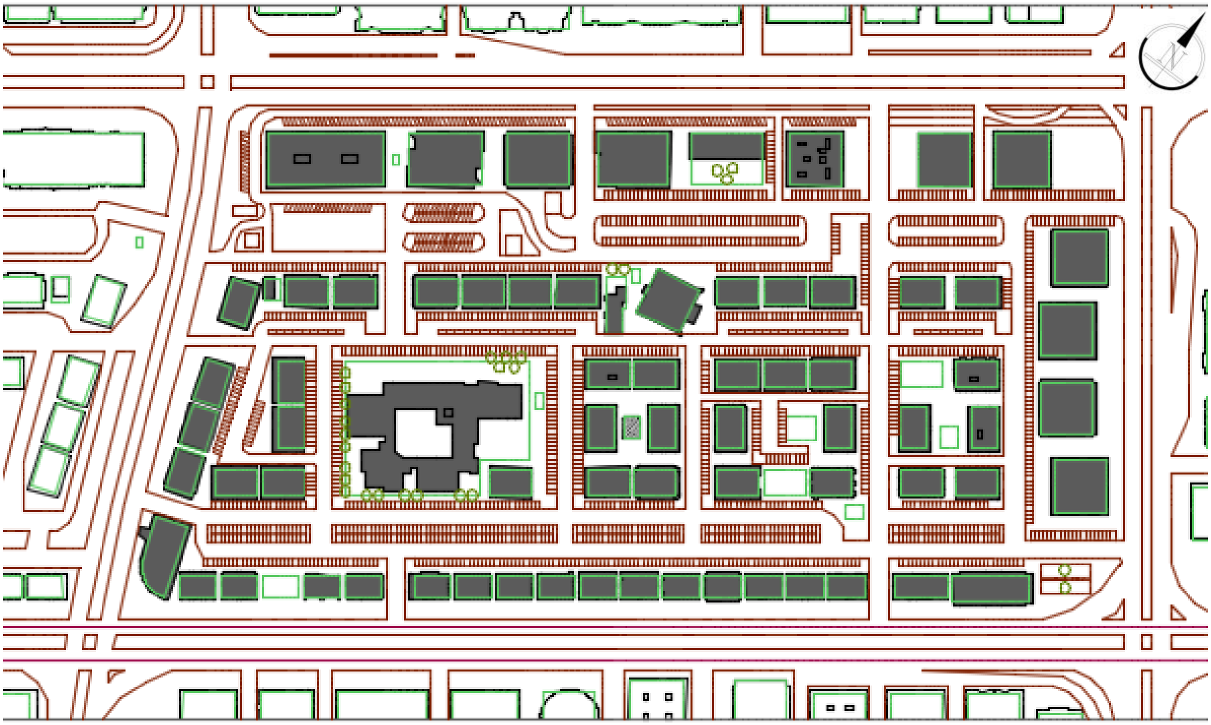


Figure 22: E3 District, current conditions (scale 1:500).

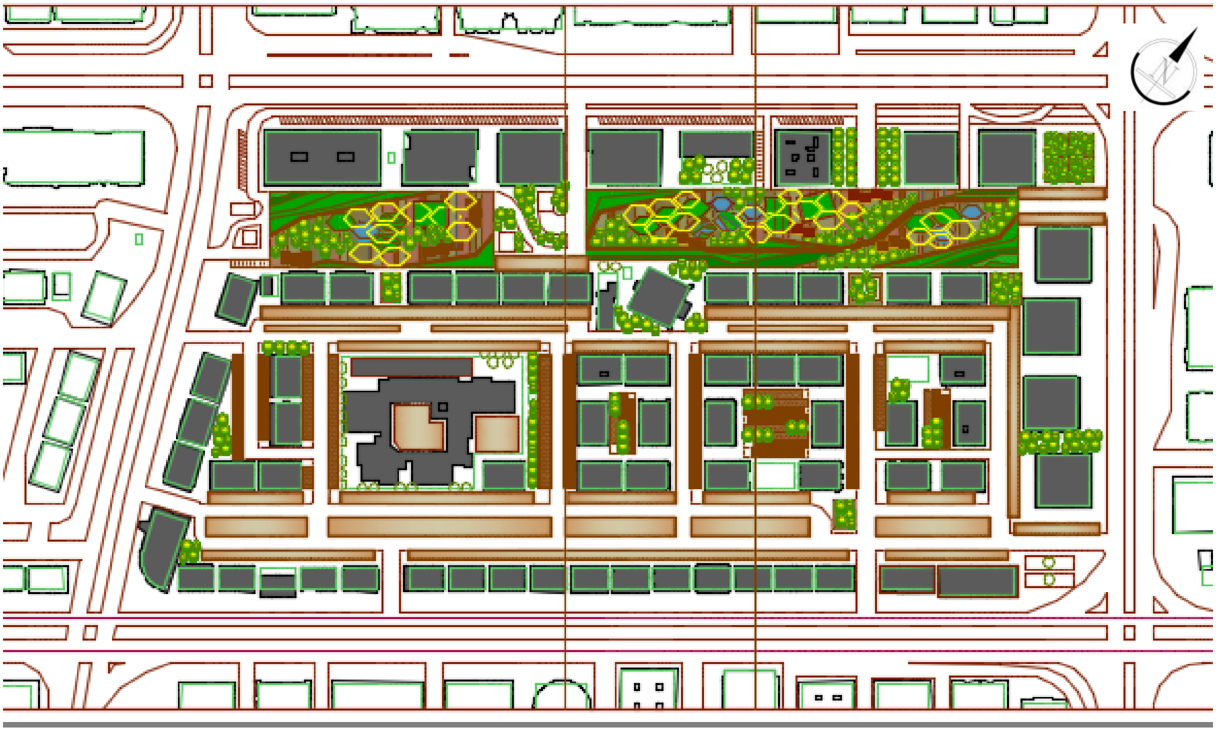


Figure 23: E3 District, improved conditions (scale 1:500).

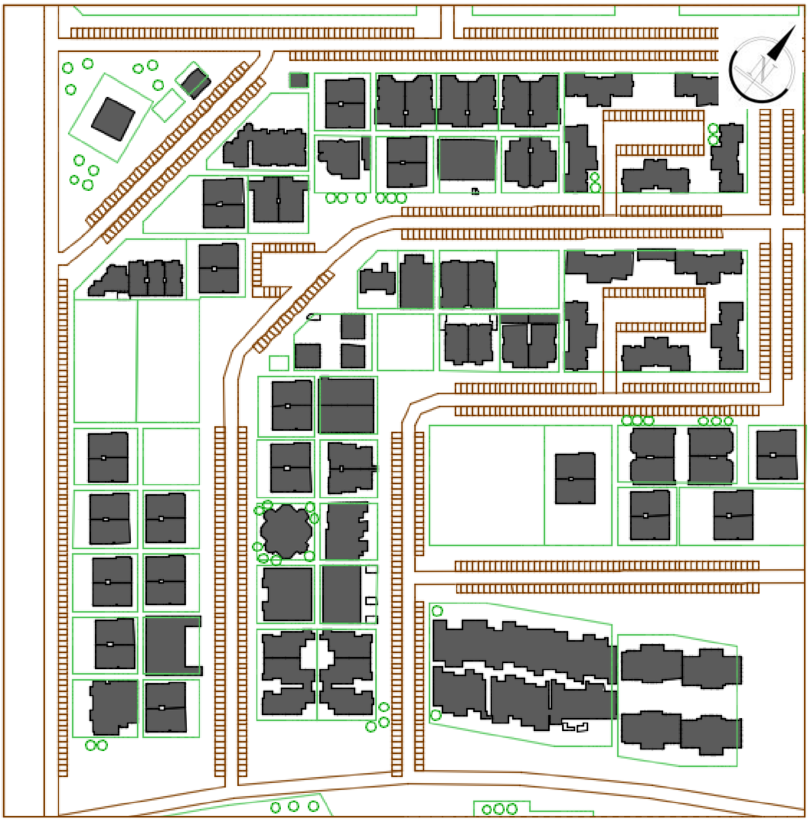


Figure 24: Villa District, current conditions (scale 1:500).

Figure 25: Villa district, improved conditions (scale 1:500).

4.2 E3 District and Villa District

The case study taken into consideration for this research (due to available data measured on site) is located on the main island of Abu Dhabi, surrounded by the streets of Zayed the First Street, Sultan Bin Zayed the First Street, Fatima Bint Mubarak Street and 5th Street. This is a representative district among others with similar properties, characterized by high-rise residential, hotel and office buildings on the borders of the area and low-rise residential buildings inside the area. The site was visited and measurements were taken. There were meetings with residents to understand the occupants' behaviour. Based on the information taken from the Abu Dhabi Municipality and from the site verifications, the table below was elaborated as a base for the templates that were created later on in the UMI program for the energy evaluations.

High residential and office buildings creating a barrier to the external conditions surround the district. This influenced the temperature values on ENVI-met. We will see below that the change of the temperature is visible also because of this influence. The internal part of the district has Medium Rise residential buildings. From the material and the façade architecture, the different building edge is easy to recognize. In the older buildings built round 1990, the windows are smaller and inserted inside the façade wall. In the buildings built after 2000, the buildings have fully glazed façade. In the perimeter, two of the older buildings were demolished and new Office/Residential building will be put up. The same process is happening also in other similar districts.

The city of Abu Dhabi is being transformed every day. Despite the architectural and construction studies, the urban planning analysis is crucial. In a hot arid climate city such as Abu Dhabi, the decisions made in the urban planning scale influences the building scale. Decision-making must analyze many factors and one of them is the Heat Island Effect. In this case, this study aims to prove that, by making such interventions at an urban scale, there can be a significant impact at an urban scale. Urban Shading Devices as UHI mitigation strategy can improve the energy consumption of buildings. This is a result besides others such as improving the outdoor comfort and walkability.

The inhabitants of the buildings in this district are mostly non-UAE citizens. Since Abu Dhabi is a developing city, most of the inhabitants work in the construction sector and recently services sector. This influences the templates in terms of occupancy. This fact was taken based also on a previous survey done in the area. The highest range of the cooling load is in the evening time due to the occupancy of the buildings. Furthermore, a part of the building is an elementary school and a mosque. The district is characterized by open parking lots along the buildings line. The biggest ones are oriented in the southern and northern part of the district. In the southern part, the building line creates shading over the parking lots. This can be defined better with Ecotect as mentioned below. The pavement used in the district is a standard one, and the asphalt does not have special characteristics in mitigating the UHI. [138]

By making this categorization it was easier to define the rest of the information. The 3D view elaborated from 3D max helped understand the intervention scale (Figure 26-27). This volume helps understand the different heights of the buildings and the space created in the centre of the district. The air volumes between the buildings are different and, in some cases, the distance between them can reach 2 meters. In the 3D the different façade treatment can also be noted. The older buildings located in the centre have frames around the windows and the balconies come forward compared to the façade wall. The space dedicated to the parking lots and the space dedicated to parks and common areas can also be noted. The surrounding buildings are marked as white in order to keep the focus on the district that is analyzed. However, it can be seen that the scale of the sounding environment is similar to the one of the E3 district. The vegetation is integrated with the shading devices in several areas such as the linear park created on the northern side and the small green corners within the low-rise buildings in the centre of the district. [139]

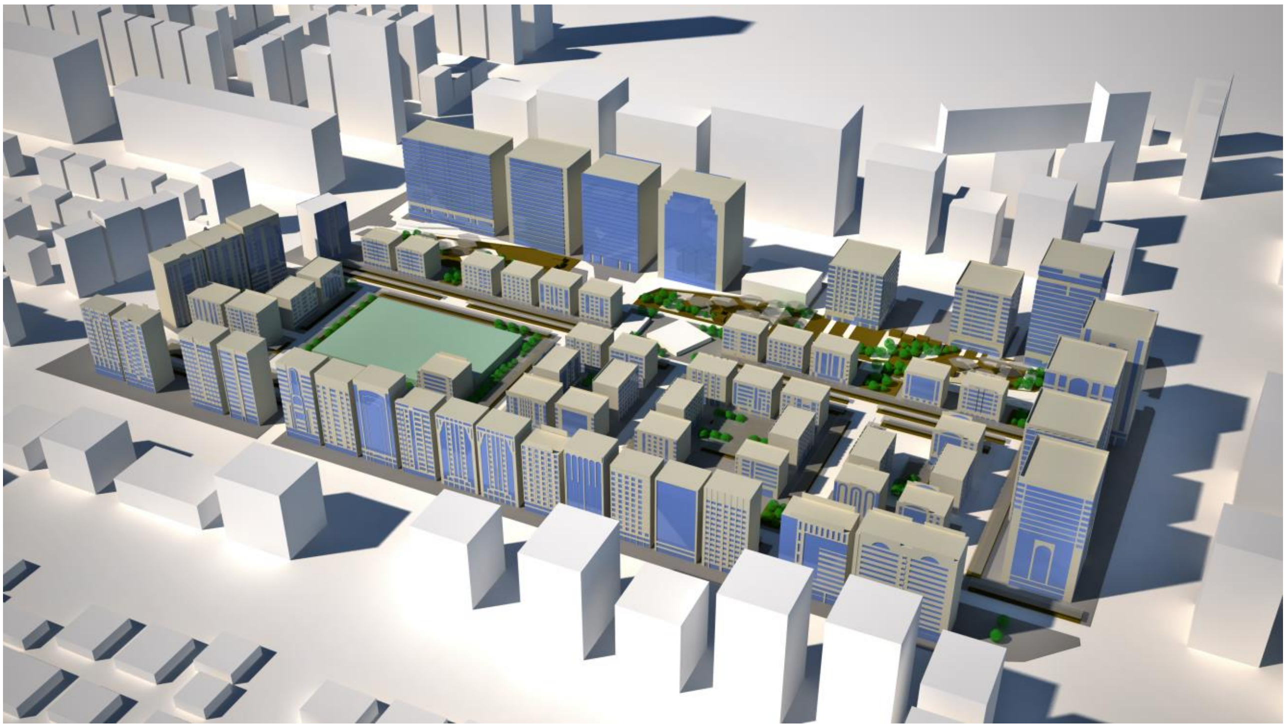


Figure 26: 3D view of the E3 District taken from the south facade.

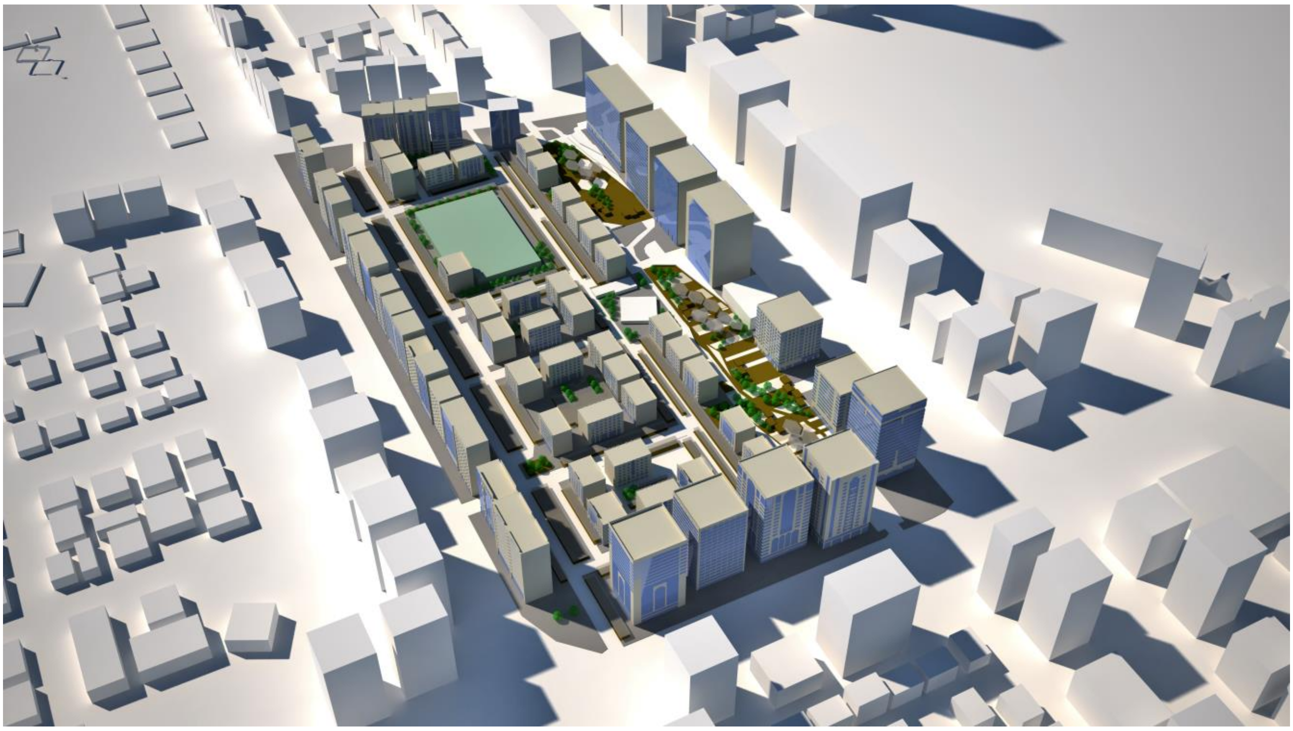


Figure 27: 3D view of the E3 District taken from the east facade.

Chapter 5: Proposals for the outdoor UHI mitigation strategy

5. Proposals for the outdoor UHI mitigation strategy

5.1 The shading devices

Historical background.

The main role of a Mashrabiya is the regulation of light, heat, humidity, airflow and privacy. For centuries it has been used in the Gulf region and elsewhere. From Morocco to India, there are many cities conserving the Mashrabiya partitions, even today. It was helping the decoration of the house with the different geometry. The temperatures were reduced because it was creating shade inside the house. The privacy obtained from the screens was also connected to the culture of each country (Figure 28).

The openings of the Mashrabiya or so-called porosity can be determined from the length and the width. Depending on this it was possible to control the light inside the rooms, the privacy and the wind passing through the openings. In our study this parameter has an important function, as in this case the interest is to have the maximum shaded surface with the maximum flexibility of the wind movement.

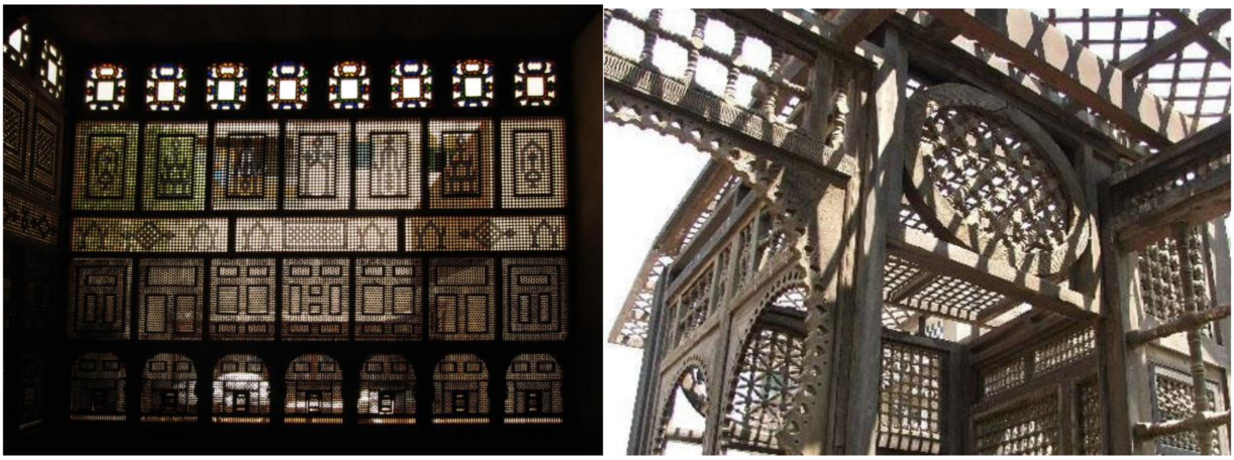


Figure 28: Marabiya samples. [229][230]

Light and temperature reduction.

The use of the Mashrabiya as a double layer, a screen that can be controlled, helped in controlling the light access inside the internal parts of the houses. During the summer, the light reduces as the sun has a higher position in the horizon and during the winter when the sun was lower the amount of light entering inside was increasing. Controlling these two main seasons, the summer and winter, was crucial in improving the cooling inside. The solar gains due to the control of the openings were the best way to reduce the temperatures inside. By creating this boundary from the outside to the inside and by improving the airflow, it was possible to cool the different areas of the houses. In some other cases there was also the use of water near the Mashrabiya area so it would improve and regulate the humidity.

Airflow improvement

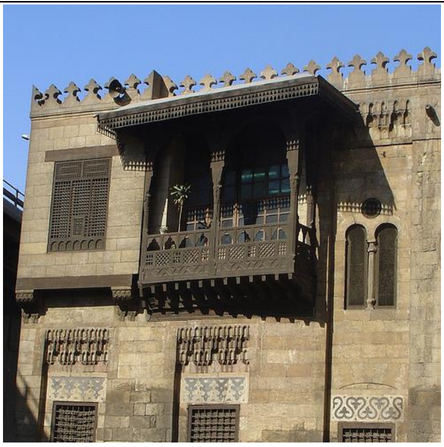
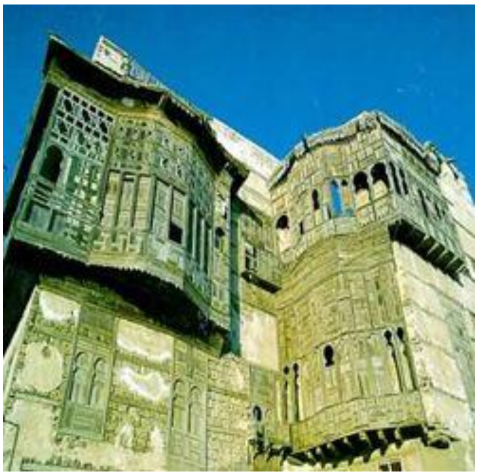
The desert climate houses from the architectural point of view have such a placement in their plan and 3 dimensions to improve the airflow in the building. With all the shading created all around the external openings, it was possible to cool the environment. The wind catchers had a major role in creating this airflow. There are many examples taken from the historical cities such as Yazd in Iran until the modern use of the Linz City in Austria, the so-called solar city.

The porosity of the Mashrabiya used in different desert areas is adapted to the specific climate. A porosity of 80% seems to have a positive impact still. In this study the porosity is important to define the number of louvres that are proposed to be used. Furthermore, the position of the windows was important in improving the airflow. The windows were on opposite walls or L-shape walls; in this way the breeze could continue and take the hot air outside. All these windows had the mashrabiya screens that would filter the airflow through the openings and block the direct sunlight, reducing in such way the solar gains. In many cases as mentioned above, the water was another element that was added in the court that helped improve the humidity in the dry season. The wind flow would spread it in a natural way in all the rooms. The screens were part of this process.

The openings and the shape of the mashrabiya used in Fes (Morocco), in Cairo (Egypt), in Jeddah (Saudi Arabia), in Sanaa (Yemen), in Punjab (Pakistan), and in Isfahan (Iran) are different from each other (Table 15). [81] [140]

In some cases there are geometric forms and in some others straight and simple lines. In the eastern part of the Arabic countries, there is a major use of the floral design, crossing all over to Morocco where the geometry takes place. All of them are used for the same purpose to reduce the solar gains as well as improve the temperatures and the airflow. In this research the ‘cool’ shading device design is more connected to the central part of the region, using straight lines of woos. This is due to more flexibility, cost, performance and maintenance. Maintenance is a very important part of the lifecycle of a device. Since what is proposed in this study is a massive use, the cost of each element and the maintenance cost must be considered carefully. Below are some images connected to the geometry of the mashrabiya used in the different countries this analysis is based on (Table 15). The performance of such structure has been proven to be efficient in cooling the internal building spaces. The modern use of such structure has been successful in the Paris Arabic Centre, Abu Dhabi Business Centre, Abu Dhabi Louvre Museum, etc. [141][142][143][144]

Table 15: Mashrabiya historical background [140] [145].

Fes, Morocco	
	
Cairo, Egypt	
	
Jeddah, Saudi Arabia.	
	

5.2 Previous shading, city structure.

The street pattern in the old cities such as Sanaa, Fes, Jeddah, etc. (Figure 29), is simple, straight lines connecting in intersections. Since at the time that these cities were built the car was not yet in use and the city physiognomy was very different, the streets have the major characteristic of being narrow. The height of the buildings was enough to give shadow and cool the walking path. Even though the social life evolved in the internal courts and not in the external parks as in countries with colder climate conditions, the walking paths were cooled due to this blocking of the solar gains. This is a concept that Fosters and Partners brought at Masdar City. Walking in the narrow streets of Masdar, there is no direct sun coming down to the pavement. People walk around and feel comfortable in comparison with the streets in the city (Figure 30). The same side should be used in the new neighbourhoods but this varies and depends on the development plan designed and approved.

In the modern cities of this region, with a hot arid climate, due to the use of the cars and other means of transport, the requirements of the citizens, and the changes in lifestyle, the streets are wide. The shading of the buildings does not cover the pavements. In this study only one district, with buildings of 20 floors on average, has its streets shaded most of the time.

The conclusion is that additional measures should be taken to create a sustainable city in the direction of the outdoor comfort and, in this case, as per this study, the improvement of the outdoor comfort due to the temperature reduction. The sustainability of a city is a very large concept and can be achieved at many levels. In the urban planning point of view, it can start by requalifying each district at a time.

This proposal is to place shading over the parking lots, the main walkways and in the play areas inside the districts. The wide streets and walkways can have this type of solution to reduce the temperatures and to improve the airflow. In the main island of Abu Dhabi, where the UHI has a major effect, such solutions can be applied on a large scale. .

The new neighbourhoods being built all around the main island of Abu Dhabi towards the desert have a different typology of housing from the downtown Abu Dhabi, but also in the main island there are some districts in the entrance of the island that are mostly villas. In this type of areas, some proposal (analyzed in point 5.7 of this chapter) for a connection with the past and an improvement of the outdoor life of the citizens are given.

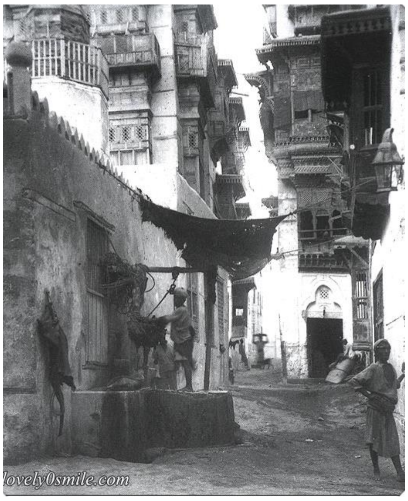


Figure 29: Ancient Cities, Jeddah and Saana [231].

Figure 30: Downtown Abu Dhabi. Masdar Institute Campus.

Figure 31: Existing shading devices, Bateen Area, Abu Dhabi.

Figure 32: Existing Shading devices Khalej Al Arab Street, Abu Dhabi.

The shading devices used currently in the city of Abu Dhabi are made of PTFE (Polytetrafluoroethylene, a plastic material) and are used mostly to cover the parking lots. They have a simple geometrical shape and there is no particular attention towards the performance of each device. The steel structure holding the fabric most of the time has corrosion problems that require periodic maintenance. In some cases the PTFE is adapted to non-stable shapes (oversized, 6 meters over the parking lot) and there is no proper stability calculation from the contractors. In Figure 31 the conic shape is two meters above the vertical structure. Another type of material commonly used is a plastic net in beige colour with the aim of having natural ventilation. However, in many cases, because of the humidity and the dust, this net is blocked and loses the initial scope of improving the ventilation. (Figure 32).

5.1 Design concepts

Even though the proposed shading devices in the E3 and Villa districts are modelled as one typology (Chapter 7), in this paragraph some design proposals for detailed 'cool' shading devices are described. The idea of this design proposals is based on the traditional mashrabiya design (Chapter 5, paragraph 5.1). The main purpose of the mashrabiya used in the traditional architecture was to create shading and improve the ventilation in the buildings. The wooden structures were having vertical installation. In the design proposals of this chapter the structures are horizontal, inclined and placed in two levels in some other cases. However, the structure is fragmentized in order to have sections that can be posed vertically. The design proposed in figure 33 has a general dimension of 10 meters by 25 meters and is divided into modules of 2 and 4 meters. The idea is to create blocks of different wooden designs that will create shading and improve the natural ventilation. The use of such structure could be in the inner area of the E3 district. Figure 34 shows a device divided into two layers. The module is 5 meters. This module is connected to the dimensions of the parking lots. The idea is that the same model can be kept in the parking lots and in the inner parts of the districts to create a uniform design. The double layer helps to have a better ventilation. Figure 35 has the same concept but the scale is different (7.5-meter module) and the geometry is based on some configurations of the mashrabiya used in the region. Figure 36 is designed considering a tent installation into a steel structure. The analysis is based on the lowest and highest position of the sun during the equinoxes. The openings are positioned towards the prevailing wind direction in order to improve the speed of wind into the district. The shading devices mentioned in paragraph 5.7 are based on their design. Figures 37 and 38 have different modules. This is based on the linear design and the second is based on the round design. Both of these proposals are connected to the mashrabiya used in the region (the geometry use).

Abu Dhabi is growing every year in terms of construction and population. The connection with ancestors is very important for the Emirati citizens. The national identity is a legacy that the founder of the UAE, Sheikh Zyed, left to succeeding leaders. Using historical concepts of the shading devices and integrating them into the modern city of Abu Dhabi gives to this project a greater value. The social development of a society must be connected to the environmental change, the building style, and the urban development. The use of local materials connects these devices to the region's traditions and teaches the future generations lessons on sustainable development.

The Liwa project is a good example of the re-use of the traditional materials and lifestyle. In the town of Liwa a small village is reconstructed with the same conditions as the early settlement. The covering material used is Arish, translated differently as palm leaves. This project belonged to the Abu Dhabi Authority for Culture and Heritage. It won several prices due to the values it taught to the young generations in revaluating the local architecture, local solutions of the previous generations and the use of local materials. Recycling the palm leaves is an important process as they can last for different seasons. They can allow the air pass through and decrease the temperatures by the shading they create, providing a sustainable environment in this way. [142]

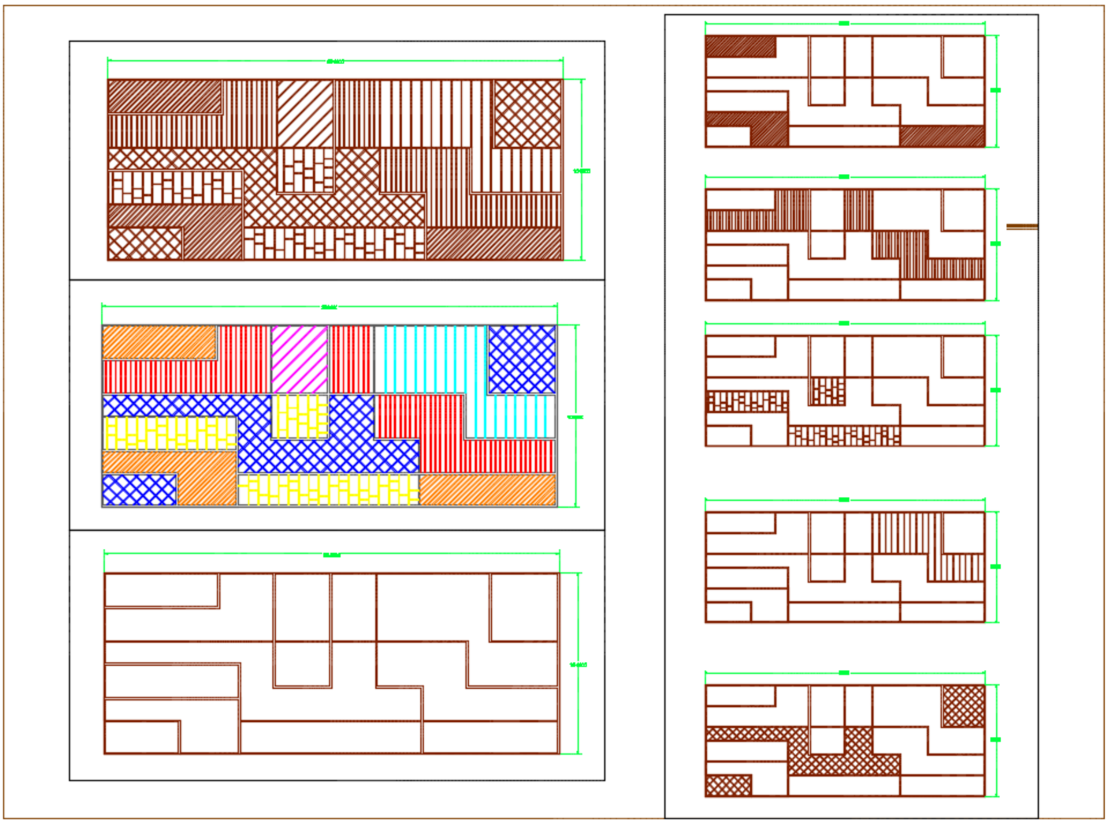


Figure 33: Shading devices 1.

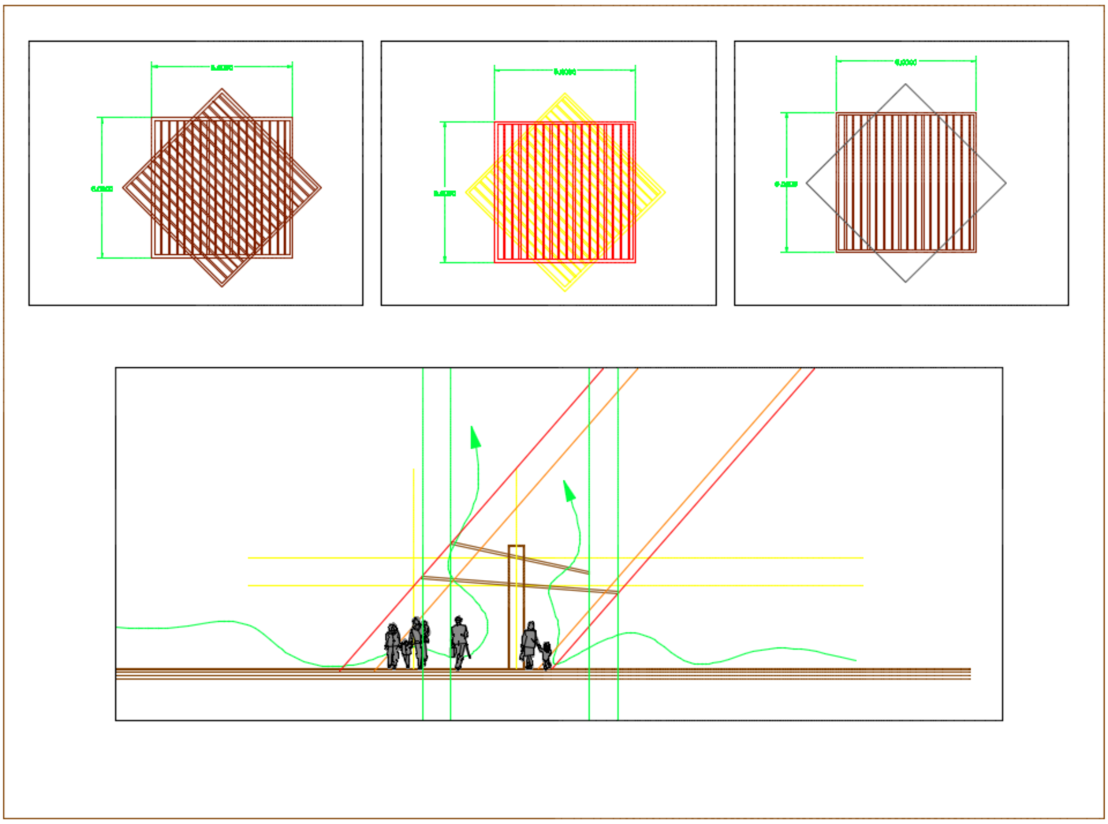


Figure 34: Shading devices 2.

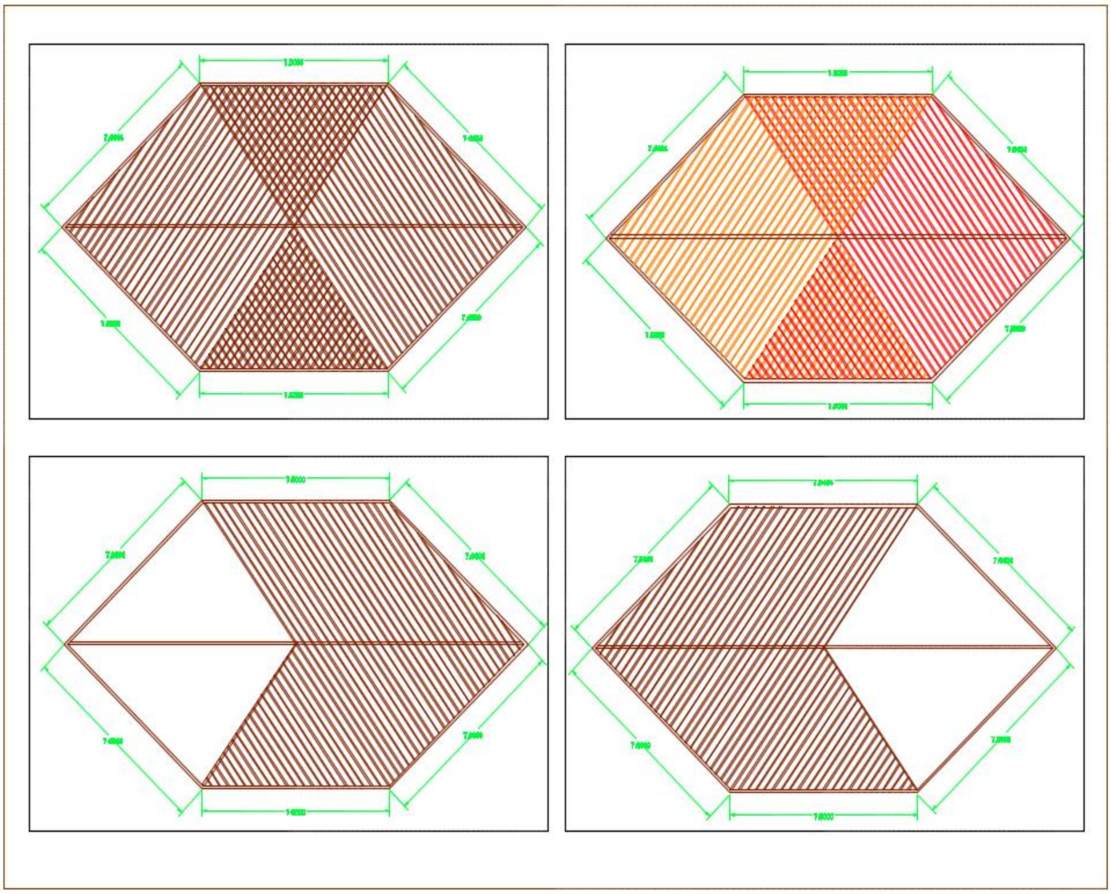


Figure 35: Shading devices 3.

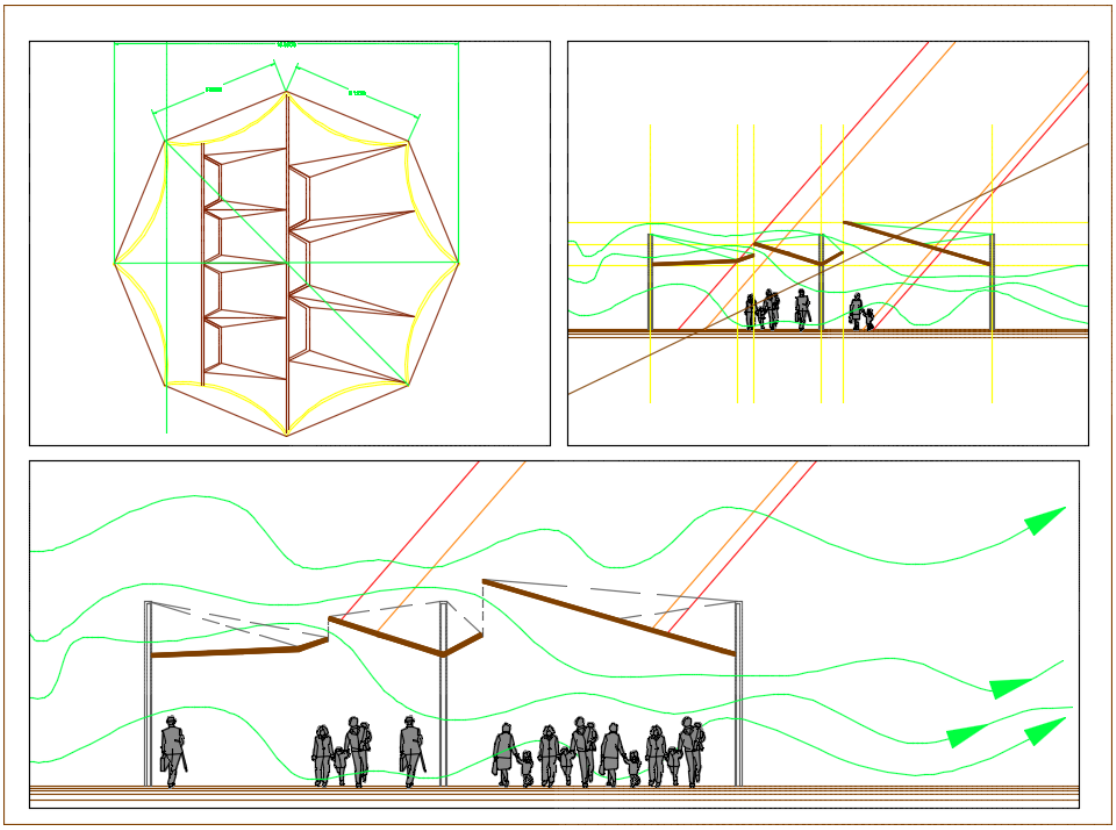


Figure 36 Shading devices 4.

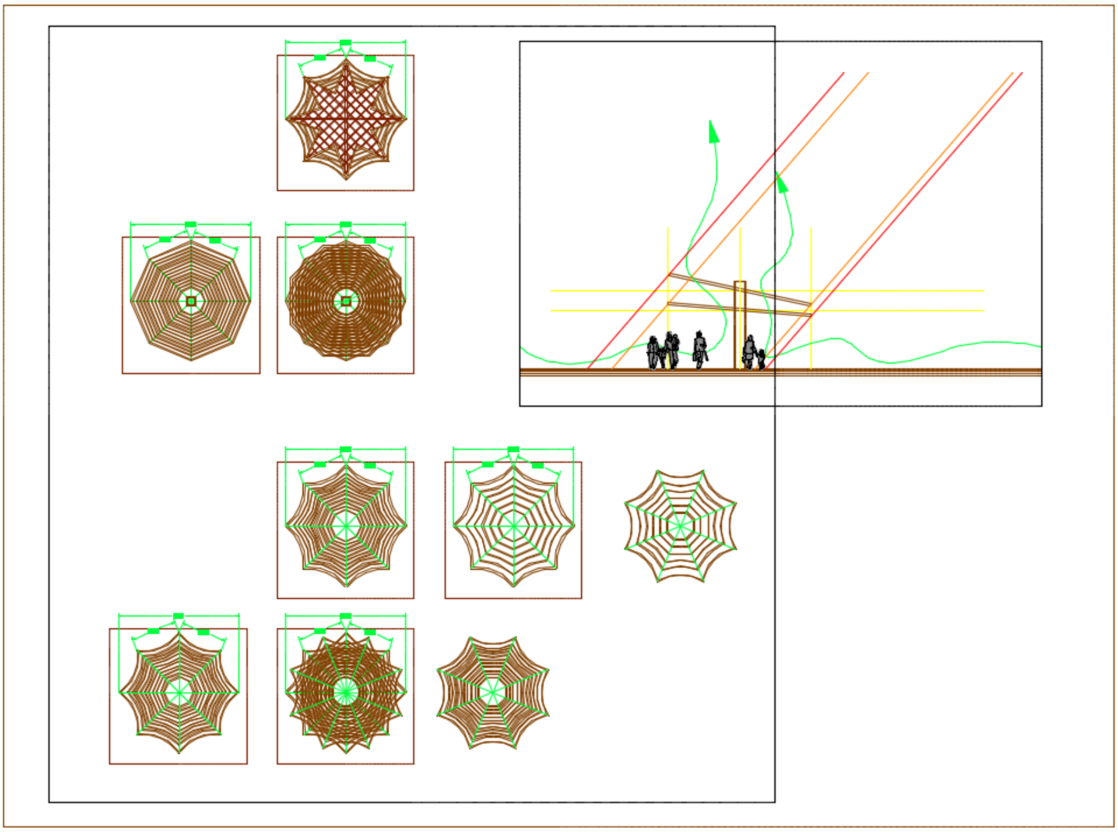


Figure 37: Shading devices 5.

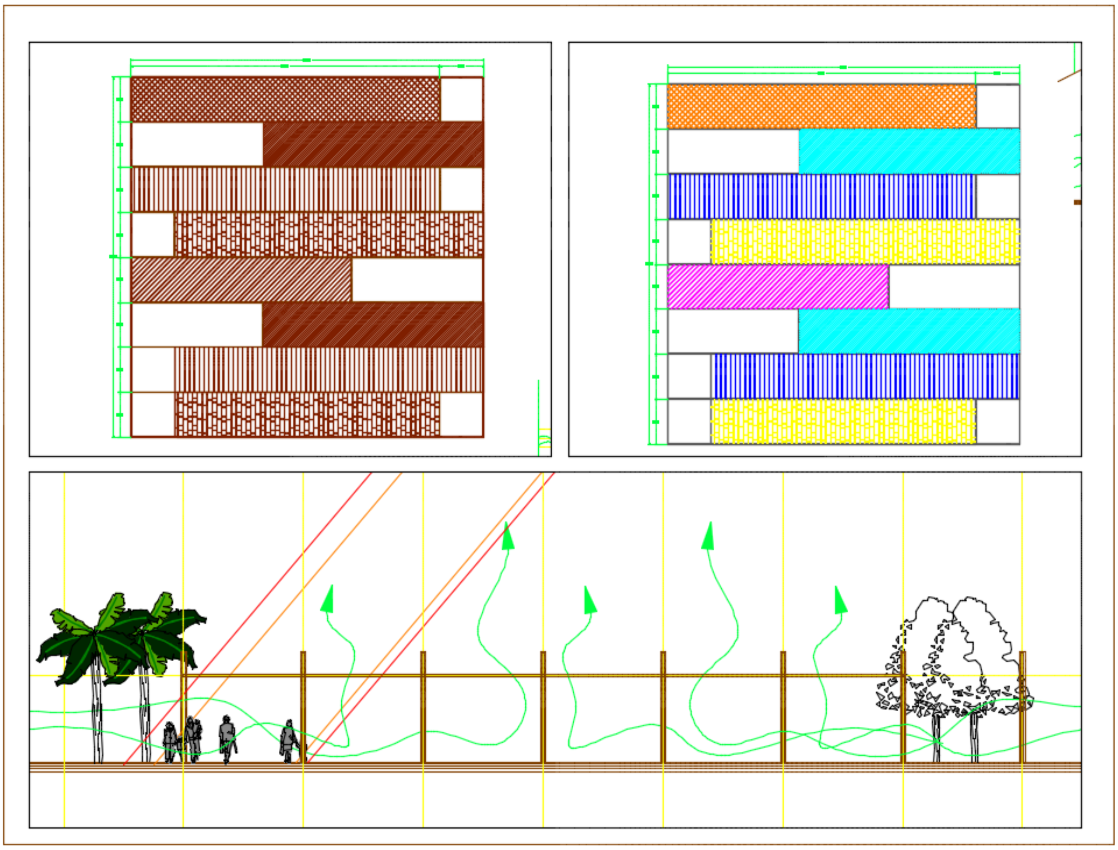


Figure 38: Shading devices 6.

5.2 Vegetation Impact into the microclimate.

The effect of the green roofs over the UHI mitigation is very promising. There are existing simulations of how the green roofs can reduce the ambient temperature from 0.3 to 3K when applied on a city scale. There are limitations concerning the maintenance and the life cycle of such strategy.[146]

A study carried out in two linear parks in Singapore, one natural and the other one artificial, shows a difference of 1.3°C on average, in the surrounding area of the parks compared to the built area after this one. According to the simulation done in TAS (simulation software), the cooling load reduction to the buildings surrounding the parks could be reduced by 10% due to the air temperature reduction. It is also concluded that in the zones where the green part was denser the air temperatures were lower. [147]

The effect of the shading of the trees over two houses is studied in Sacramento, California. After monitoring the cooling load consumption, the indoor and outdoor air temperatures, humidity, surface temperature of the walls and the roof, it was concluded that the energy saving due to the reduction of the cooling load is 30%. This reduction was achieved due to the reduction of the surface temperature because of the shading effect of the trees surrounding the houses. It was shown that the simulation software used in this case (DOE-2.1E) was underestimating the cooling energy saving and the peak power reductions. [148]

The outdoor thermal comfort in Singapore has been analyzed in different urban canyons with vegetation. Since the city has had a fast development, the UHI phenomena presents high levels. Government policies have returned the city to a green zone. Beside the analysis on the green walls and green roofs, the vegetation around the pedestrian areas has a direct impact on the outdoor thermal comfort. It is shown that the mature trees have a bigger impact in improving the OTC (outdoor thermal comfort) due to their shading. [136]

A network of sensors placed in southern California showed that the near earth air temperatures in the green areas are 1-2°C lower than the background areas. In the green established zones, the air temperatures are 1-3°C lower than the non-vegetated zones. Due to this reduction there is an estimation of energy savings in these specific areas. [149]

In the city of New York, an analysis of four different areas showed a difference of 2°C between the most and the least vegetated areas. The research shows that the green roofs can decrease the peaks of energy use and can be used as a strategy to mitigate the UHI phenomena.[46]

A mesoscale model of the calculation of the energy balance at the lower boundary level shows the importance of the soil and the interaction between the canopy layer and the vegetation. This study is focused on improving the model in order to give realistic results. It points out the importance of the soil hydrology to the soil heat fluxes and latent heat flux as well as sensible heat flux.[150]

An analysis on the streets of Biska in Algeria done with ENVI-met shows a difference of 6.57°C between the vegetated trees and the non-vegetated ones. The study took place in the summer season (July). It is shown that the streets with mature trees have a cooler impact than the new ones due to the amount of shading they create and the evapotranspiration process. The global radiation is reduced by 4000W/m^2 between the empty street scenario and the vegetated street. [151]

5.3 Vegetation in UAE

According to a study done in residential neighbourhoods in Dubai, the average air temperature can be reduced by 0.27°C by changing the type of vegetation. This means more irrigation water since the leaves of this type of vegetation improve the evapotranspiration process more. In one of the neighbourhoods, a reduction of 0.5°C can be achieved during the peak hour. Another factor influencing the air temperature changes is the wind. If the vegetation is dense and blocks the wind then the air temperatures will not have a significant change from one scenario to the other. The simulations of this research are conducted in the month of June and the software used is ENVI-met. An analysis of the plants that grow in the Gulf region is conducted to have a sustainable irrigation system. The analysis is narrowed down to five tree typologies in order to test them through the ENVI-met software in Chapter 7. [23] [152]

Among these five typologies, Palm Washingtonia, Populus alba, Privet Ligustrum, Senegalia greggi, and Acer Platanoides, that can grow in this region, the model selected in this research is Populus alba since Abu Dhabi has a similar tree growing in natural conditions (Table 16). The mangrove area surrounding the eastern part of the island is a natural park hosting several species of the green belt created from these local trees. The palm tree is not included in the model, as in the main island of Abu Dhabi the local trees mentioned are the ones that cover most of the area.

Many of the trees used in the different landscapes are imported from different countries that are outside the region, with different climate conditions. Despite the positive impact that they might have in improving the outdoor thermal comfort (the subject of further studies), the LCA of these types of trees is not sustainable in a long-term use. The type of the tree and the maintenance cost are also connected to the location of the final application. If they are used in private residences the cost estimation has a different significance, but if used in retrofitting the neighbourhoods then the cost of such investment and the maintenance are under strict supervision due to the desalination process of the water used in the irrigation system.

As per a site survey shown in Table 17, some of the trees used in the residential districts in Abu Dhabi are Frangipani (can reach a height of 4 meters), Privet (height 3 meters), Flamboyant (height 3 meters). The picture of the Privet is taken in Al Ain, a city near to the border of Oman where the levels of humidity are higher than Abu Dhabi. This type of vegetation can climb existing structures improving the shading. The distance between the leaves is enough to let the h=wind pass and create a natural ventilation..

Table 16: Local Plants used in Urban Landscape [153] .

	Evaluated Trees Typologies in ENVI met		Currently used in Abu Dhabi	
No	Description	Reference image	Description	Reference image
1	Palm Washingtonia Palm tree Height 20m Width 3m Cells 3x3x20 Leaf type: Decidous leaf Foliage albedo 0.6Depth of the roots 2mDiameter of the roots 10m		Plumeria Tree	
2	Populus alba Silverleaf Poplar Height 7m Width 5m Cells 5x5x7 Leaf type: Decidous leaf Foliage albedo 0.7 Depth of the roots 2m Diameter of the roots 10m		Frangipani	
3	Privet Ligustrum Height 5m Width 5m Cells 5x5x5 Leaf type: Decidous leaf Foliage albedo 0.4 Depth of the roots 2m Diameter of the roots 10m			
4	Senegalia greggi Thorntree Height 2m Width 3m Cells 3x3x2 Leaf type: Decidous leaf Foliage albedo 0.6 Depth of the roots 2m Diameter of the roots 10m		Petunias	
5	Acer Platanoides Height 15m Width 7m Cells 7x7x15 Leaf type: Decidous leaf Foliage albedo 0.18 Depth of the roots 3.45m Diameter of the roots 10m		Flamboyant	

Table 17: Local plants used in private residences in Abu Dhabi and Al Ain.

APPLIED CASE STUDY IN UAE PRIVATE SECTOR	
Bateen Area, Abu Dhabi	Bateen Area, Abu Dhabi
	
Plant on the brick wall, private villa, Al Ain	Green wall, private villa, Al Ain
	
Climbing plant, private villa, Al Ain	Climbing plant, private villa, Al Ain
	

Urban Shading Devices - Samples
SAMPLE No. 1- Sierpinski Forest: New technology of cool roof with fractal shapes.

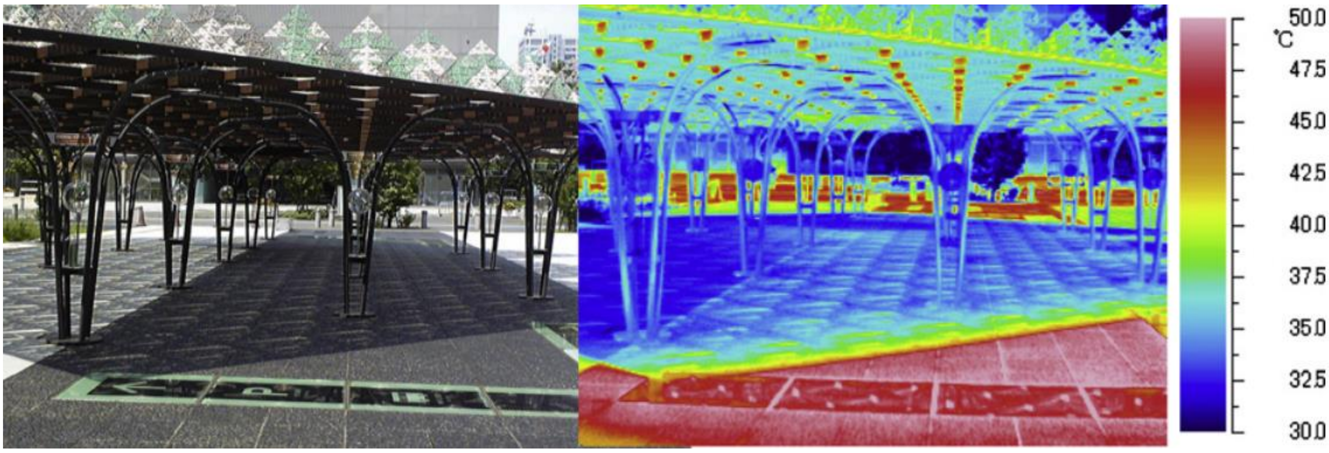


Figure 39: Visible photograph (left) and thermal image (right) of the Sierpinski's forest at Miraikan. The temperature scale of the thermal image is shown on the right hand side. (a) Top view (8/20/2009, 11 am) and (b) side view (8/18/2009, 12 am) of the thermal environment under the Sierpinski's forest [43].

One of the main contributors to the effect of Urban Heat Island is the ground surface temperature in the urban area, creating strategies to mitigate the thermal radiation emitted by the pavements and asphalts. People feel hot in the urban areas because this emitted thermal radiation does not get absorbed at the lowest levels only but also at higher altitudes in the urban canyon. There is a great difference between the ground surface of the urban and rural area during the day. [43].

The authors of this study show that by creating a Sierpinski forest the surface of the shade has a difference of 10 degrees compared to the air temperature, and in the full shade a difference of 20-30 degrees. The Sierpinski model is based on the tree leaf structure. The 3D of a tree crown that uses less water has a more complex 3D distribution that allows the tree to grow with less water but in the meantime to have the biological process. The leaves are smaller but they have a fractal spread allowing the wind to pass through them and create a shade at the same time.

Two different materials were tested in two experiments. The first one is PVC shade and the second one is a Fabric shade. The first experiment was done in the entrance of the National Museum of Emerging Science and Innovation in the summer of 2009. The second experiment took place on the rooftop of a shopping centre in Kagoshima, Japan, on the summer of 2010. In both cases the results were similar.

With this shading design the sunlight can be totally blocked from a certain direction during the peak hour, but light will enter from the other directions. This kind of shading devices provide shade without being heated themselves. This kind of structure can be used in normal roofs where there is a lack of strong wind. The surface of the pavements and asphalt can also be painted in cool paints but due to high usage the effect of such strategy gets diminished with the passing of time. [43]

SAMPLE No. 2 – GREENET / Netafim / in collaboration with Zaiv Let Architects & Alon Razgur

Figure 40: GREENET creates a forest-like canopy with plant [232]

The climate in the Middle East requires protection from the direct solar radiation. There are many shapes and designs of urban shading devices. In this paragraph there will be a short description of a competition regarding the design of urban shading devices in 2014. Among the winners there is one specific design that relates to the main topic of this thesis. The green is combined with the structures that merge the nature into the urban environment. The competition took place in Holon, Israel.

For a long period of time, the shading in the public places has become a secondary project and it has not been given the priority that it needs. The public spaces in such a climate have no shading, which makes their function unrealistic. People gather in public places not only for social purposes but also because the thermal conditions are better than the rest of the neighbourhood or the city. However, local governments are paying more attention to this subject and they are starting to have this kind of competition. The shading device implementation in public spaces must become a priority since it is connected with the health of the citizens.

This project is inspired from the vine tendrils and wants to create a forest canopy within the urban area, an eco-friendly solution that helps reduce the surface temperature of the piazza where more and more people can gather together. The irrigation system is computerized in order to ensure the long life of the plant. In such climatic conditions it is quite difficult to have plants that survive during the four seasons, especially in the hot middle-eastern summers where the air temperatures can reach up to 50°C. [51]

5.4 Cool Surfaces impact in the microclimate

'Cool Materials' or high solar reflectance materials are used as UHI mitigation solution in the study done in Rome in the month of July. The analysis is done in several residential buildings inside the dense area of the city and in the suburb. The 'cool' material is applied on the roof, walls of the building and on the asphalt. As per the simulation results and site measurements, the air temperature at a height of 4.5 meters varies from 1.8 to 3.4°C. This surface improves by 3.5°C of PET for values of air temperature above 32°C. [154]

A study done in Sacramento, California, shows a saving of 30% in cooling load by using cool roofs in residential building and a value of 40% in a school building. These measurements are referring to the summer season. Meanwhile, the energy saving is in cooling loads of 28-38% in three homes by applying cool roofs.[155]

The PET values do not have a significant change due to the use of cool wall/roof materials in the residential buildings in the city of Colombo, Sri Lanka. In this study it is mentioned that even though high albedo reduces the surface temperatures and the air temperatures, it increases the amount of the reflected short-wave radiation in the canyon at the same time. The mean radiant temperature values take this process into consideration; therefore, the PET does not have significant changes. Furthermore, a study done in Phoenix shows an increase of 11% of the cooling load due to the increase of the pavement solar reflectivity from 0.1 to 0.5. The effect of the cool pavement is related to the H/W ratio (height/width) in the urban canopy, the building insulation conditions, the window type of the buildings, etc. [156][157]

A coupled model's simulation located in Nantes, France, shows results of the impact of the cool materials on the building energy demand. The simulation is based on a model that is based on the weighting factor method. In this model the thermal balances indoor and outdoor were simulated in parallel for the full district. The use of the cool paint on the vertical walls was more efficient than its use on the roof. The surface temperature was reduced by 10°C. The district analyzed has a low density of building and their surface takes full direct solar radiation; therefore, there is no reflection from the building facades to the opposite buildings. The energy savings generated from the simulation reached values of 78%. This strategy could have a bigger effect if combined with a proper inner ventilation system to remove the heat from inside the buildings. [158]

A study conducted in Athens, Greece, shows that by applying high albedo materials at the rooftops on a city scale the air temperature can be reduced by 2°C at a height of 2 meters. The biggest reduction of the air temperature is achieved during the daytime and there is almost no change during the nighttime. If combined with vegetation such a strategy could be very effective. The study done at a city scale could be improved if the high albedo materials could be used in the pavement of the large canyons of Athens. [50]

5.5 E3 district

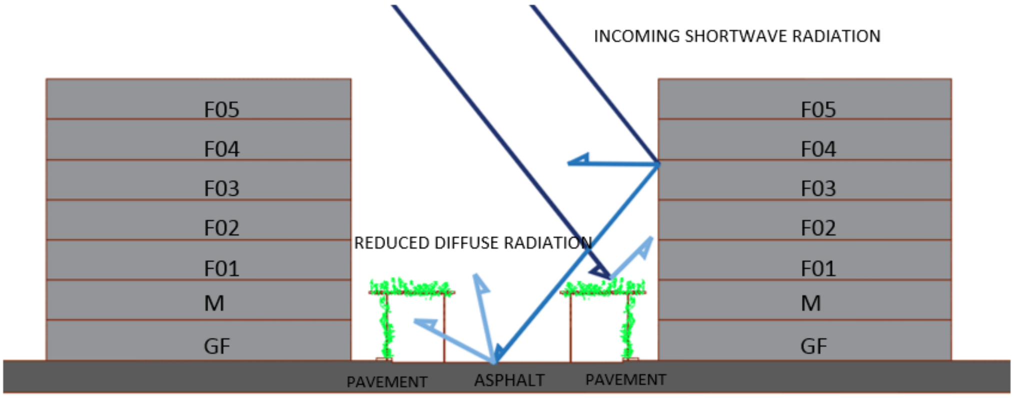
Based on the literature review (paragraph 5.6) and considering the H/W ratio of the E3 district, the design proposal for this district is to use 'green' shading devices as a proposed UHI mitigation strategy. The concept is to use wooden a structure based on a characteristic mashrabiya design (paragraph 5.1) and integrate the vegetation (local plants, paragraph 5.5). In chapter 4, paragraph 4.2, there is a detailed description of this case study. Opened parking lots characterize mainly the district before the proposed intervention. No shading is applied anywhere and there is only one underground parking on the north-west side of the district. There are few trees placed near the elementary school. The residents do not have a park inserted into the district or a play area for the children. The aim of this proposal is to prove that having a minimal intervention on the urban shading devices over the parking lots and in the internal parks can potentially improve the outdoor thermal comfort and urban microclimate.

In the proposed intervention there are different typologies of shading. There is an internal park created with shading devices integrated with trees that are typical of the Middle Eastern countries. This will help save irrigation water and maintenance costs but on the mean time will provide shading. The area where the park is located covers all the parking places that are thought to be placed in a second underground parking.

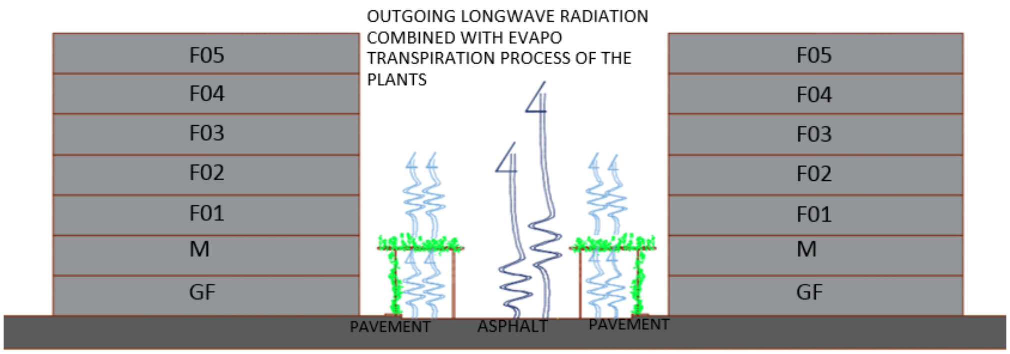
All this landscape and shading are being used as UHI mitigation strategy, which means decreasing the air temperatures will also bring a better life quality and outdoor comfort that the inhabitants can take advantage of in the free time of long working days. The idea of having such an intervention in each district can improve the city scale sustainability. This area is characterized by straight line streets, like the main island of Abu Dhabi; this helps the design to be standardized and also reduces the costs of the intervention. The ark takes place on the northern side, as this area has more access to the sun and a modification in this part will have a bigger feedback. Furthermore, there is already an existing underground parking there that can simplify the possible construction of a new underground parking. In figure 41 the modification of the northern side of the E3 District by integrating 'green' shading devices with water features (not included in the CFD simulations) and local trees is suggested. This 3Dimension view is elaborated in Max [139] and the shading devices is based on the mashrabiya concepts (paragraph 5.3)

Figure 41: 'Green' Shading devices in the north side of the E3 District

In figure 42 and 43 the behaviour of each shading device toward shortwave and long-wave radiation is shown. The 'Cool' Shading Device reflects the biggest part of the shortwave radiation. The reflected parts go toward the building facades contributing in such way in the increase of the cooling load. On the other side, the 'Green' shading devices are absorbing most of the direct solar radiation. There are many urban canopy model describing the process of the solar reflectance such as where the simulations show a decrease of one degree in the air temperature between the case with and without the shading device. [44] However, in the above models the comparison between these two typologies of shadings shows that the 'green' shading is more efficient in mid-rise and high-rise districts. Villa district

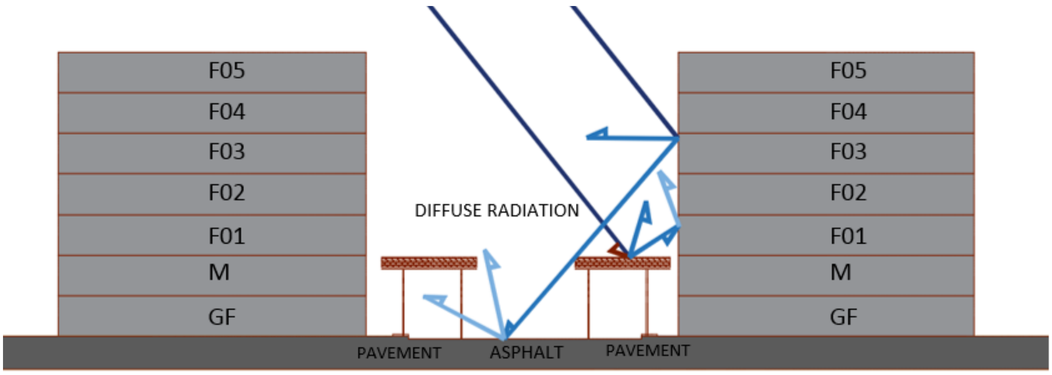


SCHEME OF THE URBAN CANOPY MODEL WITH THE 'GREEN' SHADING DEVICES SHOWING THE SHORTWAVE RADIATION AND DIFFUSE RADIATION DURING THE DAY TIME.

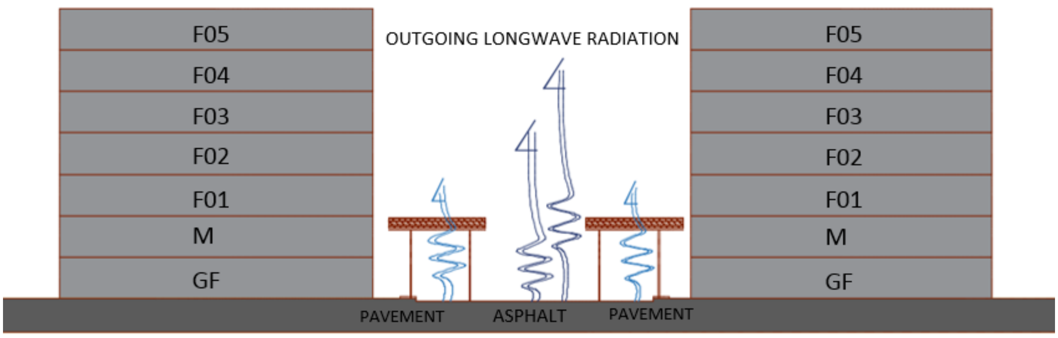


SCHEME OF THE URBAN CANOPY MODEL WITH THE 'GREEN' SHADING DEVICES SHOWING THE OUTGOING LONGWAVE RADIATION COMBINED WITH THE EVAPOTRANSPIRATION PROCESS OF THE PLANTS DURING THE NIGHT TIME.

Figure 42: Section of the mid-rise/high-rise districts showing the behaviour of each shading proposal ('green' shading) toward the solar radiation.



SCHEME OF THE URBAN CANOPY MODEL WITH THE 'COOL' SHADING DEVICES SHOWING THE SHORTWAVE RADIATION AND DIFFUSE RADIATION DURING THE DAY TIME.



SCHEME OF THE URBAN CANOPY MODEL WITH THE 'COOL' SHADING DEVICES

Figure 43: Section of the mid-rise/high-rise district showing the behaviour of each shading proposal ('cool' shading) toward the solar radiation.

5.6 Villa district

The villa district has two-floor villas located on the northeastern side of the main island. (Chapter 4, paragraph 4.2). After the literature review and the H/W (height/width) analysis, in this district 'cool' shading devices are proposed. These devices are mainly of two design typologies (chapter 5, paragraph 5.3): Traditional 'cool' shading devices and modern 'cool' shading devices. An analysis of the performance of the traditional design based on the mashrabiya historical use of the shading elements is analyzed in chapter 7. However, the design concept phase is described in Chapter 5, paragraph 5.3. The idea is to use the traditional geometric shapes in practical modules and painted in high reflective paints. The main modules suggested are 5 meters by 5 meters (based on the parking lots), 7.5 meters by 7.5 meters for the inner areas but divided into 1-meter and 0.5-meter modules. This division makes the production process much more practical in case this kind of device gets mass-produced (Annexe). As mentioned in Chapter 5, paragraph 5.1, the mashrabiya design varies from one country to another. For example, the openings and the shape of the mashrabiya used in Fes (Morocco), in Cairo (Egypt), in Jeddah (Saudi Arabia), in (Sanaa) Yemen, in Punjab (Pakistan), and in Isfahan (Iran) are different from each other. The material proposed for this typology is wood painted in high reflectance paint. There are different types of wood for external use. Beach wood and merandi are the most used ones.

The modern shading device is a combination of steel structure and PTFE material (plastic material in a type of high reflective tent). The concept is based on the function of the mashrabiya in improving the wind flow in the inner spaces. The first concepts are done in AutoCAD (figure 44). [159] In this software it is possible to calculate the optimized sizes of the structure by orienting them towards the north and by adding the direct solar radiation angle during the highest and the lowest position of the sun (solstice and equinox). Then the model is detailed in 3D (AutoCAD) in order to understand the geometry evolution (Figure 45). After an optimization processes (Chapter 7, paragraph 7.2), the proposed shape was tried in an existing project. The openings of the structure are oriented toward the prevailing wind and toward the north-eastern side. They are located on the south-east side of a villa in the same district (currently used as a nursery). The images in figure 46 show the applied sample over the play area. The materials used for this structure are steel structures painted in high reflective paint, PTFE beige tent with an opening in order to maximize the wind flow process in the area. At a certain point the structures cover each other, creating a full shaded area but yet well ventilated. The sizes of one unit are 8 meters in length and 3.5 meters in width. Before installing the steel structure, it was necessary to have the installation of the supporting steel structure on the walls of the villa and on the surrounding wall (according to the load calculations). The positive impact of this structure is not only towards the outdoor thermal comfort but also towards the cooling load reductions of the villa since the south-east walls are fully shaded.

Figure 47 shows a section of the villa district with the behaviour of each shading proposal ('green' shading) toward the solar radiation. The incoming solar radiation gets partially diffused and partially absorbed by the vegetation at the height of the second floor. During the night the longwave radiation gets released toward the sky. As per the analysis of the cost of the irrigation (Annexe), this type of structure has a higher maintenance cost than the 'cool' shading devices. However, the investment difference between one option and the other is not significant.

A section of the villa districts showing the behaviour of each shading proposal ('cool' shading) toward the solar radiation is shown in figure 48. The amount of solar radiation reflected in the sky is higher than the first proposed structure. This figure corresponds to the applied 'cool' shading device behaviour. During the day most of the incoming solar radiation gets reflected and during the night the longwave radiation gets released toward the sky. As per the cost analysis, this kind of shading structures (Annexe) has a lower maintenance cost. Since the H/W is low, this structure is more adaptive (literature).

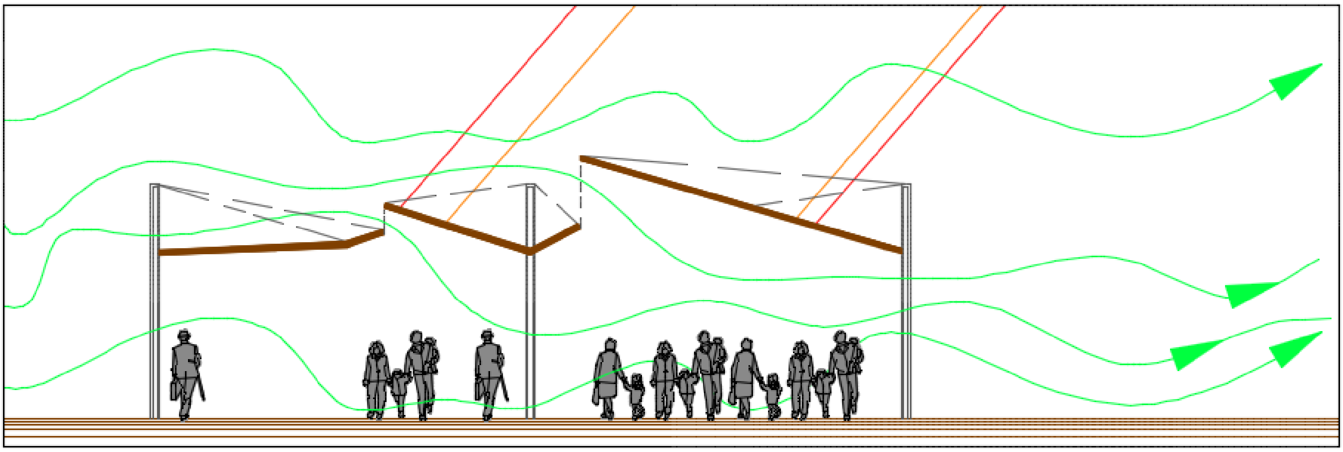


Figure 45: Auto CAD section of shading device concept.

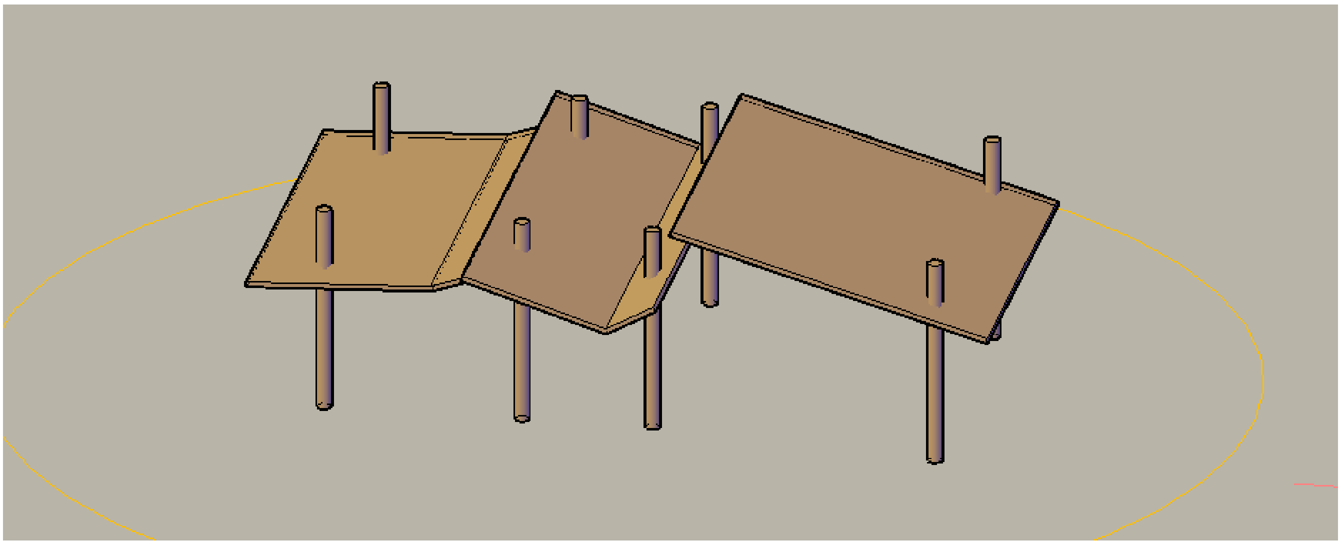


Figure 46: Auto CAD 3D of the shading device concept.

Figure 44: Site application of the shading device.

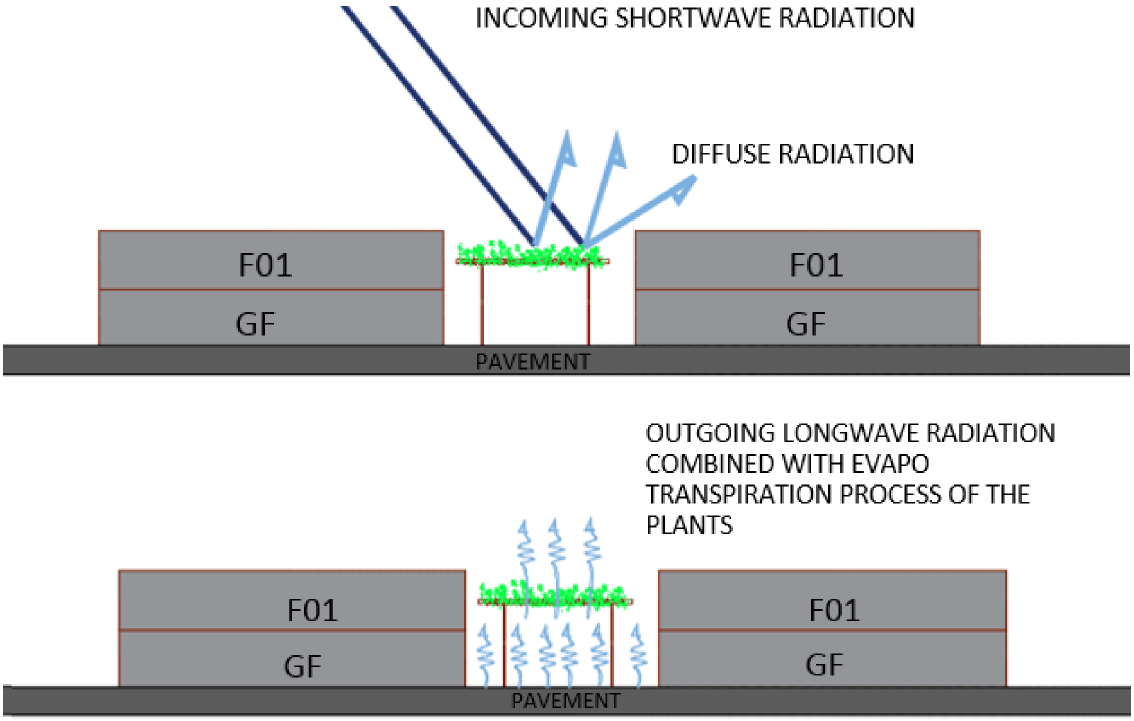


Figure 47: Section of the villa districts showing the behaviour of each shading proposal (‘green’’ shading) toward the solar radiation.

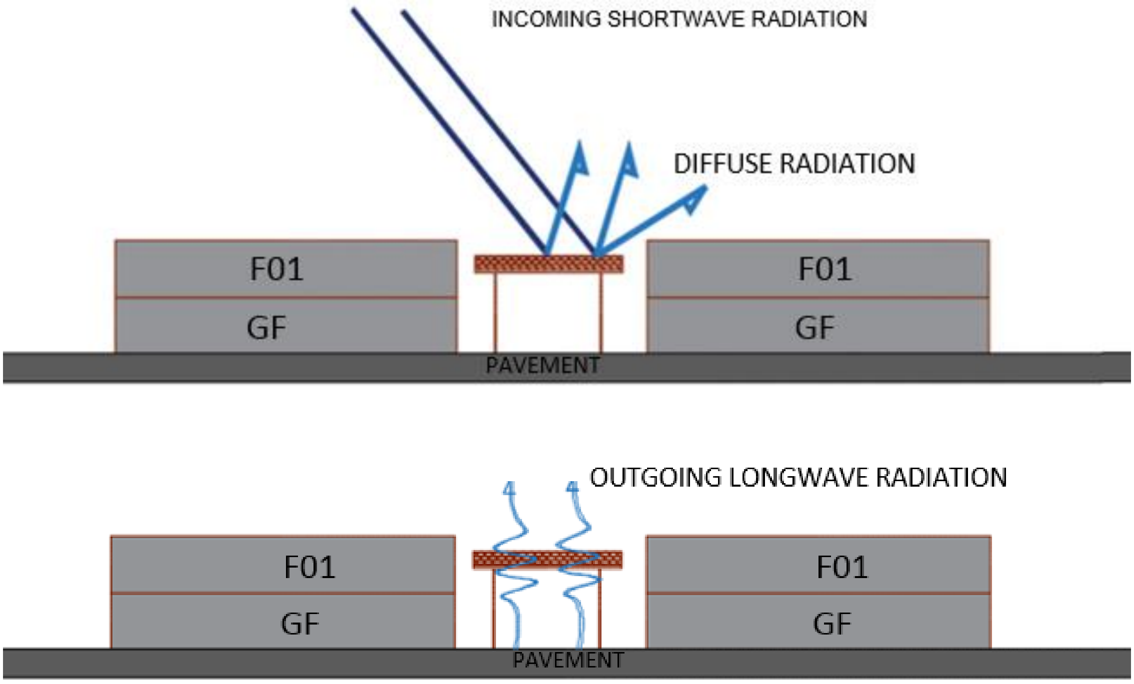


Figure 48: Section of the villa district showing the behaviour of each shading proposal (‘cool’ shading) toward the solar radiation.

Chapter 6: The site measurements campaign

6. The site measurements campaign

6.1 Site measurements Phase I (PET)

In this paragraph the measurement process and equipment used to calculate the PET in the E3 district, specified as Phase I, will be described. The measurements were taken in three main points (Figure 49): A (middle of the parking lot, northern side), B (five meters from the low-rise residential building), C (middle of the parking lot, southern side). The measurements were taken on two main seasons: Spring and Summer. For the Spring season the site measurements were taken on April 21st instead of March 21st due to the uncommon weather condition. The spring of 2016 in Abu Dhabi has been colder than average spring conditions that were studied in ENVI-met. The measurements are taken two different times of the day: at hour 15.00 and at hour 16.00. For the summer season, the measurements were taken on 21st June. In the summer the measurements are taken only at hour 16.00, due to difficult site conditions.

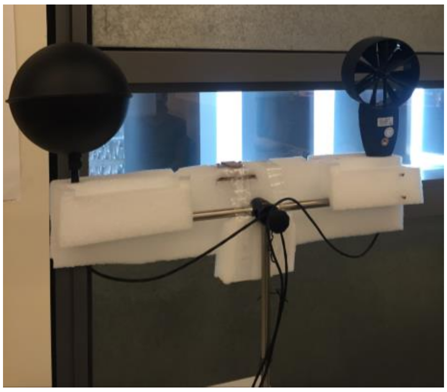
Figure 49: E3 site measurements locations.

On the table below the pictures of the different sensors used in the site measurements are shown. The values of each sensor are then placed in Rayman [160] in order to calculate the PET in the different selected points of each district. The first three sensors are part of the Testo brand of sensors and equipment [161]. They were calibrated according to the factory calibration protocol and were ready to use and take the site measurements. These sensors are used in several studies and maintained carefully in order not to compromise the results obtained from the field studies. In table 18 the sensor specifications are shown. The results of the site measurements are analyzed in chapter 8. Table 19 shows the mean radiant sensor, the wind speed sensor, the relative humidity sensor, the data reader and the position they take before starting the measurements. The equipment was carefully transported to the site. The summer conditions were the most difficult ones due to the high value of air temperature and relative humidity.

Table 18: Sensors Specifications

Sensors Specifications		
	Measurement range	**Accuracy**
Wind Sensor	+0.25 to +20m/s	+0.1m/s to + 1.5 %
Temperature sensor	-20° to 70°C	±0.21°C from 0° to 50°C
Humidity sensor	1% to 90% (non-condensing)	±2% from 20%

Table 19: Sensors used for the PET parameters measurement [161][162].

Sensors used for the site measurements	
	
Sensors arrangement	Mean radiant temperature and wind speed sensor
	
Mean radiant temperature sensor	Wind speed sensor
	
Data reader	Air. Temperature and relative humidity sensor

6.2 Site Measurements Phase II (ENVI-met/UWG)

The rural file is the base used in the UWG simulation. The data used for this validation is taken from the weather station of the Field Station, an isolated laboratory building. This station undergoes regular maintenance to ensure data quality and continuity. The weather station is located near the Abu Dhabi Airport. The area is surrounded by a desert that connects Abu Dhabi to Dubai and Al Ain. The Abu Dhabi airport is located 28 km from the downtown area. There were some tests done also with the TMY from the nearby airport weather station, taken as rural reference. However, since this validation is done for the year 2015 (when the downtown sensors were operating), it was decided to use the Field Station's rural measurements exclusively (figure 50).

The measurements used in this section of the research are called Phase II and took place in spring 2016 during the months of March-April. This data is part of a wide sensor network installed in October 2015. The sensors are still recording the values of the air temperature, wind speed and relative humidity in several locations (Figure 51). The different districts are located mainly in the downtown area (3 sensors). Two of the sensors are located respectively near the UPC building (Urban Planning Council) located in the center of the island and the second sensor is located in the batten area, north-western side of the island (this side of the island partially faces the seas and partially faces the new islands around the city where there is no construction yet). The values used for the calibration of the model are a daily average of 20 March 2016- 10 April 2016. The values used as boundary conditions correspond to the same days but refer to the measurements taken in the rural station located near the Masdar Institute. The site measurements taken in this Phase II are used mainly to validate the ENVI-met model, comparing it with the UWG Urban Weather Generator) and estimating the contribution of the anthropogenic heat to the air temperature in the E3 district (as a representative district of the downtown area). The winter measurements of the sensors are shown in the annexe. The temperature and humidity sensors were in different district typologies (Figure 52-54, Table 20). The sensors were carefully placed on the site, making sure to minimize perturbations due to external conditions such as direct solar radiation, air-conditioning waste heat release, etc. Measuring the real data proved to be difficult. Foreign citizens who move very often mainly inhabit the city centre. Since the downtown sensors are installed in private residences and apartments, keeping them in place for an extended period was a challenge. Nonetheless, several sensors registered reliable data that is used in this validation. The district typology selected in this analysis is E3 (high-rise/mid-rise buildings) and has a structure similar to H04. Therefore, the results of this sensor are used as a base for the comparison of the three different files.

The main purpose of the downtown sensors was to measure temperature and relative humidity. This real data is used to validate the energy simulations. Sensors are carefully positioned on different urban sites (usually outside the premises of private houses/apartments). The measurement sites were selected to represent different typical urban typologies (similar district structure as the five typologies analyzed in Chapter 3 of this research). The sensors are shaded all the time and have direct access to the urban canyon. The sites were inspected every two weeks in order to check the condition of the sensors. In table 21 the weather stations components are listed, specifying more details about their installation and the distance from the canyon, etc. As is customary in such measurement campaigns, there were some technical problems depending on the location of each sensor. For example, one of the sensors was damaged due to façade maintenance. Another sensor was shifted from its initial location since the tenants moved. A list of this site defects is shown in table 22. Figures 52-54 show the buildings where the sensors are located. The 3D models show the district physiognomy and the orientation toward the northern position. The main typologies of districts where the buildings are located are villa district, high-rise district, high-rise/mid-rise district, mid-rise district.

Figure 50: Rural weather station location.

Figure 51: Five urban sensors location.

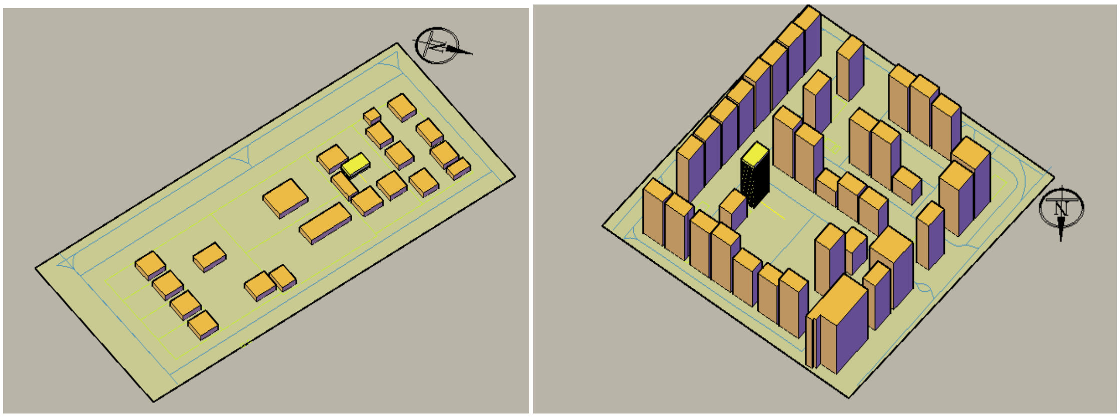


Figure 52: Sensor H01 (Villa District) and sensor H02 (High-rise district).

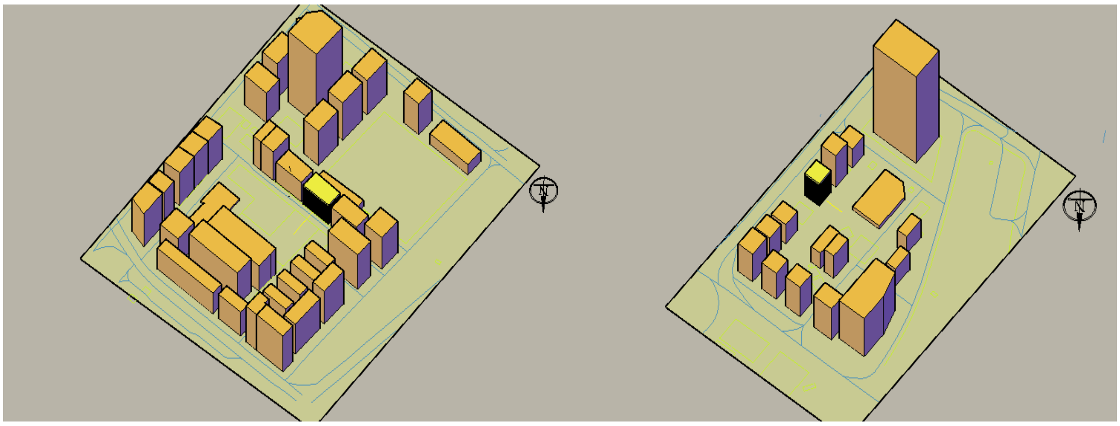


Figure 53: Sensor H03 (High-rise district) and sensor H04 (High-rise/ mid-rise district).

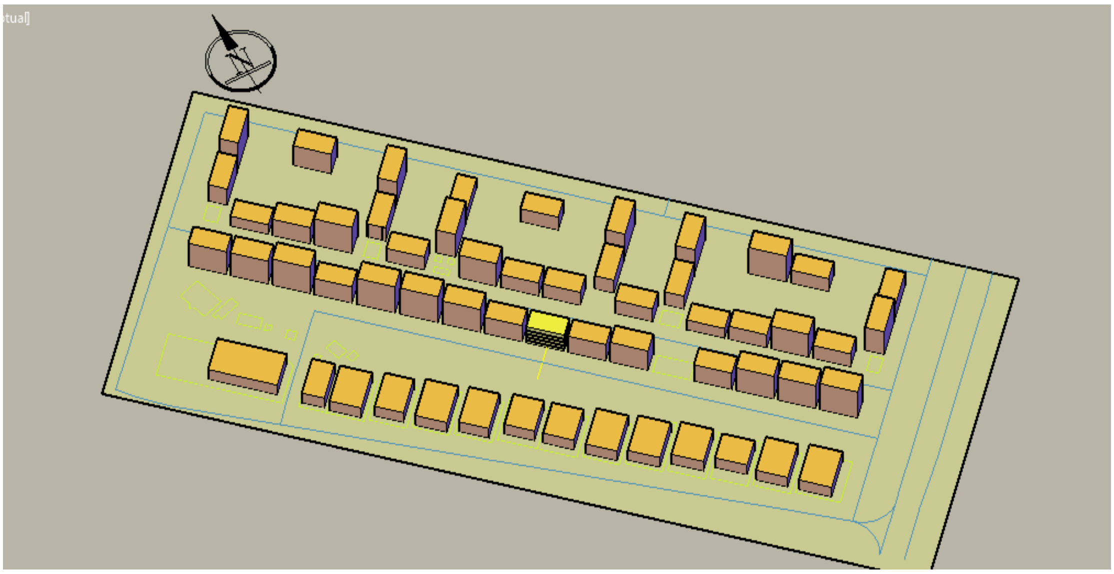


Figure 54: Sensor H05 (Mid-rise district).

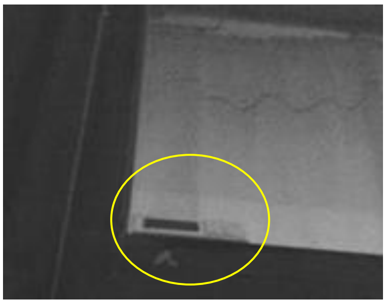
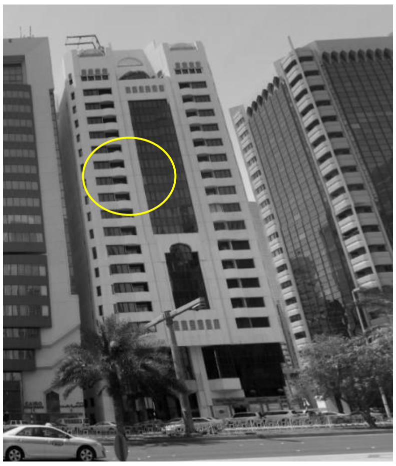
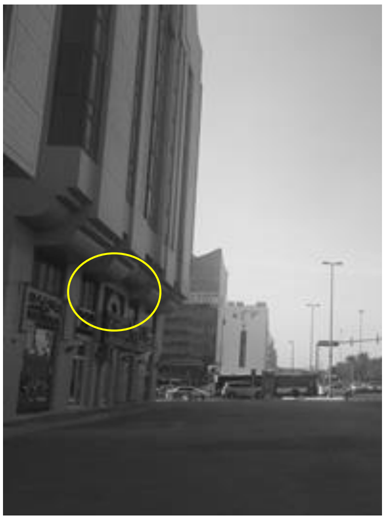
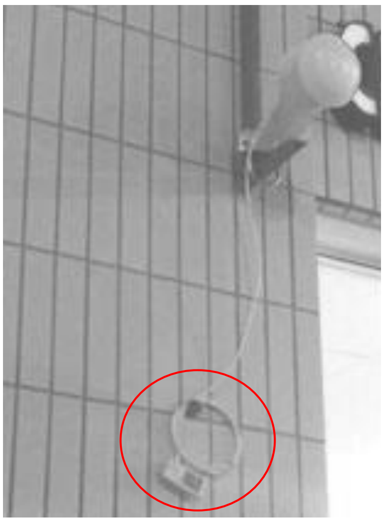
Table 20: Sensors Information

Sensors Information			
Sensor code	**District type**	**Location**	**Reliable data**
Sensor H01	Villa district	Bateen Area	January-June, September- December
Sensor H02	High-rise district	World trade Centre Area	January-July, September- December
Sensor H03	High-rise district	World trade Centre Area	January-June, September- December
Sensor H04	High-rise/ mid-rise district	Corniche Area	January-June, September- December
Sensor H05	Mid-rise district	UPC Area	January-June, October- December

Table 21: The weather stations components.

District typology	**High-rise district**	**Villa district**
Distance from the street level	Ground floor (2.5m from the street level)	Second floor (9.5 m from the street level, 1.5 from the roof level)
Distance from the street level	50 cm, sensor protected from the solar radiation	30 cm from the vertical wall, 50 from the horizontal roof border.
Measured parameters	Air temperature, relative humidity	Air temperature, relative humidity, vertical wind speed, horizontal wind speed
Source of energy	battery	Solar panel, reserve battery
Unit image		

Table 22: The defects incurred during the site measurements.

Sensors Defects		
Cause of the defect	**Building image**	**Building detail**
High values of air temperature. Iron profile round the sensor		
High values of relative humidity Window condensed water		
High values of air temperature. Signage lights too close to the sensor.		

The Urban Weather Generator file (UWG)

The UWG is a software model developed by Bueno to estimate the urban air temperature based on a rural weather file. The tool is user-friendly. There are some steps to follow during installation. The computation time was less than expected, around 20 minutes per file, much less than ENVI-met, although the purpose of study in ENVI-met was different. Gathering the configuration information is the most important step. It significantly affects the results. In this case, as shown below, the input values obtained from site observations and preliminary studies were used. The UWG can calculate the air temperature in a neighbourhood by considering the prevailing urban environment. The characteristics of the urban area define the intensity of UHI. [163]

The UWG has been validated for the city of Singapore and previously also for the city of Toulouse and Basel. The software has been recently improved in terms of accuracy of the calculation method. It can be used to estimate the UHI effect and building energy consumption at a neighbourhood scale, considering the green area, the density of the buildings, etc. [164][165]

The temporal variation of the urban canopy level of UHI intensity in the city of Singapore shows that the highest intensity occurs 3 to 4 hours after sunset in the commercial areas and that it has a significant seasonal variation. The impossibility of accounting for anthropogenic heat is an important limitation of the ENVI-met model [166][20]

The urban air dry-bulb temperature is an important parameter in all building energy simulations given the primacy of sensible heat exchanges. The UHI phenomena have been studied for decades and there have been several attempts to determine air temperature data that are closer to the urban reality than the rural Typical Meteorological Year data used in standard building energy simulation software. [167][167]

Linear roads characterize the street pattern. Abu Dhabi is a car-oriented city and there is a tendency of increasing the commercial areas, therefore, the need for more cars. The problems of the insufficient parking areas in the main island can also be seen in the district's physiognomy and the urban design concept of the city expansion (capacity of hosting the increasing amount of cars). A study done in two different scenarios (variable and constant anthropogenic heat fluxes released in the canyon) shows that the release of the anthropogenic heat creates an unstable layer in the lower level of the atmosphere even during the night compared to the countryside. [168][169]

A study done recently in the city of London shows that in certain areas of the city where there is dense traffic the anthropogenic heat can arrive to 200 Wm^2. The impact is higher during the winter than during the spring season. The impact of the anthropogenic heat in the dense areas can reach 1.5K according to the results shown in the study. The higher temperatures are noted during the night showing a delaying effect of the anthropogenic emissions. [170]

A combination of a top-down and bottom-up method showed that the anthropogenic heat values in the city of Singapore can reach values from 13Wm2 in the low-density areas, 17 Wm2 in the high-density public areas and 113 Wm2 in the commercial areas. The contribution of the buildings due to the heat released in the canyon can reach values from 49%-82% during the week days. [171]

In this paragraph the creation of the UWG file referring to the E3 district based on the site measurements and on the site survey of the buildings is described. The site survey was conducted to compile the construction characteristics of the buildings, the district urban location, the street pattern, the location of the green areas, the number and type of the trees, the parking, lots and the number of cars at the peak hours, etc. The UWG files are generated in a comparatively short time. However, ENVI-met is a CFD software and provides a level of modelling accuracy that UWG lacks. The UWG considers average characteristics of the urban area such as the building height, the surfaces parameters, the building characteristics, the anthropogenic heat, etc. This brings the results closer to the real conditions in an urban environment, which can be beneficial not only to urban planners and architects but also to other professionals that need to run the energy simulations of a building located inside the city. The main input data to UWG consist of the rural weather file, the city location, the urban parameters, the district parameters and the building parameters. The urban parameters include the urban road characteristics and the anthropogenic heat. District parameters include the use of the buildings, the average height, the built area ratio, vertically to horizontally built ratio, the vegetation density, etc. Building parameters include the wall and roof packages with corresponding thermos-physical characteristics such as heat capacity and thermal conductivity.

Other parameters that are considered are the air conditioning efficiency and the fraction of the waste heat released into the urban canyon by the chillers. Since UWG was previously validated for Toulouse, Basel and Singapore, its validation for a city such as Abu Dhabi, with its special type of climate, contributes to a complete characterization of the software's applicability (table 23-24). Some UWG inputs were kept at their default values, such as soil properties and albedo of the pavement, but the main characteristics of the walls, windows, roof, and urban planning are specific to this district. An important input value that UWG considers in generating the weather file, the vertical-to-horizontal built ratio (VHu), was calculated to be 2.202. Detailed information about the code used from the Matlab (software that runs the code for the UWG in this case) is given in the annex section.

The anthropogenic heat calculated in the simulations is based mainly on the literature. The linear structure of the city and the recent urban development has similarities to the cities studies in several studies mentioned in the above mentioned references. However the calculations of the anthropogenic heat levels in the city of Abu Dhabi is an ongoing research. There are attempts done using the satellite images to calculate the amount of cars in a certain hour of the day, in different seasons. This methodology calculates indirectly the anthropogenic heat emitted from the cars. [172]

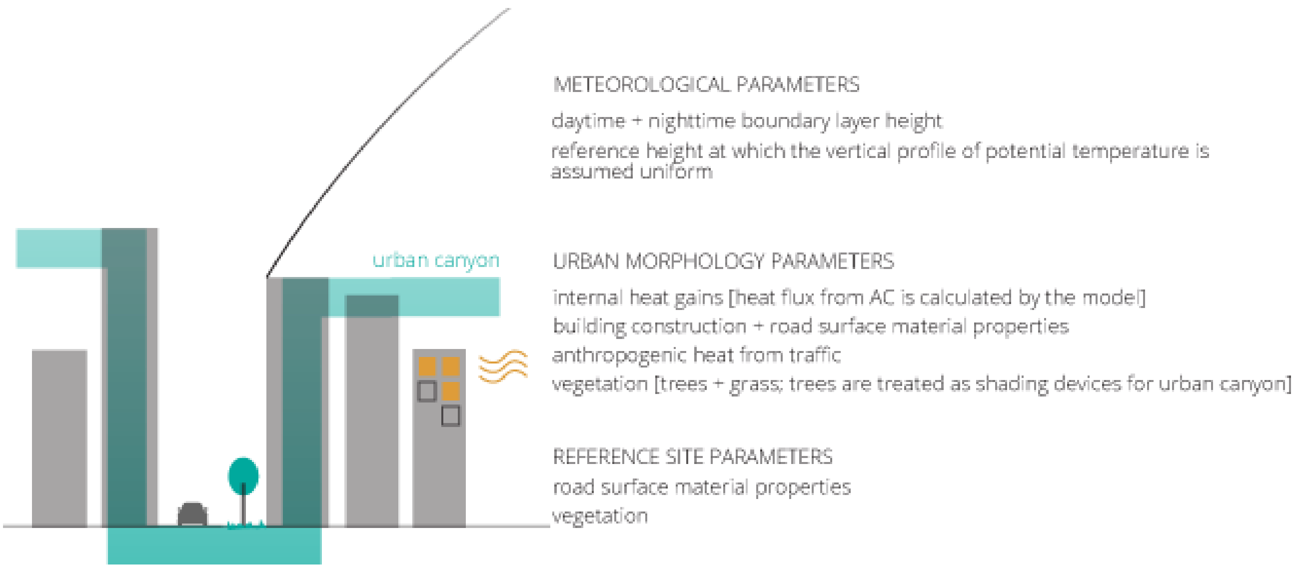


Figure 55: The UWG simulation parameters [14].

Table 23: The building parameters.

Description	District E3
Typology	Medium and High Rise Buildings
Building use	Residential
Glazing ratio	0.5
Cooling setpoint	24
Building albedo (walls)	0.5
Building emissivity (roof and walls)	0.91

Table 24: The Urban Parameters.

Description	District 3
Non Building Sensible Heat (W)	50
Non Building Latent Heat (W)	0
Urban Road albedo	0.165
Urban Road emissivity	0.95

Chapter 7: The modeling process

7. The modeling process

7.1 Background work

The energy performance of the buildings depends on the external conditions. The microclimate changes influence the different values of cooling loads in buildings. The neighborhood and district scale building energy performance is an ongoing research that improves the energy saving at a larger scale. There are some attempts of combining ENVImet and building energy simulation (BES) together. The study shows the effect of different microclimate changes on the energy balance of each building in the district. A second study done in Italy and Switzerland uses GISs (Geographic Information System) to estimate the energy consumption at a district scale. This is a de-coupled model, meaning the energy simulation runs separately from the microclimate simulation model. [173][174][175]

Another method of estimating the UHI phenomena at a mesoscale level in the cities is the dynamic downscaling method used for the city of Tokyo. This method uses the data from Global Climate Models and into Regional Climate Model. Although this method seems to show the difference between the present scenario and the future scenario, it does not include the expansion of the built-up environment, which is crucial to the use of energy for the cooling load.[176]

The energy consumption of different districts is connected to the building typology, their construction characteristic, the local urban microclimate, etc. Small changes in any of the mentioned parameters can improve the building performance. The building envelope defines the cooling load energy consumption in buildings. It is proven that a compact building envelope can save up to 10% in the cooling load used energy. The use of the glazing and the roof insulations have different impacts in different climates. [177][178][179]

The building energy performance is strictly connected to the urban microclimate and its changes. An updated measured database can improve the simulated models by calibrating them and then testing the UHI mitigation strategy. A study done in Athens, Greece, shows that the cooling load in buildings is almost double within the city. The peak electricity load for the cooling purposes may be three times higher than the suburbs. Another study shows that for tropical climates the overall cooling load increases by 25% due to climate change in the cities and for mid-latitude climates the energy spent in cooling increases by 15%. [180][181]

According to different studies, there can be energy savings in terms of the cooling load if the urban microclimate changes due to the different UHI mitigation strategies. A study conducted in France using a de-coupled model (metrological data and GIS software) shows an increase of three times the cooling load used currently in buildings due to climate change in a period of 100 years. This simulation model considers the building architecture; however, it does not consider changes in the urban form. Another de-coupled model simulated with detailed Building Energy Modeling shows that standalone buildings consume less energy for the cooling load than multiple buildings in an urban environment. The heat flows and the reflections in the urban canyon cause higher surface temperature.[182][183]

A study where several UHI mitigation strategies are applied in buildings such as solar reflective materials, shade trees around the building, ambient cooling achieved by urban reforestation and reflective surfaces shows a considerable reduction in the energy saving due to the reduction of the cooling loads. The study is done in 25 US cities and the simulation process refers to a de-coupled modelling. A study done in Sacramento shows a reduction of the peak load until 19% due to the application of reflective materials. The simulations used building energy analysis (DOE-2.1C) and a microclimate/planetary boundary layer model that calculates the changes in the air temperature due to the use of the highly reflective materials. [184][185]

The urban energy models have a potential to improve in terms of time consumption of the simulations, precision of the results, flexibility in the scale of the model, precision in the boundary conditions, etc. The urban areas have a large scale of heterogeneous sources and sinks of anthropogenic heat and natural factors. In the urban canyon there is a continuous exchange of energy. [186]

European cities have a clear definition of urban area and rural area. However, development tends to merge these two environments. In Dubai the city develops along the seaside, creating a linear city and making it more difficult to define the UHI phenomena. In Abu Dhabi, a densely built environment characterizes the main island. Meanwhile, different residential areas are developed in the desert part, creating a gap with the downtown area. The connection between the rural and urban site is not clearly defined. However, in the UAE, there is a continuous attempt at improving the energy savings in buildings, through different measurements. The air conditioning in the UAE is used in an excessive way, and finding retrofit strategies is a priority. [187][188][189]

A study conducted to quantify the uncertainty of the microclimate variables in the building simulation (local temperature, wind pressure, solar irradiation) considered as boundary condition for the simulation tool (in this case Energy Plus) shows that the uncertainty has a significant magnitude. The different model simulations have a percentage of error that must be considered while presenting the results. By assessing such error, the models have a bigger improvement; therefore, the results will be closer to the reality. Another study shows that the MAE (mean absolute error) is more accurate in evaluating the model-performance error. MAE is a more natural measure of average error than the RMSE (root mean square error).[190][191]

The boundary conditions are crucial before starting a simulation of a certain model. The air temperature, wind speed, wind direction, and specific humidity must be determined at different heights in order to have a more accurate model. A study conducted in Sydney through ENVI-met shows the numerical equations used in creating micro-scale models that show the surface interaction (different surface typology). These models show the microclimate analysis under different mesoscale conditions. [192][193]

The modelling of the vegetation and the impact that it has in reducing the external air temperatures is analyzed in different climates. The evapotranspiration process helps in reducing the air temperatures, thereby improving the outdoor thermal conditions. An increase of the vegetation in the urban 'pockets' can decrease the air temperature by 0.5°C. The study considers six variables (surface albedo, sky view factor, altitude, shrub cover, tree cover and average height to floor area ratio) using a regression model. [194]

The anthropogenic heat has an important impact in improving the urban microclimate. Cities with an efficient public transportation and central district cooling plant have a positive impact in improving the urban microclimate. According to the simulations done in city centers, it is shown that the anthropogenic heat can contribute an increase of almost 2-3°C. Annual average values show that cities like Chicago (53 W/m^2), Montreal (99 W/m^2) and Budapest (43 W/m^2) have anthropogenic heat variation from 20-40 W/m^2 in summer and from 70-210 W/m^2 in winter. In the anthropogenic heat, graphic has a peak in the morning time and in the afternoon time corresponding to the high traffic schedule. The impact of the anthropogenic heat into the microclimate models must consider all the factors contributing to it (it should include the general, major sources of energy use in buildings, industry and vehicles). [195][196]

A combination of numerical mesoscale model and physical street canyon pollution dispersion model shows that the shape of the roof of the building has a bigger impact on the urban air quality than the distance between the buildings. It is also shown that the impact of the building shapes goes three times higher into the impact of the wind. These factors are considered while modelling the boundary layers of a district. The wind specifications are important in specifying the wind flow within a certain district considered in the study. The more accurate the database (site measurements) the closer the model is to the reality. The cooling effect of the wind helps in mitigating the UHI effect. Different geometric scenarios of buildings prove that the air temperatures can be reduced by improving the wind flow. Another study which analyzes different model geometries in a wind tunnel shows that increasing the wind direction from perpendicular to the façade to 45° drastically improves the wind flow. [197][198][199][200]

The surface temperature parameter has an impact on the mean radiant temperature; therefore, to the mean radiant temperature. Defining the correct soil layer that make possible the heat fluxes determines the mean radiant temperature that is connected to the surface and air temperature. A land surface temperature documenting process showed how the urban landscape can change and how the decrease of the vegetated area and the increase of the buildup are in the city of Indianapolis, Indiana. The system created makes a time change description of the land use. There is also an impact on the UHI phenomena. The zoning of the different urban districts and that landscape distribution is connected to the surface energy exchange, micro- and mesoscale climate. [201][202]

Another important parameter is the definition and the use of the specific and relative humidity. Depending on the different urban climates, the importance of the relative humidity is different. Furthermore, the albedo of the materials as a first setpoint into the models and defines the reaction of such surface toward shortwave and long-wave radiation. A study conducted with different urban models shows that the absorption of an irregular urban model increases to 20% compared to a flat surface of the same material. The models reassemble the urban context and canyon by cubic concrete blocks. [203][204]

Software description

In this section the comparison of the models done in ENVI-met will be shown. This is a CFD tool designed for urban planners and other professionals in the construction and urban planning field. It takes into consideration different obstacles and calculates the temperature, relative humidity, and wind speed changes (it simulates the microclimate in different design conditions with UHI mitigation interventions) due to different proposed interventions within the city. In paragraph 7.3-7.4 the comparison process of the models is described. Basically, a base case is created in order to be as close as possible to real conditions of the same district. A second model is created by adding the shading devices with the properties of a high reflective material. The results of the PET and air temperature between the first and second scenario are compared in showing the difference between both models. [205][153]

The models can be designed in 2D or 3D, giving flexibility in testing different geometries. This software is used also to compare different scenarios of the trees in one district although the evapotranspiration process is limited. The latest version of ENVI-met (2017) shows an improvement in the post-processing part.[20][206]

Several studies have been conducted to analyze the effect of the greenery in mitigating the UHI phenomena. ENVI-met makes this possible due to the large library and the different plants variations present in the software. In other cases the empirical models show similar results. The definition of the boundary conditions and the size of the models are crucial to the precision of the results. [41][152][207]

Another software used in this study is Grasshopper. It is a tool developed for several purposes and calculations; however, in this research it is used for the optimization of the shading devices and for the cooling load calculations in the E3 district and villa district. Grasshopper has a large possibility of adaptation towards the scale of the analysis and its purpose. Several plugins such as Ladybug and Honeybee are used and tested in this study. These plugins are created for designers and engineers to create sustainable buildings and environment. [11][208]

The position of the shading devices is defined by the shaded areas and the zones that take the higher amount of solar radiation. To calculate the correct position, tools like Ecotect and DIVA-for-Rhino are used. DIVA-for-Rhino is a plugin that runs with Rhino and Grasshopper. It helps in having validated simulations on the first phase of the concept design. It can be used for thermal, daylight, and glare simulations, but in this study it is used for the solar radiation analysis. An earlier version of Ecotect is also used in this research to define the shaded areas in the districts. (Independent version of Ecotect, currently this software is part of Revit, an Autodesk production). [209] [210] [211]

Matlab is a software that in this research is used to prepare the script that runs the UWG. The information of the buildings, the environment, and the boundary conditions are inserted into the script. The result from the simulation is a yearly weather file. Matlab interacts with the UWG since there are several versions of it. Matlab is also used to elaborate the results obtained from ENVI-met post-processing part. With basic scripts the values obtained from the simulations can be averaged and processed in graphs that visualize the changes in the district taken into study. [212][213]

Defining the boundary conditions and the boundary layer is a crucial point in CFD software as it defines the initial condition from where the simulation starts. The more precise the initial information is, the closer to the reality the results will be. The microclimate modelling is used more and more to define the effects of the different UHI strategies and define the most efficient one. However, the coupled models take time and the precision of the results has to be improved. The decoupled model combining the microclimate with the building energy gives reasonable results. Table 25 makes a list of all the software described above. [214][215]

Table 25: Software description.

Software Description				
Software	**Description**	**Usage**	**Advantages**	**Limitations**
ENVI-met	CFD software	base simulations	fast processing user-friendly	AH calculations are not included
Grasshopper	Plugins: Ladybug and Honeybee	energy simulations	user-friendly	Not a CFD software
DIVA-for-Rhino	Plugin for rhino	solar radiation	fast processing	-
Ecotect	Revit plugin	shading analysis	fast processing	-
Matlab	mathematical model	post processing	fast processing	scripts analysis

7.2 The Shading Devices Modelling

Figures 56-58 show an analysis of the traditional design of the shading devices proposed in chapter 5. Figure 59 is an analysis done in scSTREAM and it shows the wind flow through the louvres proposed in this design. The optimization process, done partially in Grasshopper and in scSTREAM, shows a combination of the maximized shaded area and the best wind flow speed passing through the louvres. Optimizing the height of the louvres to have both maximum shading but also the necessary ventilation was the main aim of the research for this typology. Moreover, the idea is that the role of this opening is to improve the wind flow within the districts. The width of the louvres in both cases is 20 cm, the optimized angle 60 degrees, and the number of the louvres 16. Figure 60 shows the direct solar radiation reductions under the ‘cool’ shading device design proposed in chapter 5. Figure 61 shows how the wind flow is improved by using scSTREAM. This model tries to improve the traditional concept of ventilation. Even though in a single device the impact might be very low at a higher scale, the impact is very important as the wind flowing in the district can be improved. In this case the optimal opening is 19 degrees and the optimized length is 3 meters. In the Annexe section an application of this shading device type is shown in a real case study in the villa district on the main island of Abu Dhabi.

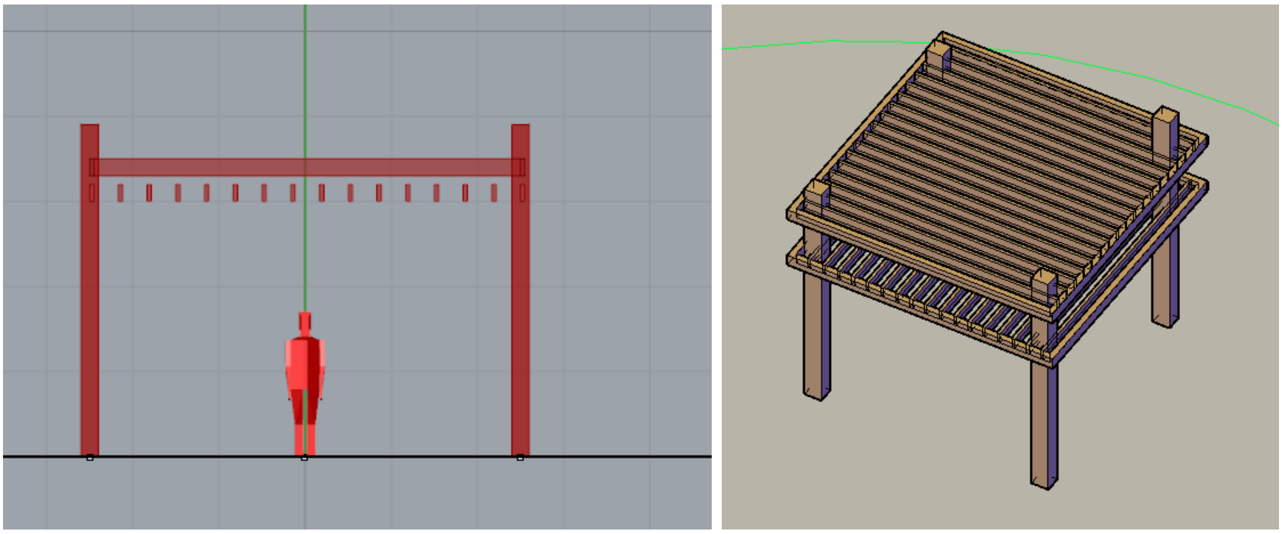


Figure 58: Section of the traditional device in Grasshopper.

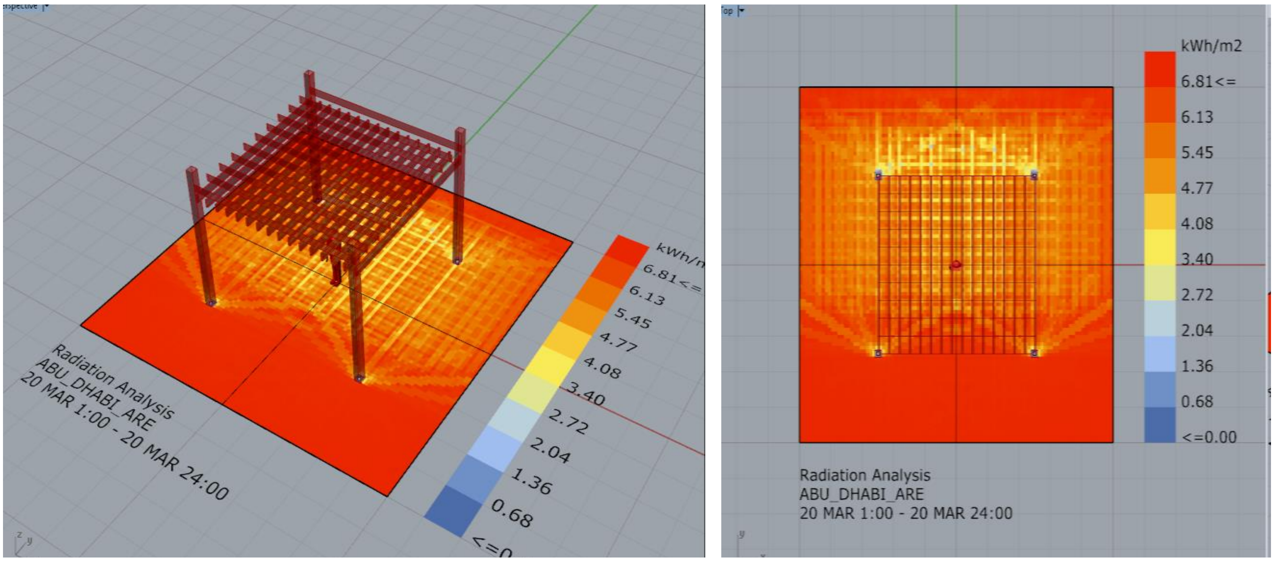


Figure 56: Axonometric view of the traditional device in Grasshopper, model A.

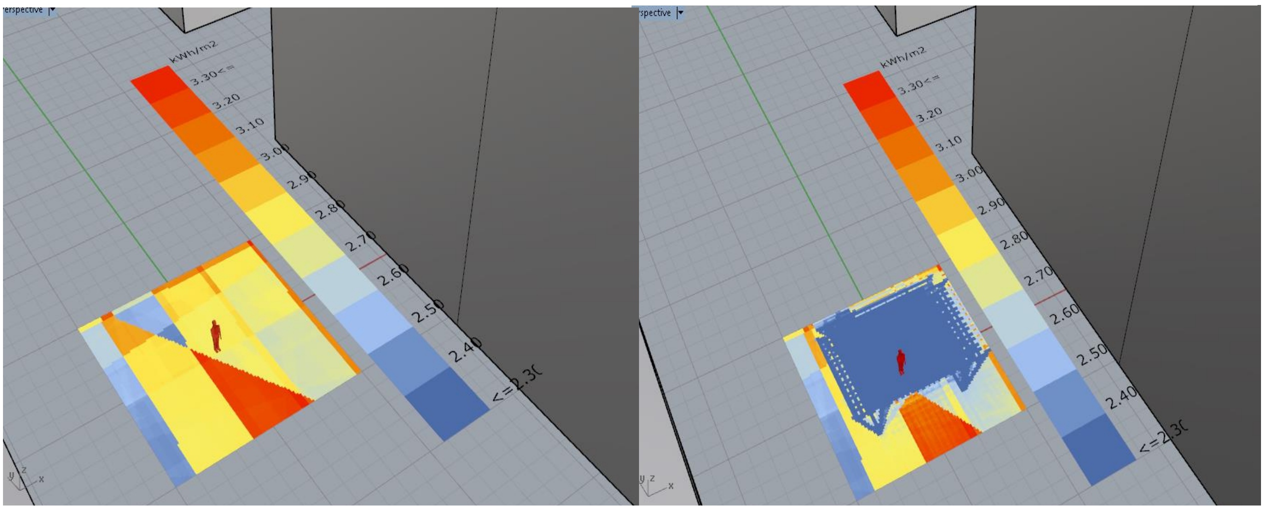


Figure 57: Axonometric view without the traditional device in Grasshopper.
(Scale 2.3-3.3 kWh/m2)

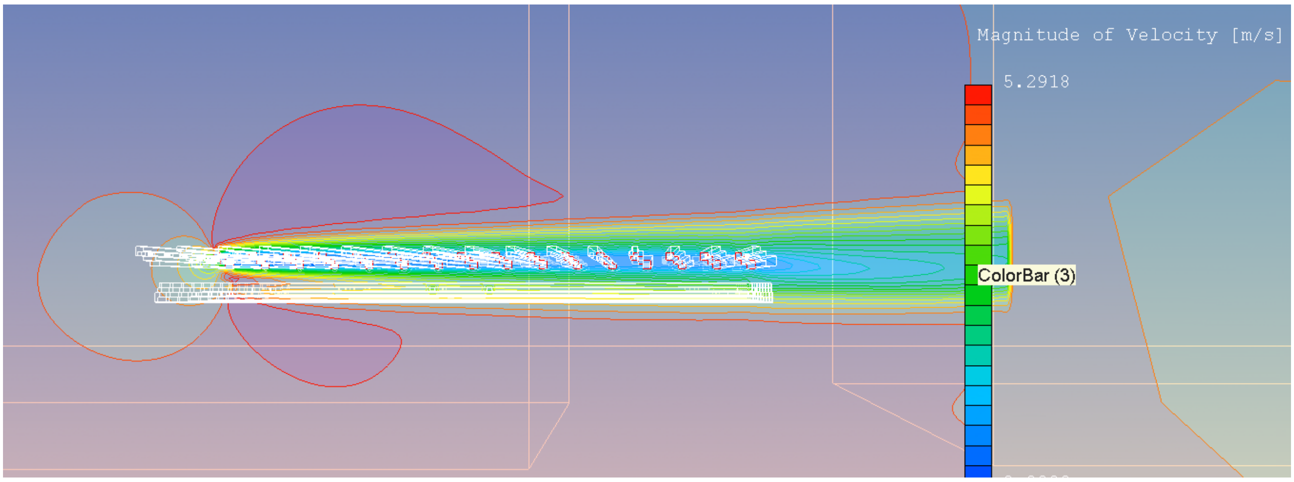


Figure 59: Wind flow direction through the optimized traditional device in scSTREAM. (Scale 0.02-4.6 m/s)

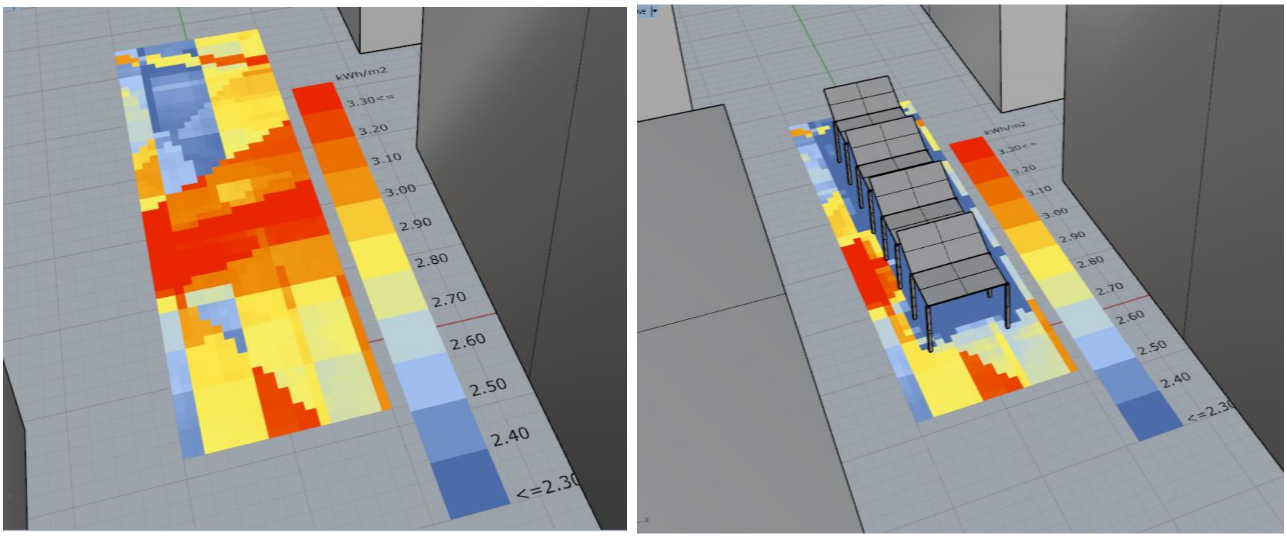


Figure 60: Axonometric view without the traditional device in Grasshopper, model B. (Scale 2.3-3.3 kWh/m2)

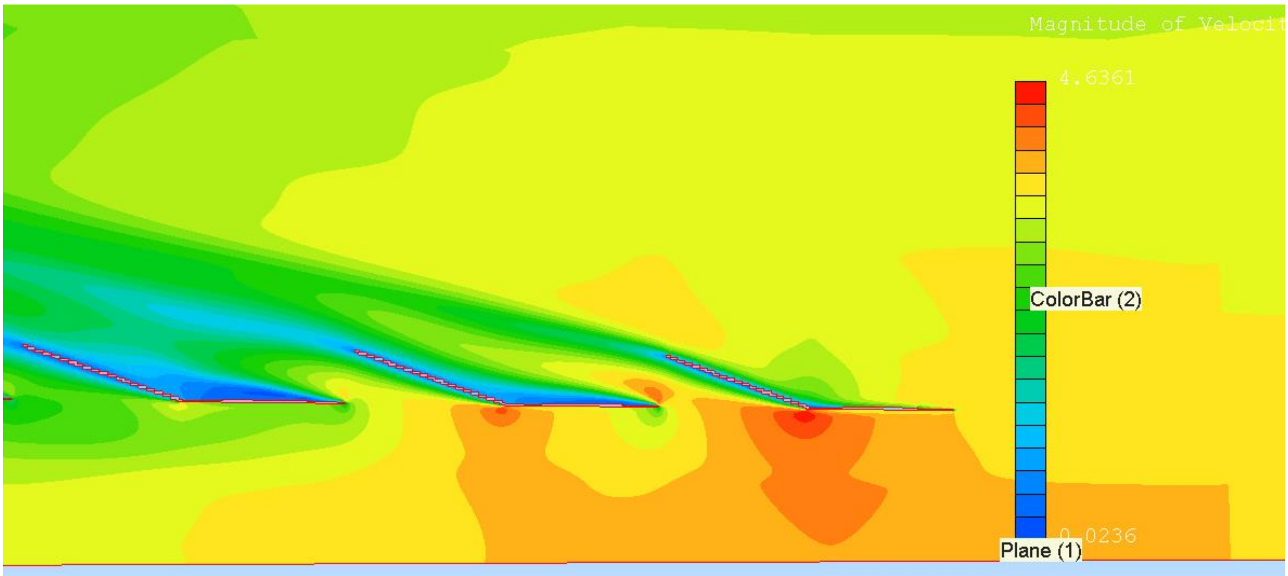


Figure 61: Wind flow behaviour thru the optimized traditional device in acSTREAM. (Scale 0-5.3 m/s)

7.3 Outdoor Thermal Comfort Models

For this scope of work, the most important part is to show the improvement of PET due to the shading devices. The results are focused on the E3 and the villa district since they represent the biggest amount of the district typology in the main island of Abu Dhabi. Table 26 lists the plan from ENVI-met of both districts, the 3D model done in this software and some initial PET results from the post-processing tool: Leonardo. Table 27 shows the details of each shading device applied in the model and Figure 62 shows a detailed profile of the soil modified from the standard one found in the ENVI-met library. These modifications improved the heat fluxes in the soil and the irrigation process.

Table 26: ENVI-met Models

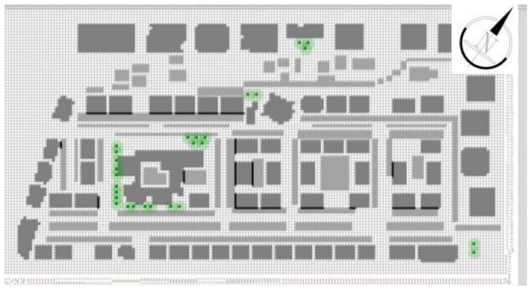
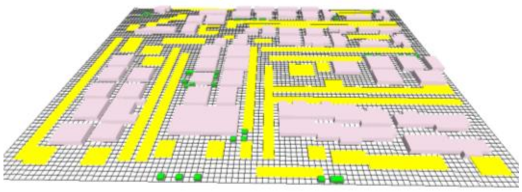
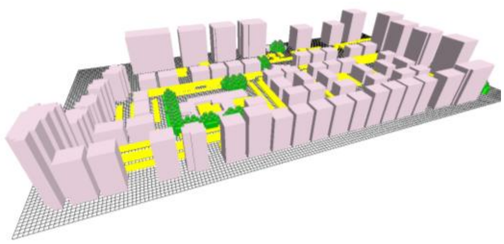
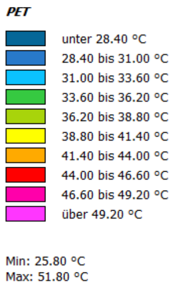
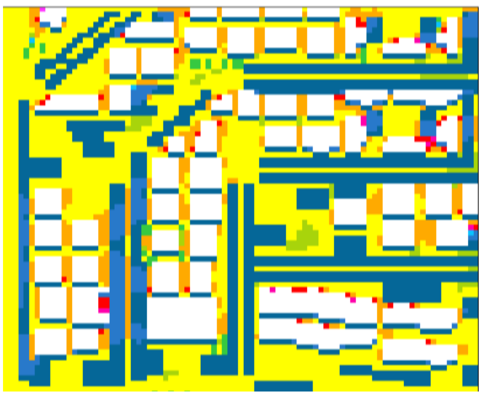
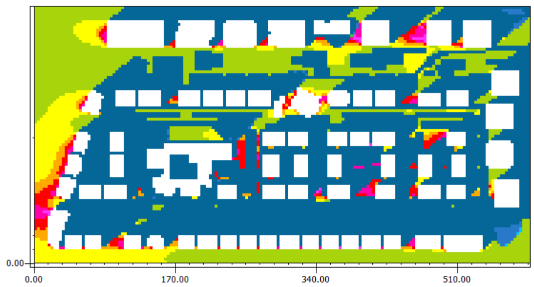
ENVI-met Models (ENVI-met scale 180x180)		
	District 1 - Villas	District 1 – E3
PLAN		
3D MODEL		
PET Results from LEONARDO 		

Table 27: E3 District, ENVI-met detailed shading model.

'Cool' Shading	'Green' Shading
Height: 500cm	Height: 500cm
Width: 500cm	Width: 500cm
Thickness: 10cm	Foliage albedo: 0.7
Albedo: 0.85	Leaf type: Deciduous leaf
Thermal conductivity: 0.17	Root depth: 1.4M

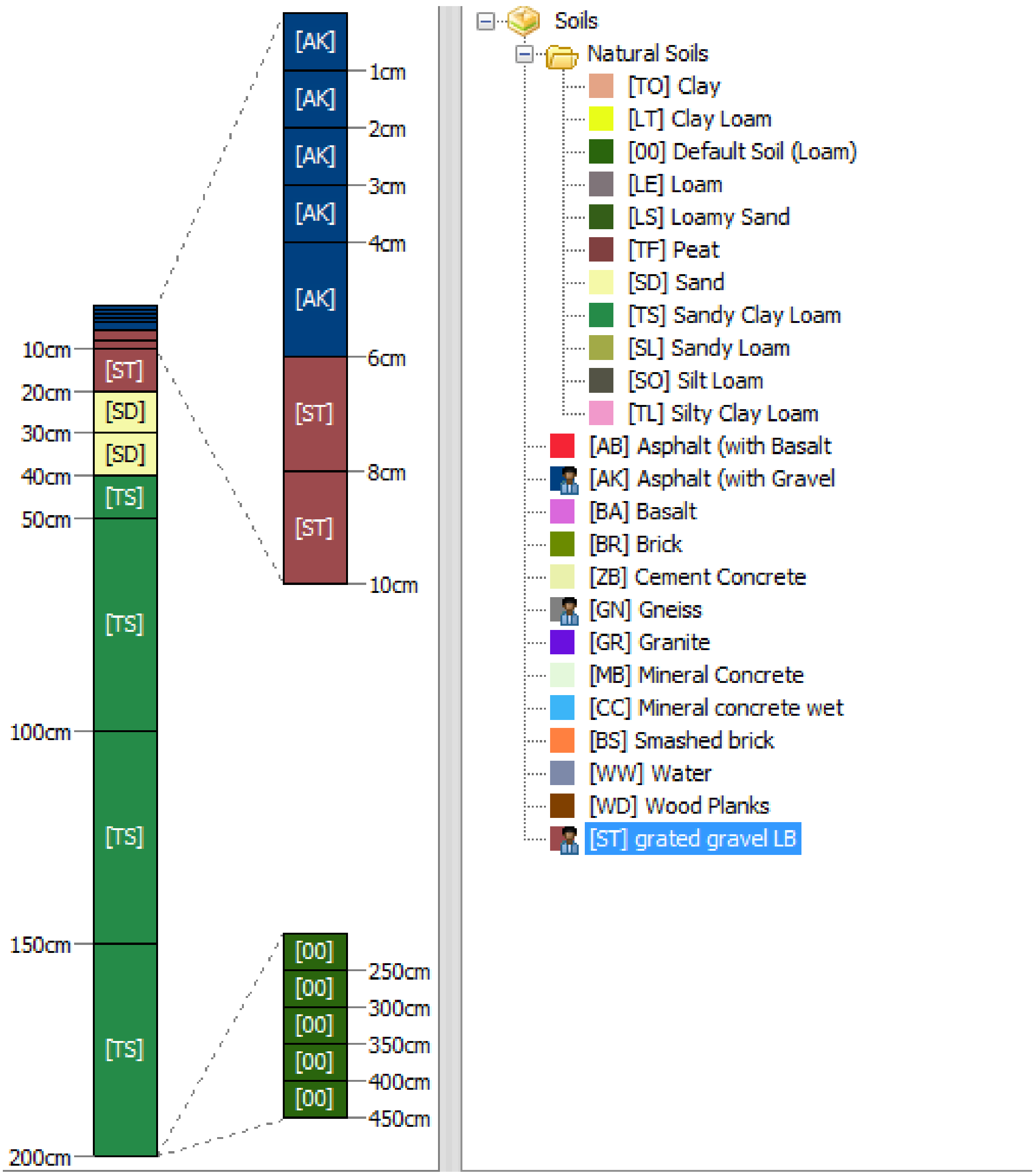


Figure 62: ENVI-met modified soil profile.[216]

Table 28: E3 District, ENVI-met detailed model.

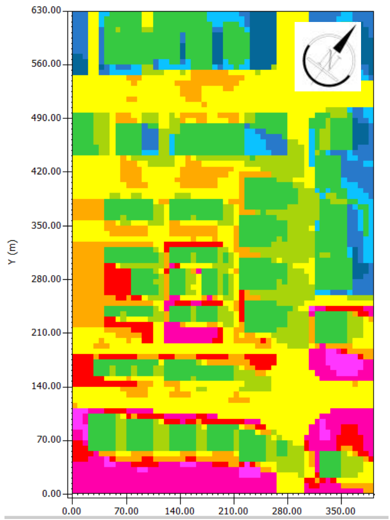
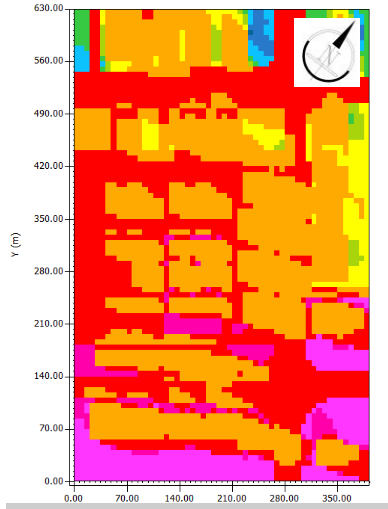
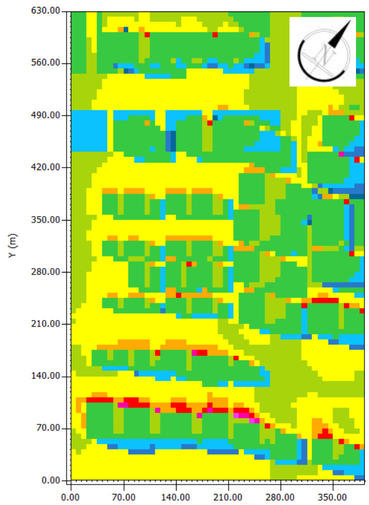
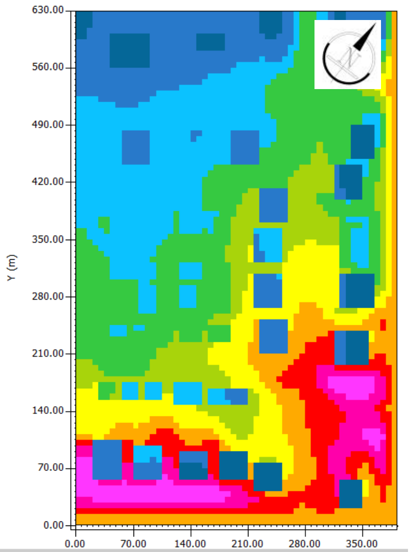
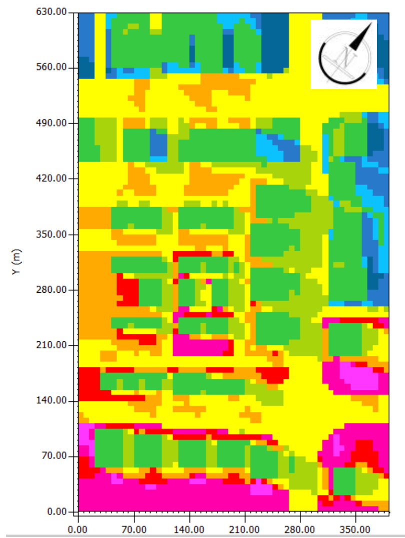
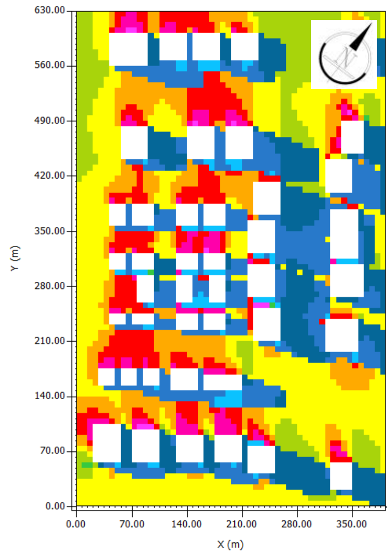
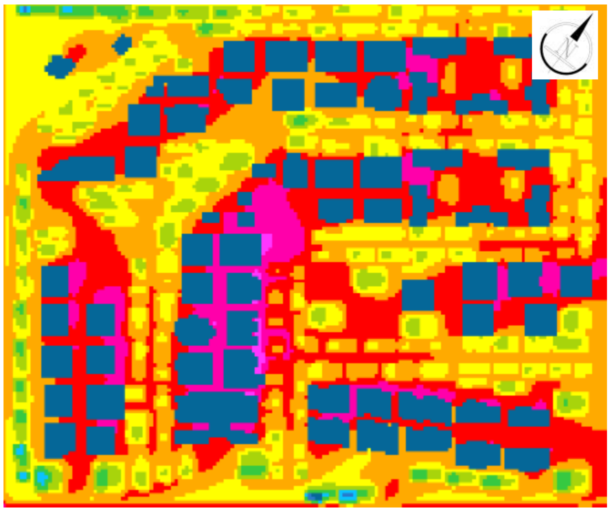
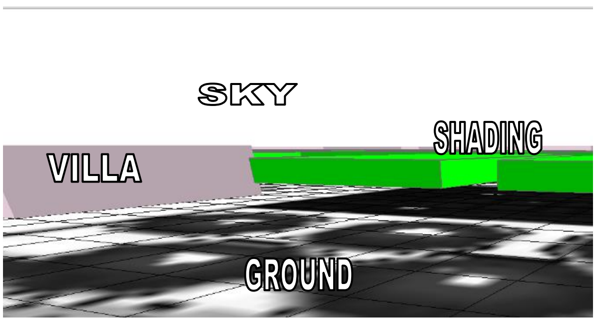
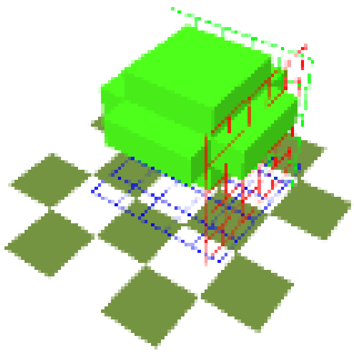
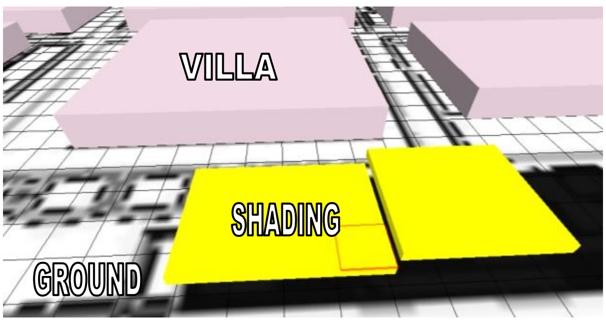
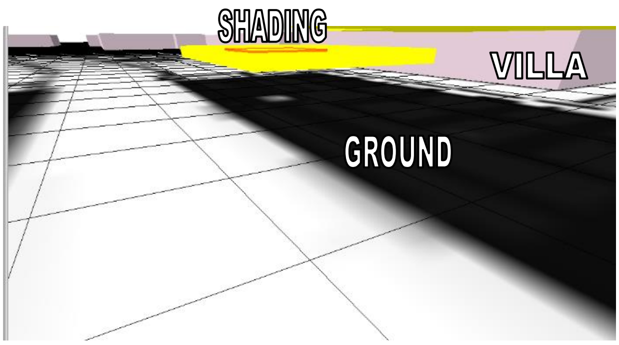
E3 District_ENVI-met Detailed Model (size 180x180)		
SURFICE TEMPERATURE (°C)	SENSIBLE HEAT FLUX (W/m²)	SOIL HEAT FLUX (W/m²)
		
AIR TEMPERATURE BIOMET (°C)	AIR TEMPERATURE (°C)	PET (Scale 28-50°C)
		

Table 29: Villa District, ENVI-met detailed model.

<table>
<tr><th>The district 3D model (size 180x180)</th><th>The villa district temperature changes (scale 30-32 degrees)</th></tr>
<tr><td></td><td></td></tr>
<tr><th>3D of the ‘green’ shading device</th><th>Single unit of the ‘green’ shading device</th></tr>
<tr><td>
</td><td></td></tr>
<tr><th>3D of the ‘cool’ shading device</th><th>Single unit of the ’cool’ shading device</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

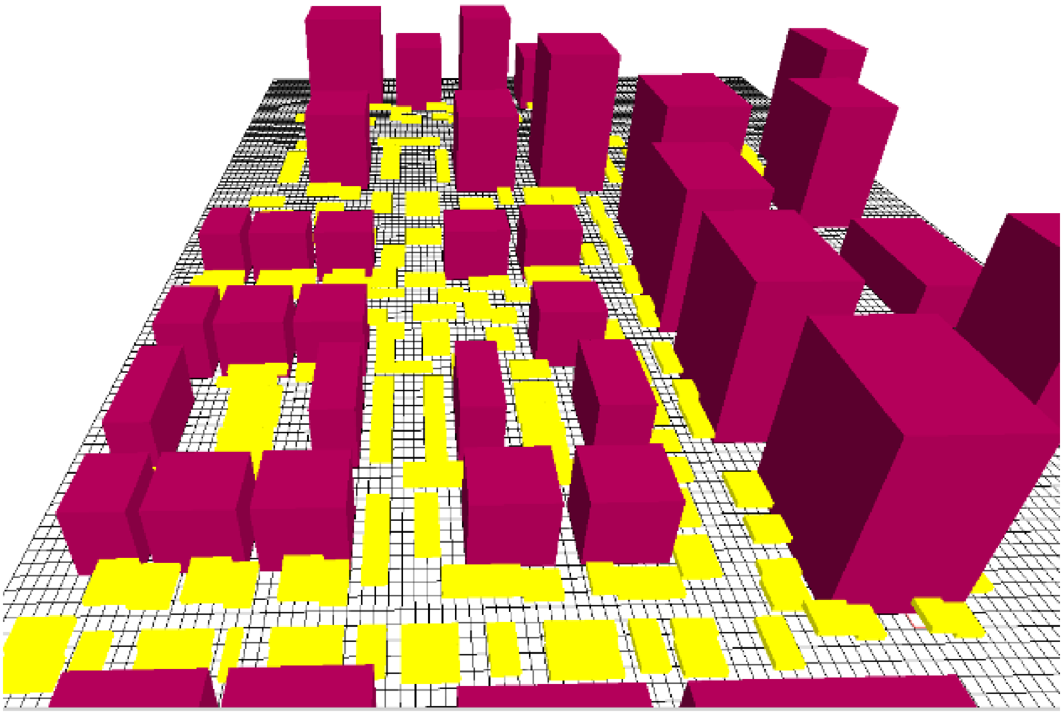


Figure 63: E3 District, ENVI-met detailed model.

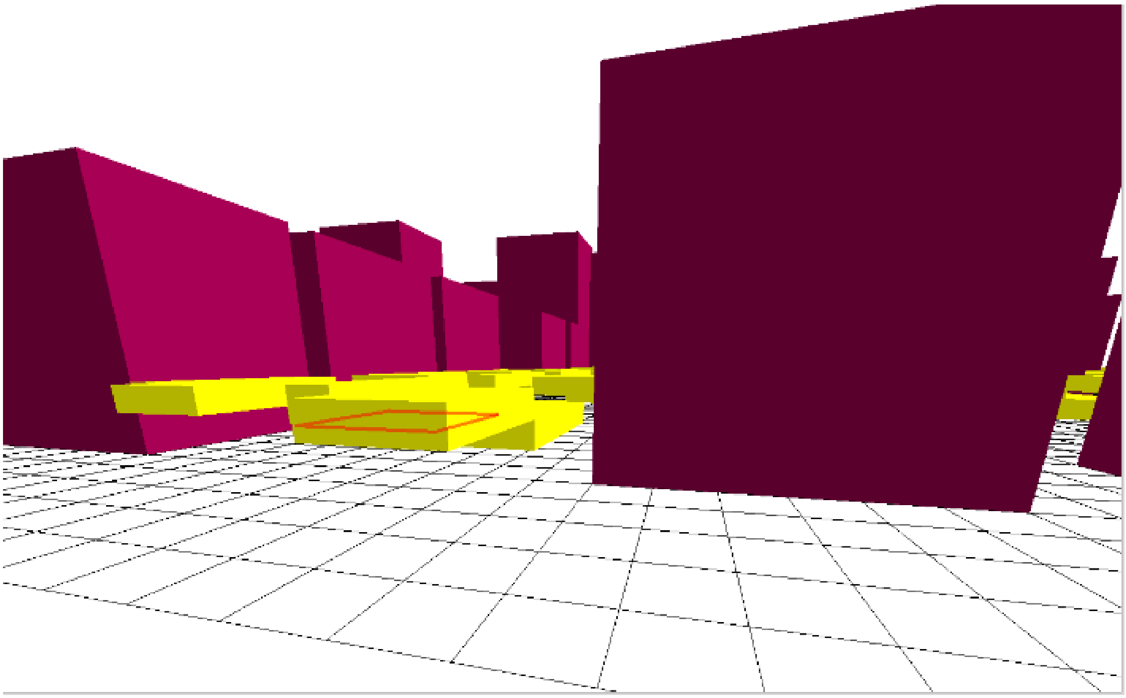


Figure 64: E3 District, ENVI-met detailed model showing the two levels of the shading devices.

Table 28 shows the surface temperature, the sensible heat fluxes, the heat fluxes, the air temperature at one meter, the air temperature at 2 meters, and the PET of the base case. In this table a part of the E3 that was modified due to several trials of the 180x180 model is shown. Since the full district model required excessive time for the scale of details that this model runs, the E3 is divided. Previous trials with the materials from the ENVI-met library were showing constant heat fluxes; meanwhile the modified soil profiles show changes in the heat fluxes of the soil as expected. Table 29 shows a detailed model of the villa district with the two different shading devices proposed. The 3D is detailed and the shading devices are played in two levels, five and six meters.

In figures 63-64 the 3D done in ENVI-met of the 15 buildings (a section of the district) are shown. It is shown that they cover the parking lots and the inner parts of the district. It is also shown that they are positioned at two different levels to improve the wind flow. The ‘cool’ shading device (shown in yellow) has the properties of a cool surface and a reflectance of 0.85, assuming that it is a white tent. The thickness is considered 0.1 m or 10 cm, as this was the smallest size that would be allowed to build the model at this scale. Even though in the 3D it seems that the height is one meter, it is not the real size. In the 3d model the size depends on the pixel sizes. The dimensions of the shading devices are 300 cm x 400 cm x 500cm and 300 cm x 400 cm x 600cm. The soil is more detailed. The asphalt is recreated, as the one in the template did not consider the heat fluxes in the different layers. The walls of the buildings do not have window division; however, there is a new wall with average characteristics. The green shading is assumed to be a tree, created with the characteristics of local trees, a height of 5 meters, and a root system that can take water from the soil. The thickness of the tree is one meter while in reality it might reach 0.5 meters assuming the planting of the specified types of plants. The shading devices in this model are not linear but interrupt in order to improve the air circulation and bring the model closer to the real conditions.

7.4 The Energy Models

After all the evaluations in terms of urban scale intervention and shading analysis, one of the aims of this research is to measure this intervention in terms of energy. The whole process starts with the base files, then there is the creation of a link between the files and the simulation. The base files are elaborated by ENVI-met then the weather results coming from it were processed under Matlab with 2 different scripts as described below and then in the end brought to Grasshopper. The biggest difficulty in this process was the weather file link. Since the simulations at the first step are daily ones, and the ones in the last step are yearly ones, the weather file had to be created for a full year based on the 4 existing days. There were difficulties met on the way that will be better described at conclusions but this study pointed out the important steps and defects in each step that will have a place for improvement. This can make it possible for different stakeholders such as urban planners, architect, engineers, real estate developers, and government entities to analyze and use the results in each intervention in order to contribute to mitigating the UHI but also to increase the life quality of the citizens of Abu Dhabi.

The step before ENVI-met was AutoCAD. The district was elaborated there in the two mentioned options, before and after the intervention in the 2 dimension scale. In this program, version 4.0, it was possible to rebuild the full district based on a bitmap image taken from an AutoCAD file. The image stays as a base. The scale is adapted according to the pixels of the program. Each pixel represented 4 meters in the plan. This brought some movement from the base plan but still the model was fully constructed. Two files were built, one base file was explained better and then a new one was copied and created with the inserted shading. Basically, the first file was the same for both. The models were built in the map area, then they were brought into the simulation settings where various lists of parameters were set. In the map area, the streets, their materials, the pavement and asphalt, the building typology and height, and the shading characteristics are defined. Here the model is being built in 3d in parallel with the 2d. Since the height of the building varies there is a scale factor applied to the 3d in order to have a lighter version of the model (figure 65-67). The sizes of this models are 180x180, the second more detailed scale in the ENVI-met software (the lowest resolution is 100x100 and the highest is 250x250). There were some difficulties in applying a wide range of materials to the surfaces. At this point the program must improve the capacity of modifying the materials. On the other following step the models were set into the simulation area. The boundary conditions were one of the important steps. The files were provided from Masdar for the year 2016. Then, other parameters such as the location and the specific day of the year to run the simulation were specified and then the simulations went on. The simulation day was calculated on the equinox and solstice when there is the bigger difference of the sun angle. So the days were 23 March, 21 June, 23 September and 21 December. For each of these days as shown below, there are excel files of the temperature, relative humidity and wind speed. Among the different levels of the different pixels in the third dimensions k=0 was chosen at a height of 1.5 meters where the effect of the shading is higher. At this height there is a medium range of all the above parameters that are associated with each plan pixel. However, the gradient of temperature was calculated and then inserted in the Grasshopper energy simulations. All these values are placed in table 30 below. They were input for the Matlab script. In the different images below, the change of the temperature is visible in each day along with the temperature and the wind speed. In the shaded file there is a significant decrease in the temperatures and change in the relative humidity even though the idea of the design of the different shading is to make them breathable, meaning let the air go through them in order to improve the air movement during the night. The sample given in this table is only a part of the results before entering into the Matlab weather file creation. The day of the simulation is 23 July 2016 and the time shown in the images is 14.00. The values of air temperature vary from 40 to 44°C. This low variation is common in the summer season.

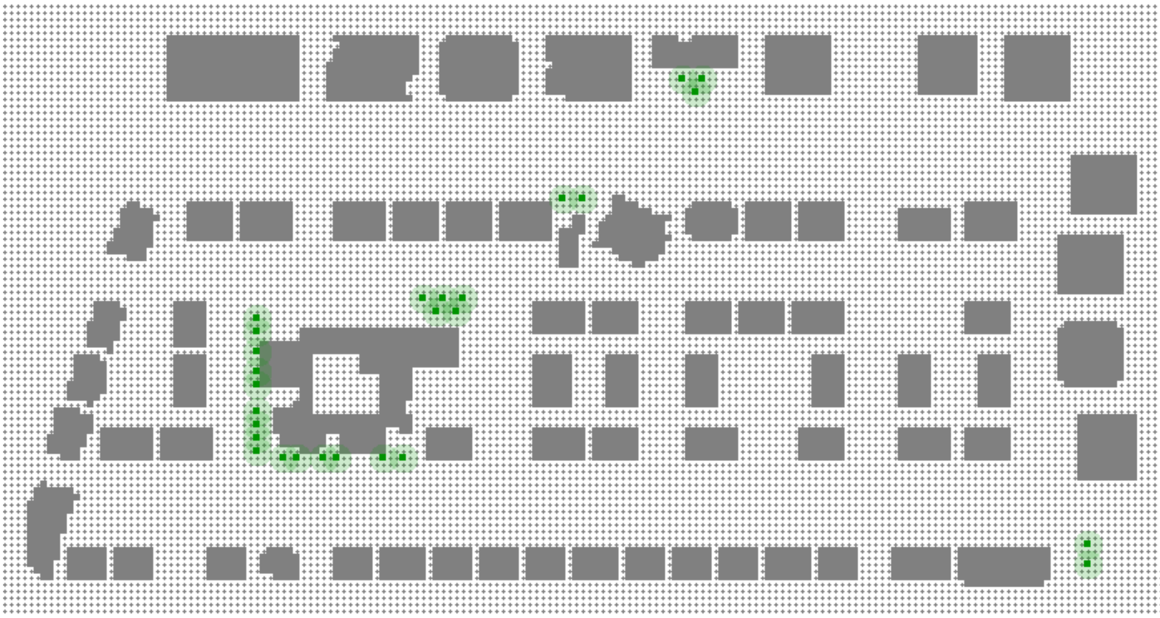


Figure 65: Base file in ENVI met (size 180x180).

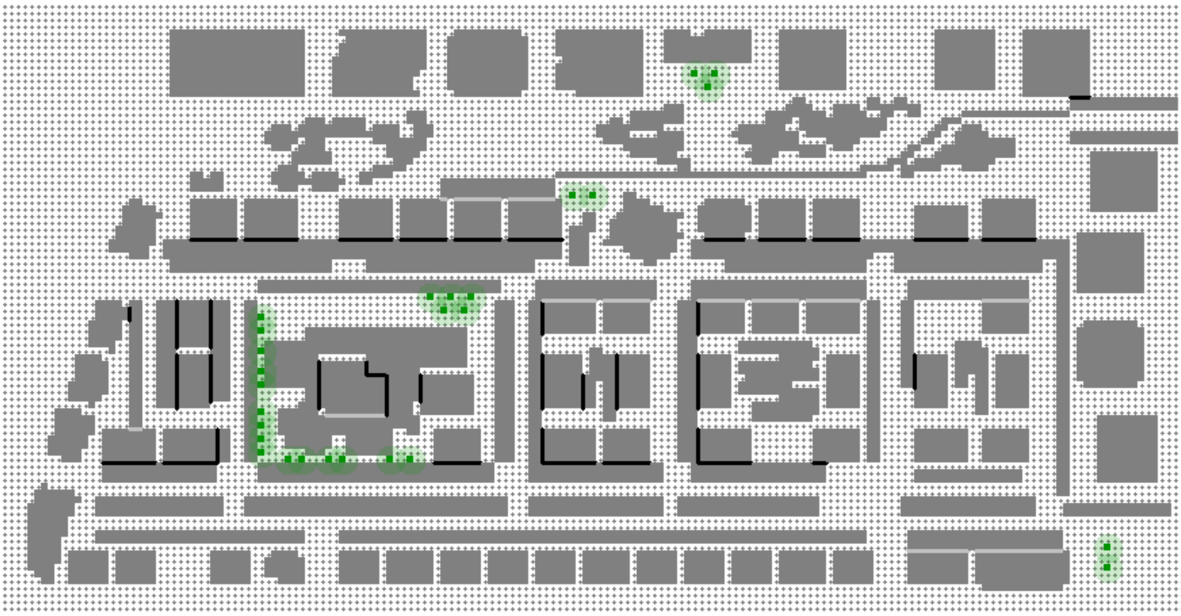
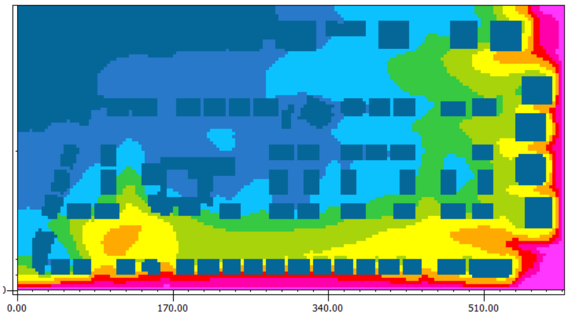
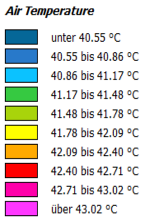
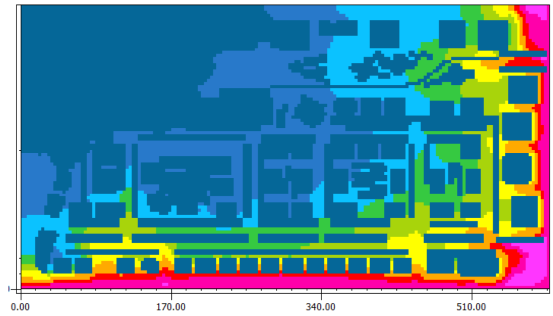
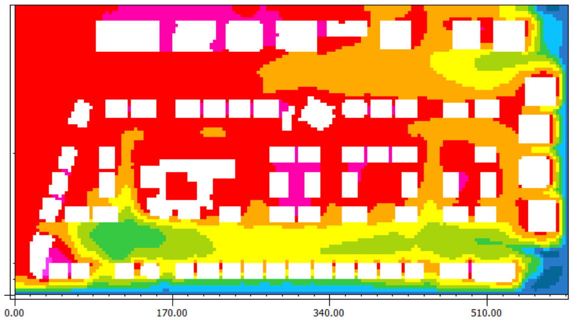
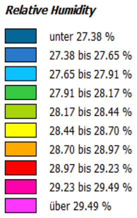
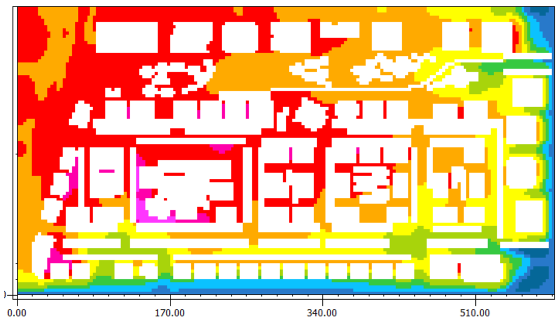
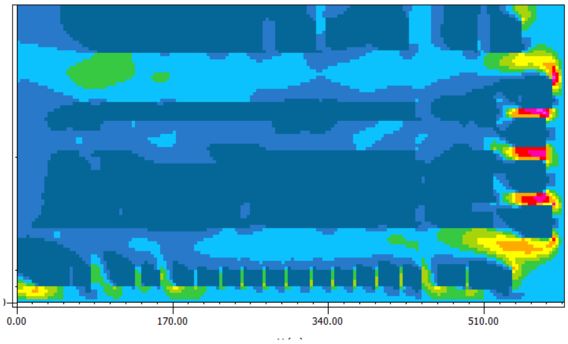
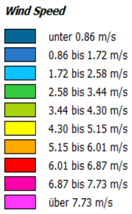
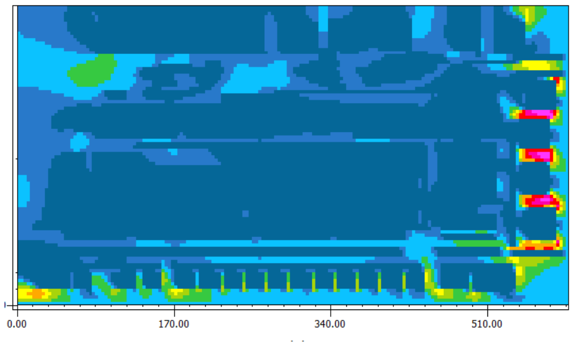


Figure 66: Second file, ENVI-met model with shading devices (size 180x180).

(The area of the shading devices is 20% of the total district area).
No additional trees are considered in this simulation.

Table 30: ENVI-met results - shaded file (example of the results 21 June 2016, hour 14.00, height 1.5 meter).

Summer results for the base file – air temperature (Scale 40-44°C)		Summer results for the shaded file – air temperature (Scale 40-44°C)
		
Spring results for the base file – RH (Scale 27-30%)		**Spring results for the shaded file – RH (Scale 27-30%)**
		
Autumn results for the shaded file – wind speed (Scale 0-8m/s)		**Autumn results for the shaded file – wind speed (Scale 0-8m/s)**
		

The shading devices location is carefully analyzed thru the software named Ecotect. Thru this software the areas exposed to the sun are pointed out and evaluated. After this analys the files went to Autocad to build the geometry and then to Grasshopper to make the energy analysis. The measured temperatures in the models are at e height oaf 1.5 meters. The gradient of the air temperature changes at different levels is calculated by averaging the differences of each pixel until the highest building. This gradient change is then considered in the Grasshopper energy simulations. The change of the temperatures and the different marks are also an important step for the outdoor comfort and walkability such that even though they are not the main aim of this study they are still a feedback that improves the lives of the citizens. It is a valuable point to achieve among the Abu Dhabi 2030 goals [211].

Abu Dhabi has a climate with high levels of air temperature during the summer season (40-44°C). Combined with the shading devices, local trees planted in the district can contribute to further improvements of the air temperature. The local trees growing in the Middle Eastern Countries (Annex) do not need a large amount of water to be irrigated. Fountains and other cooling features could be integrated into the district; however, in this research the focus is in the effect of the shading devices on the district scale. In any case, they are not considered in the simulation due to the focus on the shading devices.

Tables 31-32 show the results of the 4 days from ENVI-met. They were placed into excel and then sent to Matlab to be processed. The first script of the software creates the year weather file and the second script brought this file into an EPW file that can be used in Grasshopper. As mentioned above, the k=0 at a height of 1.5 meters is the study level of the different parameters such as the temperature, relative humidity and wind speed. The Matlab step was a very important part because due to this step it was possible to recover an EPW file needed for the Grasshopper Simulations. The rural weather file was taken from the Masdar Institute, located very close to the Airport. From ENV-met first round of simulations, it was possible to have the weather file within the city without the shading devices. An increase of the air temperature of during the evening times is noticed in the different simulations. After the shading devices appliance the simulations are showing a light decrease of the temperature as per the graphics shown in figures 67-68. In the four days of the analysis the study was narrowed to each pixel level. ENVI-met gave the possibility to create a daily weather file. The output form the four days analyzed in this study is similar. The evening time shows an increase of the air temperature. [212]

To analyze the cooling load of the buildings based on the results taken from Matlab, the software Grasshopper [11] is used with the main plugins, Ladybug and Honeybee. Having a coupled model that combines the outdoor conditions and their influence with the indoor conditions requires time. Energy Plus, which Grasshopper uses to calculate the cooling load is BEM (Building Energy Modeling) software, which uses the results obtained from ENVI-met (the weather file) to calculate the cooling load (figure 69-70). The BEM software considers the Canyon temperature constant (most of them consider this and others use the rural weather file) and the microclimate models consider the multilayer temperature (and the other changing parameters). The proposed height of the devices in the first and second district is five meters. Such height will have a bigger impact on the buildings and on the air ventilation. The width of the devices varies according to the different zones where they are applied. Over the parking area they have four-meter width in order to cover a big part of the walking path. On the open proposed play areas, they can reach a width of ten meters.[217]

In the first district the outdoor temperature considered for the cooling load simulations is taken in different layers. The gradient of temperature difference above the shading device level is used as an input for the Grasshopper software. The weather data information in the villa district is taken under the shading device in the CFD simulation. The results from the villa district are quite promising. However this part will be treated in chapter 8.

Table 31: Shaded ENVI met value of the full E3 District

	SPRING EXISTING			SUMMER EXISTING			AUTUMN EXISTING			WINTER EXISTING		
	T (degree)	H (%)	W(m/s)	T(degree)	H (%)	W(m/s)	T (degree)	H (%)	W(m/s)	T (degree)	H (%)	W(m/s)
1	21.1	59.1	2.3	30.8	60.6	2.2	29.5	64.8	2.0	18.3	74.3	1.5
2	21.1	60.0	2.3	30.2	62.0	2.2	29.1	65.3	1.9	17.8	74.9	1.5
3	20.5	60.8	2.2	29.5	63.1	2.1	28.6	65.7	1.9	17.5	75.5	1.5
4	20.5	61.7	2.2	28.9	63.6	2.1	28.1	66.5	1.8	17.2	75.9	1.5
5	19.8	62.1	2.2	28.4	63.8	2.1	27.7	67.0	1.8	16.8	76.1	1.5
6	19.7	62.7	2.1	28.0	64.2	2.1	27.6	67.1	1.8	16.7	76.7	1.5
7	20.4	63.3	2.1	28.6	62.8	2.0	28.9	67.1	1.8	16.8	77.3	1.4
8	22.4	61.6	2.1	30.9	56.3	2.0	31.4	62.8	1.7	17.9	77.5	1.4
9	24.6	55.6	2.5	33.7	47.3	2.3	33.9	52.9	1.7	19.9	74.8	1.4
10	26.5	49.0	2.6	36.5	38.8	2.4	36.2	43.4	1.7	21.8	68.6	2.0
11	28.3	43.5	2.6	38.7	33.1	2.4	38.3	35.0	1.7	23.3	63.4	1.5
12	29.6	38.2	2.6	40.2	29.4	2.4	39.6	28.7	1.6	24.3	58.6	1.4
13	30.3	34.3	2.5	41.1	28.3	2.3	40.1	25.7	1.6	24.9	54.9	1.4
14	30.1	32.7	2.5	41.3	28.8	2.3	40.1	25.8	1.6	25.1	53.1	1.4
15	29.5	35.1	2.5	40.9	30.4	2.2	38.8	28.8	2.2	24.8	53.1	1.4
16	28.7	37.6	2.5	40.0	33.4	2.2	37.6	34.0	1.5	24.2	54.7	1.4
17	27.5	39.2	2.4	38.9	36.5	2.2	36.2	38.2	1.5	23.3	57.2	1.4
18	25.9	43.1	2.3	37.5	40.7	2.1	34.7	43.8	1.5	22.4	60.7	1.4
19	24.8	47.7	2.3	36.1	45.9	2.0	33.9	48.9	1.5	21.7	64.1	1.4
20	24.1	50.7	2.3	34.0	49.9	2.0	33.2	52.4	1.5	21.1	66.7	1.4
21	23.5	53.0	2.3	34.0	51.9	2.0	32.6	57.1	1.5	20.4	68.6	1.4
22	23.1	54.7	2.3	33.3	53.8	2.0	31.9	56.8	1.5	19.8	69.3	1.4
23	23.1	55.8	2.3	32.6	55.2	2.0	31.1	58.1	1.5	19.3	71.5	1.4
24	22.0	57.0	2.2	32.0	57.0	2.0	30.6	59.3	1.5	18.9	72.7	1.4

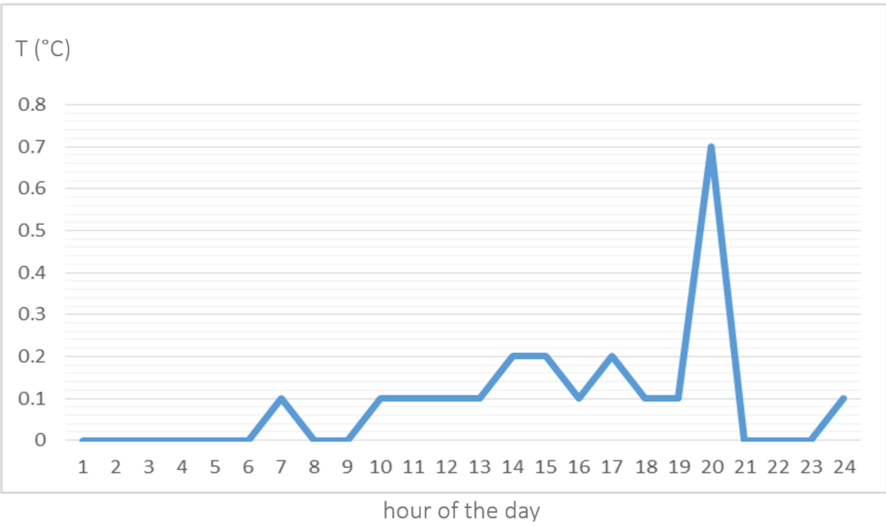


Figure 67: The difference of air temperature between base case and shaded case on the first full district simulation for the spring season.

Table 32: Shaded ENVI met value of the full E3 District.

	SPRING SHADED			SUMMER SHADED			AUTUMN SHADED			WINTER SHADED		
	T (degree)	H (%)	W(m/s)	T(degree)	H (%)	W(m/s)	T (degree)	H (%)	W(m/s)	T (degree)	H (%)	W(m/s)
1	21.1	59.2	2.0	30.8	60.7	1.8	29.5	64.9	1.7	18.3	74.4	1.3
2	21.1	60.2	1.9	30.2	62.2	1.8	29.0	65.5	1.7	17.8	75.0	1.3
3	20.5	61.0	1.9	29.5	63.3	1.8	28.5	66.0	1.6	17.5	75.6	1.3
4	20.5	61.9	1.9	28.9	63.7	1.7	28.0	66.7	1.6	17.2	76.0	1.3
5	19.8	62.3	1.8	28.4	64.0	1.7	27.6	67.2	1.6	16.8	76.2	1.3
6	19.7	62.9	1.8	28.0	64.4	1.7	27.5	67.4	1.6	16.7	76.7	1.3
7	20.4	63.5	1.8	28.7	63.0	1.6	28.9	67.3	1.5	16.8	77.3	1.2
8	22.4	61.8	1.7	30.9	56.5	1.6	31.4	63.0	1.5	17.9	77.5	1.2
9	24.5	55.8	1.7	33.7	47.5	1.5	33.8	53.0	1.5	19.9	74.9	1.2
10	26.5	49.3	1.7	36.4	39.0	1.5	36.2	43.5	1.5	21.8	68.7	1.3
11	28.2	43.8	1.7	38.6	33.4	1.5	38.2	35.1	1.4	23.2	63.5	1.3
12	29.4	38.5	1.7	40.1	29.7	1.4	39.5	28.9	1.4	24.3	58.8	1.2
13	30.1	34.7	1.7	41.0	28.6	1.4	40.0	25.9	1.4	24.8	55.1	1.2
14	29.9	33.1	1.6	41.1	29.1	1.4	39.7	26.0	1.4	25.0	55.0	1.2
15	29.3	35.5	1.6	40.7	30.8	1.4	38.6	28.7	1.3	24.8	54.9	1.2
16	28.6	38.0	1.6	39.9	33.7	1.3	37.5	34.4	1.3	24.2	57.3	1.2
17	27.3	39.5	1.7	38.7	36.8	1.3	36.1	39.0	1.3	23.2	60.8	1.2
18	25.8	43.4	1.7	37.4	41.0	1.3	34.6	45.4	1.3	22.3	64.2	1.2
19	24.8	48.0	1.7	36.0	46.1	1.3	33.8	51.1	1.3	21.7	66.7	1.2
20	24.1	50.9	1.7	34.9	50.1	1.3	33.2	54.8	1.3	21.0	68.6	1.2
21	23.5	53.2	1.7	34.0	52.1	1.3	32.5	57.4	1.3	20.4	70.2	1.2
22	23.0	55.0	1.7	33.3	54.0	1.4	31.8	59.4	1.3	19.8	71.6	1.2
23	23.0	56.0	1.7	32.6	55.3	1.4	31.0	60.7	1.3	19.3	71.6	1.2
24	22.0	57.2	1.7	31.9	57.1	1.4	30.5	62.0	1.3	18.9	71.6	1.2

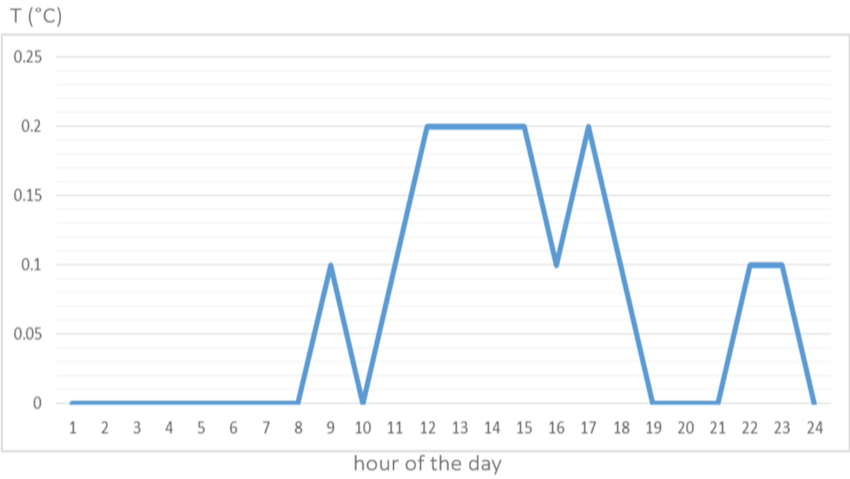


Figure 68: The difference of air temperature between base case and shaded case on the first full district simulation for the winter season.

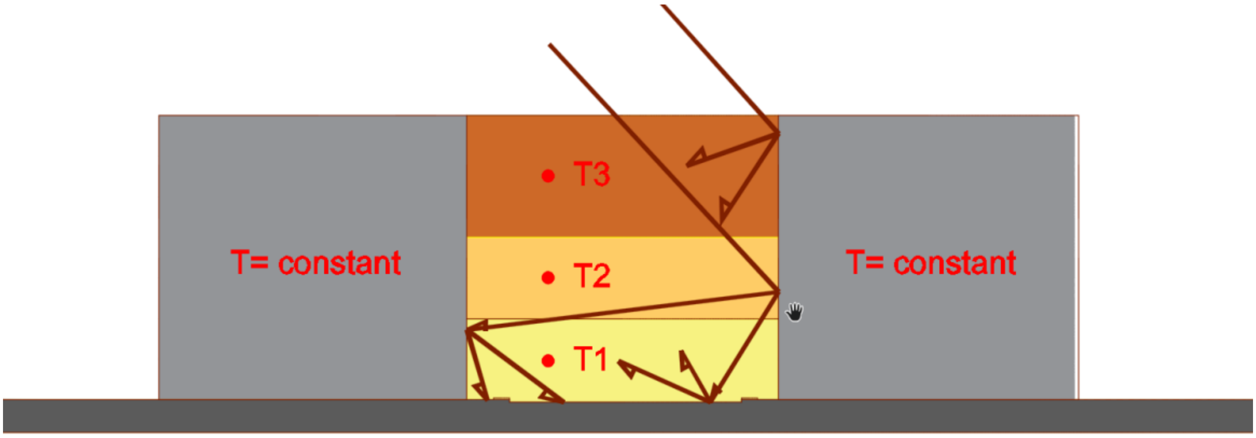


Figure 69: Microclimate Model principle of calculation.

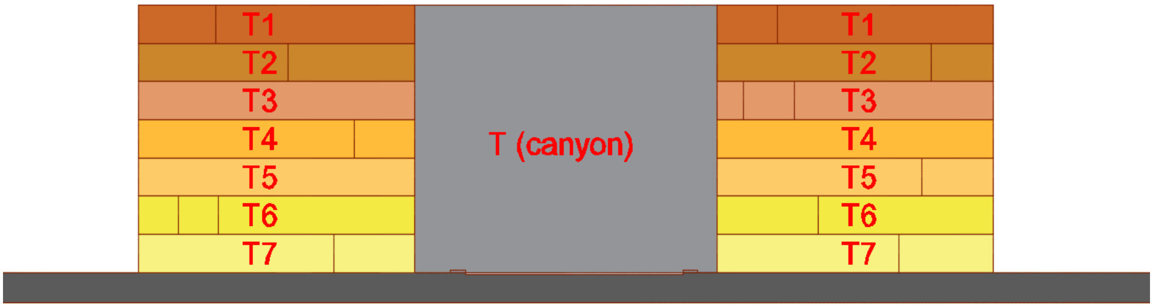


Figure 70: BEM (Building Energy Modeling) principle of calculation (wind behavior scheme is described in the main file).

A similar approach to the one shown in figures 71-72 is described in a study where the turbulent and radiative fluxes in an urban area for a mesoscale model are calculated. In this computation technique parameters like the building size, the street canyon width and the building density as a function of height are considered. One of the approaches in this technique is the calculation of the shadowing and trapping of radiation in the urban canyon. In fact, this parameterization shows the formation of the nocturnal urban heat island due to the reduction of the radiation loss during the night. An important role is played from the sensible heat fluxes from the walls (vertical surfaces). The wind flow characteristics are also analyzed. The turbulent intensity below the roof height shows a reduction in this mesoscale model. However, this model could be improved by making the building morphology spatially variable in better representing the anthropogenic heat fluxes and the calculation of the vegetation in the energy budget in the urban areas. It can also consider the three-dimensionality of the building morphology in the analyzed mesoscale model. [218]

In figure 73 the 3D view of the Grasshopper simulation is shown. The simulation is done for 15 buildings of the E3 district. The buildings are divided into energetic zones using Ladybug and Honeybee. The low-rise buildings spent less energy in the cooling load since their volume is much smaller than the high-rise buildings. The plan view of the simulation is shown in figure 74. The energy spent in the cooling load is shown in the colour bar on the side. However, the results in chapter 8, paragraph 8.4 show a higher energy saving in terms of cooling load reduction in the villa district. In figure 75 the 3D of the Grasshopper for the villa district is shown. In both districts images 73-76 are referring to the base case with no shading devices involved. The results show the resumption of both scenarios. In figure 76 there is a plain view of the villa district Grasshopper simulation.[11] [219][217]

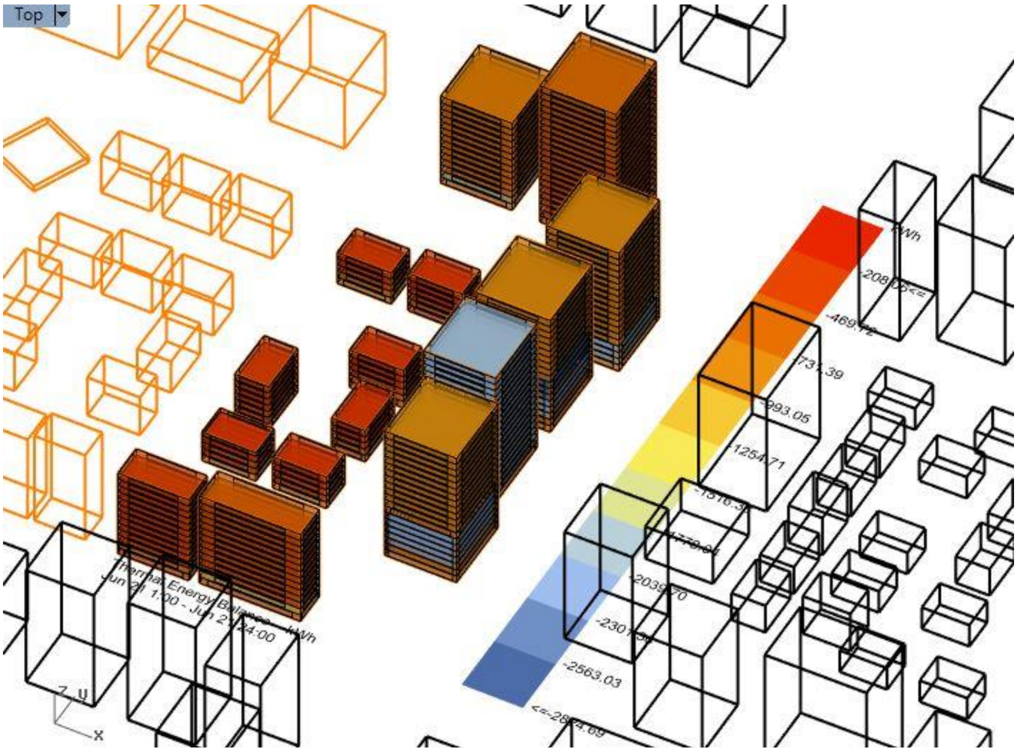


Figure 71: E3 district base case simulation in Grasshopper, 3D view.

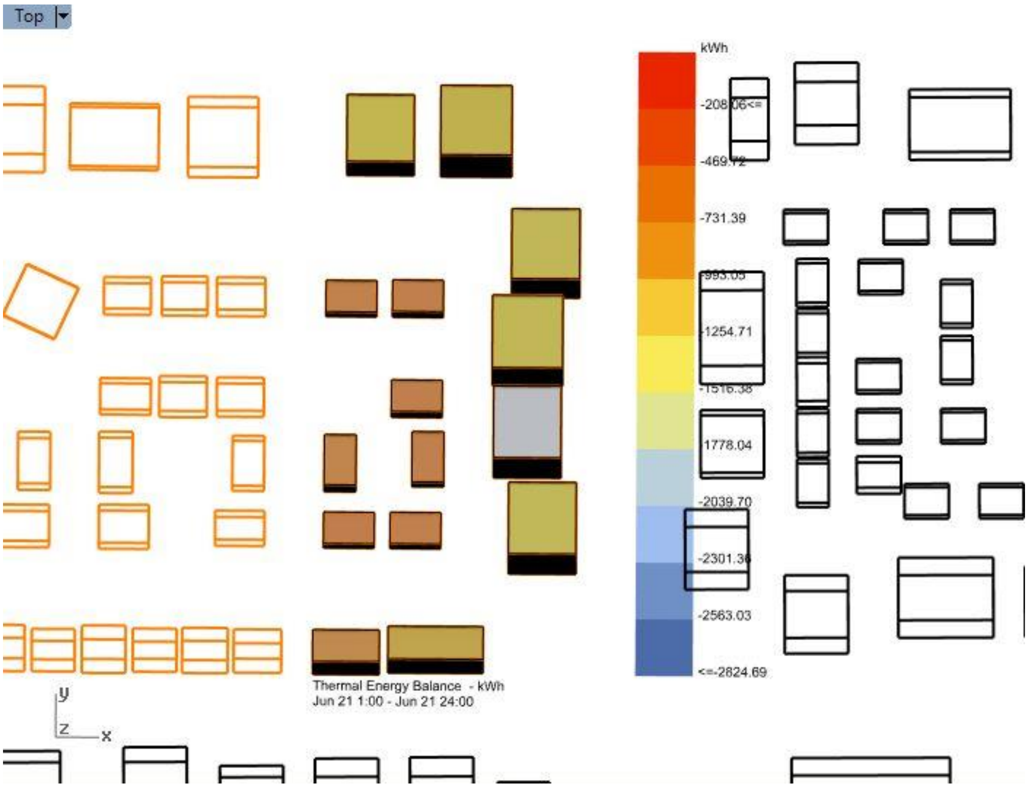


Figure 72: E3 district base case simulation in Grasshopper, plan view.

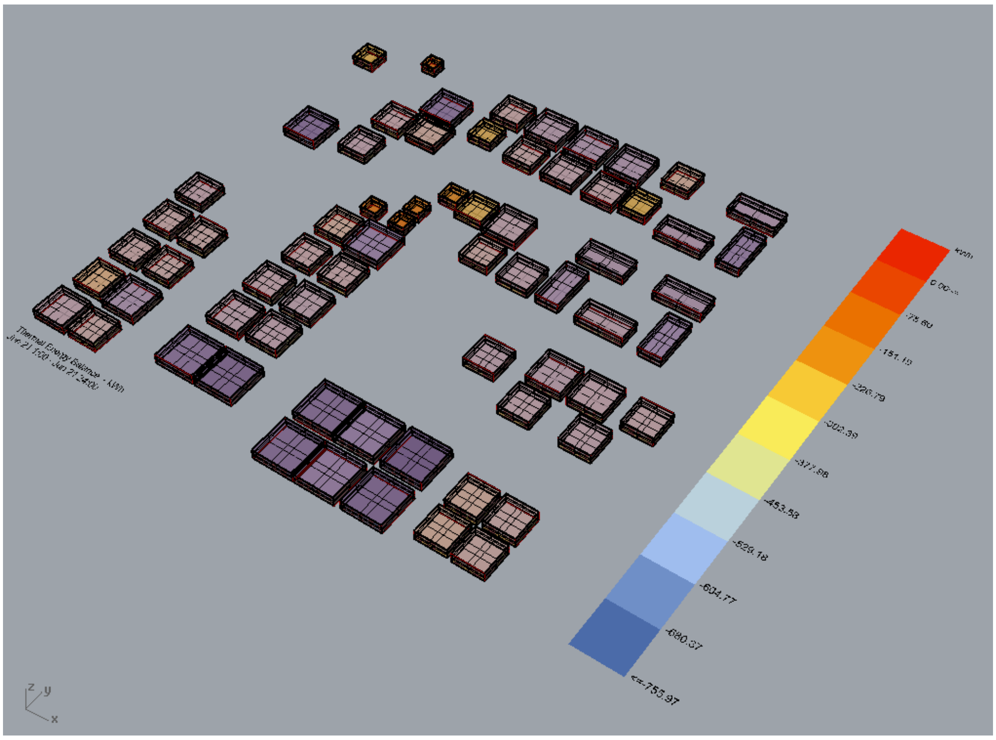


Figure 73: Villa district base case simulation in Grasshopper, 3D view.

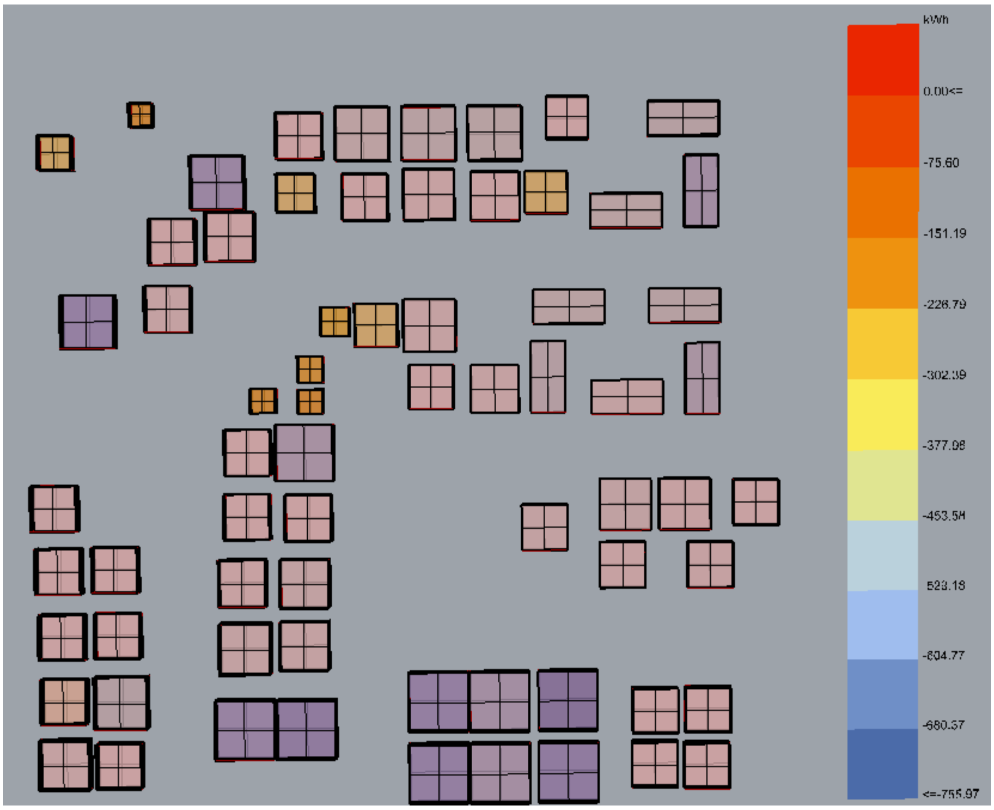


Figure 74: Villa district base case simulation in Grasshopper, plan view.

Chapter 8: Results and discussions

8. Results and discussions
8.1 PET
Results

The PET (described in chapter 3, paragraph 3.4) results are listed in this paragraph. Several site measurements conducted in the E3 District (high rise/midrise) and the villa district are reorganized in tables 33-37. Figure 75 shows the location of the PET site measurements inside the E3 district. The measurements are concentrated in the 15-building area where the detailed simulations take place. The measurements were taken in three main points: A (middle of the parking lot, northern side), B (five meters from the low-rise residential building), C (middle of the parking lot, southern side). The results taken from the site measurements are averaged and processed in RayMan. The averaged values will be then compared to the results coming out of ENVI-met. The measurements are taken two different times of the day: at hour 15.00 and at hour 16.00. In the evening, at hour 17.00 the relative humidity has the tendency to increase while the mean radiant temperature and the air temperature decrease. In the summer the measurements are taken only at hour 16.00 due to difficult site conditions. The temperatures during the spring measurements vary from 30°C to 32.3°C for the hour 15.00 and from 20°C to 30°C for the hour 16.00. Meanwhile, for the summer season, the air temperatures vary from 41°C to 42°C. The wind speed tends to increase in the second hour of measurements with an average of 0.5m/s (table 33-34).

Figure 75: Site measurement locations.

The mean radiant temperature has higher values in the second hours of the spring measurements, varying from 30°C - 36°C for the hour 15.00 and from 20°C to 31°C for the hour 16.00. Meanwhile, in the summer measurements the mean radiant temperature varies from 41°C to 43°C. Finally, the averaged PET values vary from one measurement to another as shown in tables 35-37. Basically, for the spring measurement hour 15.00, the PET is 31.6°C; for hour 16.00, it is 29.2°C. For day two it varies from 31.4°C to 28.6°C. For the summer measurement, the PET value is 43.2°C. The site measurements are taken manually and then averaged for the specified hours (Chapter 6, paragraph 6.1).

Table 33: Site Measurements Spring Day 1, E3 District.

15.00_Site Measurements													
	T (air temperature) °C			RH (relative humidity) %			Mean Radiant Temperature °C			Wind Speed m/s			PET (RayMan) °C
A	31.9	31.31	31.23	37.9	39.2	39.4	33.3	32.2	31.9	0.92	1.07	2	31.6
B	32.10	32.15	32.23	36.7	36.6	37.4	34.5	36.8	37.7	0.28	0	0.48	
C	30.7	30.14	30.32	38.8	40.3	39.3	31	31	30.8	1.18	1.18	0.84	
AV	31.4			38.4			33.24			0.88			
16.00_Site Measurements													
	T (air temperature) °C			RH (relative humidity) %			Mean Radiant Temperature °C			Wind Speed m/s			PET (RayMan) °C
A	28.99	29.29	29.47	44.8	44	43.7	29.3	29.5	29.7	1.09	0.52	1.35	29.2
B	30.17	30.09	30.14	42.3	42.3	41.7	30.1	30.3	29.9	0.69	0.41	1.26	
C	29.99	29.92	29.97	40.2	40.5	40	30	30	30.2	0.8	0.8	0.67	
AV	29.9			42.2			29.9			0.84			

Table 34: Site Measurements Spring Day 2, E3 District.

15.00_Site Measurements					
	T (air temperature) °C	RH (relative humidity) %	Mean Radiant Temperature °C	Wind Speed m/s	PET (RayMan) °C
A	31.48	38.83	32.46	1.33	31.4
B	32.16	36.9	36.33	0.25	
C	30.38	39.46	30.93	1.06	
AV	31.3	38.4	33.2	0.9	
16.00_Site Measurements					
	T (air temperature) °C	RH (relative humidity) %	Mean Radiant Temperature °C	Wind Speed m/s	PET (RayMan) °C
A	29.58	44.16	28.5	0.98	28.6
B	30.13	42.1	30.1	2.36	
C	29.96	40.23	30.06	0.75	
AV	29.9	42.2	29.6	1.4	

Table 35: Average values of the Site Measurements Spring, E3 District.

15.00_Site Measurements					
	T (air temperature) °C	RH (relative humidity) %	Mean Radiant Temperature °C	Wind Speed m/s	PET (RayMan) °C
AV1	31.4	38.4	33.24	0.88	31.6
AV2	31.3	38.4	32.2	0.9	31.4
	31.4	38.4	32.7	0.9	31.5

Table 36: Average values of the Site Measurements Summer, E3 District

16.00_Site Measurements					
	T (air temperature) °C	RH (relative humidity) %	Mean Radiant Temperature °C	Wind Speed m/s	PET (RayMan) °C
AV1	29.9	42.2	29.9	0.84	29.2
AV2	29.9	42.2	29.6	1.4	28.6
	29.9	42.2	29.8	1.12	28.9

Table 37: Site Measurements Summer, E3 District

Measurements Summer 2016_16.00					
	T (air temp.) °C	RH (relative humidity) %	mean radiant temp °C	wind speed m/s	PET °C
1	42	49.1	42.2	0.48	43.2
2	41.7	48.7	41.8	0.58	
3	41.6	48.7	42.7	0.31	
AV	41.8	48.8	42.2	0.5	

The results received from ENVI-met are shown below in the form of graphs (figure 76-80). Respectively the results are showing PET values during the spring season and summer season for the two main districts analyzed in this research, the E3 (high-rise and mid-rise district) and the villa district. In the spring season, the PET goes from 14-34°C during the 24 hours of simulation and in the summer season the values move between 22 and 47°C. The time between 12.00 and 18.00 is the focus of the research since the effect of the shading devices is higher. During this time the activity of the citizens living downtown increases. The lunchtime and the post-wok activities happen between 12.00 and 14.00 and 15.00 to 18.00. Decreasing the PET during this period improves the district life quality. During the spring season, the thermal stress moves from comfortable to slightly warm and warm. Meanwhile, during the summer, the thermal stress moves from slightly warm to warm, hot, and very hot. The peak values of PET are at the hour 13.00 for both seasons.

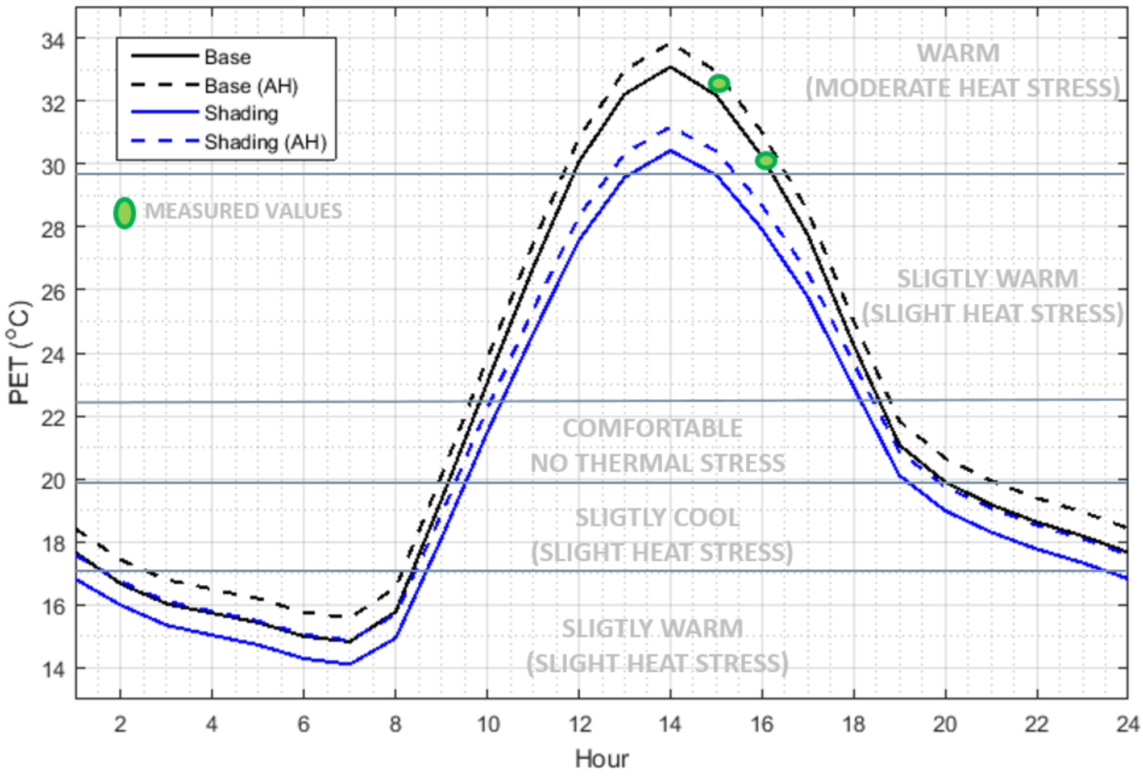


Figure 76: Spring PET values for the E3 district
(Dashed lines represents the impact of the anthropogenic heat into the PET 0.4 °C).

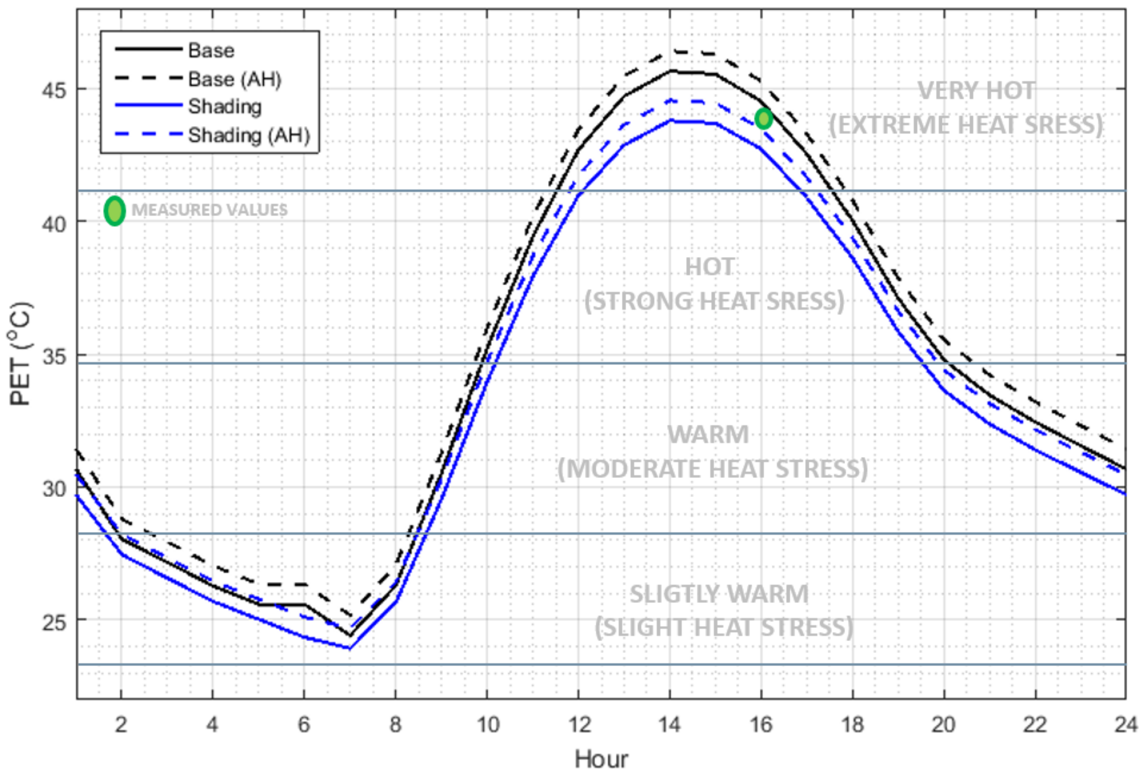


Figure 77: Summer PET values for the E3 district.
(Dashed lines represents the impact of the anthropogenic heat into the PET 0.36 °C).

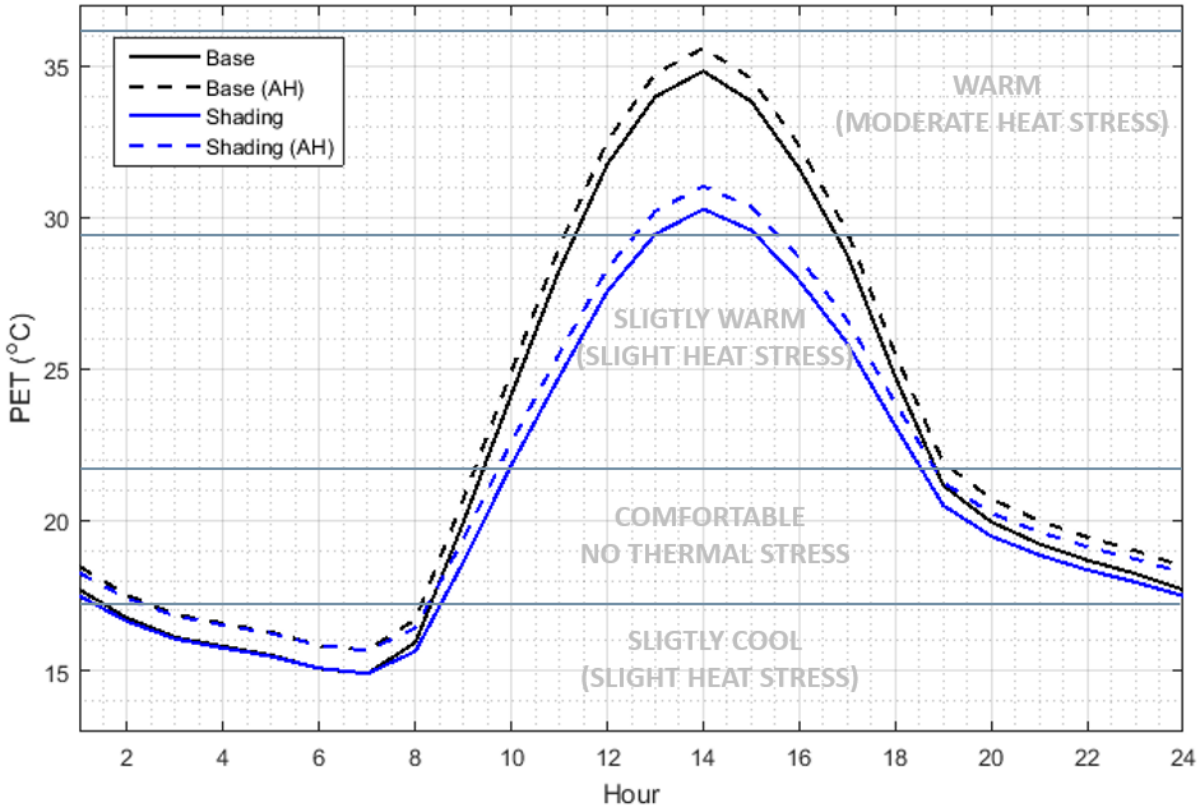


Figure 78: Spring PET values for the Villa district.
(Dashed lines represents the impact of the anthropogenic heat into the PET 0.4 °C).

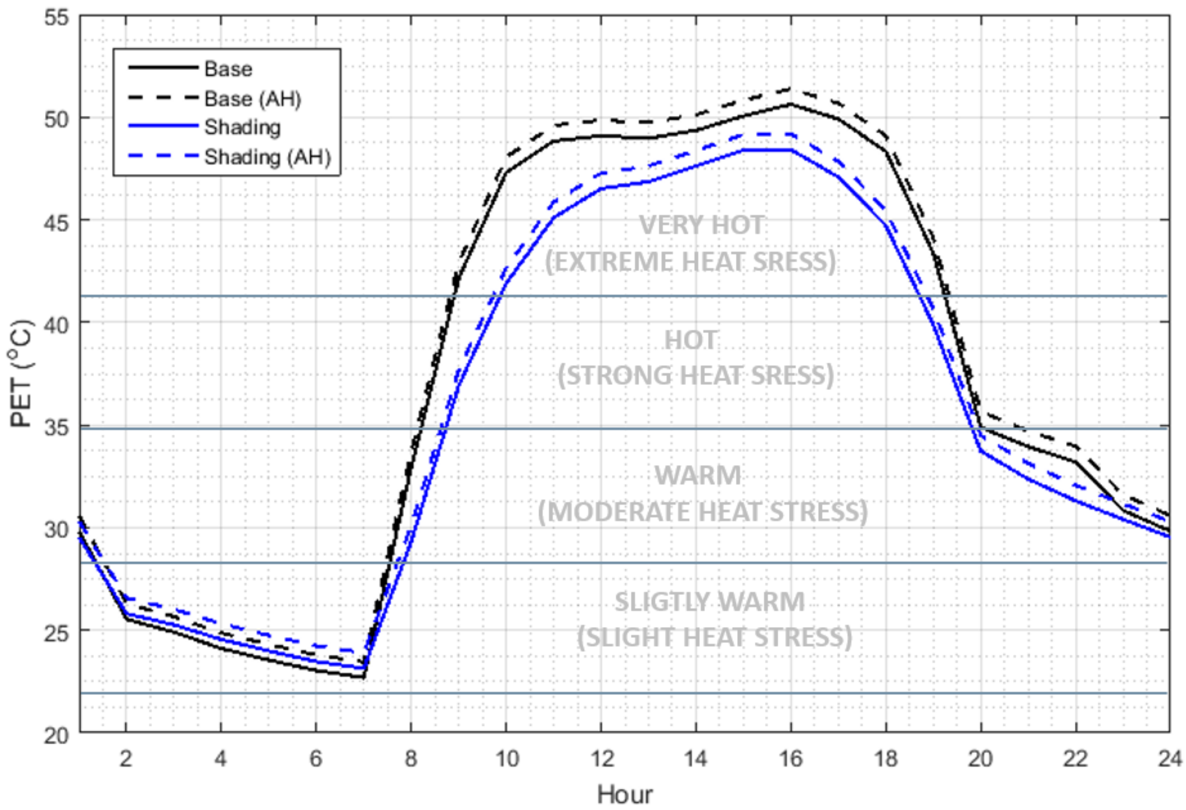


Figure 79: Summer PET values for the Villa district.
(Dashed lines represents the impact of the anthropogenic heat into the PET 0.36 °C).

In figures 76 and 78 the dash lines associated with base AH (base anthropogenic heat) and shaded AH (shaded anthropogenic heat) consider the results of the influence of the anthropogenic heat in the PET (chapter 8, paragraph 8.2). The impact of the AH in the air temperature is 0.53K. Using RayMan to convert this impact into the PET is 0.4°C for the spring season and 0.36°C for the summer season (figure 77, figure 79)[160].

Discussions

This study is focused on the spring and summer season. As mentioned in the second chapter, the climate of Abu Dhabi is characterized by four seasons: spring, summer, autumn, and winter. However, the main difference between the temperatures is between the summer and the winter. The summer air temperatures can reach 48°C. Further measurements are taking place on the E3 district in order to have a full range of data to compare with a wider range of days. The summer season is also the season where the biggest amount of citizens leave the UAE (combined with the school summer break). The months of July - September have the highest values of PET. Due to this climate conditions, improving the district's outdoor comfort is crucial for the citizens who live in this city.As shown in figures 76 and 78, the PET values in the E3 district are higher by almost 3°C. These are average areas from all the pixels of the district. In the E3 district characterized by high-rise/mid-rise buildings, the shaded pavement area during the day is higher than the villa district where the highest building is three floors (mainly villas). The paved are under the direct solar radiation in the villa district and the lack of shading or vegetation contributes in increasing the air temperatures and, therefore, the PET.

The spring and autumn season are very similar in terms of air temperature values, relative humidity and wind speed. Therefore, they represent an important part of the year that is studied in this research. The models are based on one-month average boundary conditions in order to obtain optimal results. The PET varies from 30°C to 35°C. However, the peak hours of the day have higher values of the PET decreasing the outdoor thermal comfort. [117][220]

The time of simulation for each season was 48 hours and the PET results are calculated on the second day. The scale of the ENVI-met models was 180x180 pxl. Therefore, the simulation time of the detailed models took more than 7 days. The latest improvements to the software allow faster simulations with more detailed models. [153]

8.2 The Anthropogenic Heat Calculation.

Results

From the three different trials done with UWG, as it can be seen in the graph below, the change of the anthropogenic heat from the car emissions and the air conditioning units seem to play a significant role in increasing the temperature in certain cities such as Abu Dhabi. The three different values of the anthropogenic heat generated from the traffic are 0.25 and 50 W/m^2. The AH values as mentioned in chapter 6 refer to the literature. In the last case, the AC waste heat released into the canyon is also set to zero while, in the other cases, the fraction of AC waste heat released into the canyon is 50%. Hereafter, the three scenarios are called UWG0, UWG25 and UWG50. For the last option, the air conditioning waste heat released in the canyon was also set to 0 in order to be able to compare the outcome with ENVI-met (which cannot not account for any anthropogenic heat). The values of the AH refer to the full site and are estimations of the satellite images of the downtown area of Abu Dhabi. The value 25W/m^2 is considered as a more realistic scenario and the value 50W/m^2 is referring to the busiest time of the day in a dense traffic area. However, for this study the corrections of the ENVI-met model refer to the value of AH 25W/m^2. The mean temperature differential between each trial and the rural weather file is respectively 2.28K, 2.06K, and 1.52K. This means that 0.53 K from UWG0 to UWG25 raises the average annual temperature. When the second trial (25 W/m^2) is compared to the site measurements for the spring season (February 2nd- March 28th) the difference between the UHI intensities is 0.1K This is a very promising result. This value of anthropogenic heat happens to coincide with the preliminary estimates of average Abu Dhabi traffic-related heat gain rate per road area (figure 80).

On the other hand, the results obtained from ENVI-met for the spring equinox daily profile present a mean temperature differential of 1.08K when compared to the average daily profile of 20 days of the measured site data centred on the same equinox day. The adjusted average value of the temperature differential for the equinox day (21st March) is 1.84K (1.08+0.53). This value is 0.44K lower than the temperature differential of the UWG.

As shown in the results, the UWG can give a relatively accurate estimation of the urban air temperature. This value can then be used as an input for the different urban building energy simulations. The UWG results were very similar to the measured site data with a difference of 0.1K. However further trials are needed in order to better understand the influence of the different parameters such as the building envelope, the green surfaces, the anthropogenic heat, etc. A value of 0.53K was added to the ENVI-met results to account for the anthropogenic heat. UWG contributed to the estimation of the required adjustment factor: in figure 81 the temperature differential in two main scenarios is calculated, with and without anthropogenic heat (UWG0 and UWG50).

The UWG50–UWG0 differential is highly dependent on the time of the day as can be seen in figure 81 below; therefore, the ENVI-met adjustment suggested in this study should take this variation, as well as perhaps the seasonal variation, into account. In this case the lack of information of a seasonal graphic of the anthropogenic heat narrows the research to the spring season. The validation of ENVI-met is done only for the spring equinox, while the other pivotal days remain to be investigated. The ENVI-met results might have advantages compared to the UWG values due to a more detailed modelling of the radiation exchanges and the evapotranspiration process. The internal set points in both software are the same and they are considered 19.85 (referring to the fixed ones in ENVI-met)

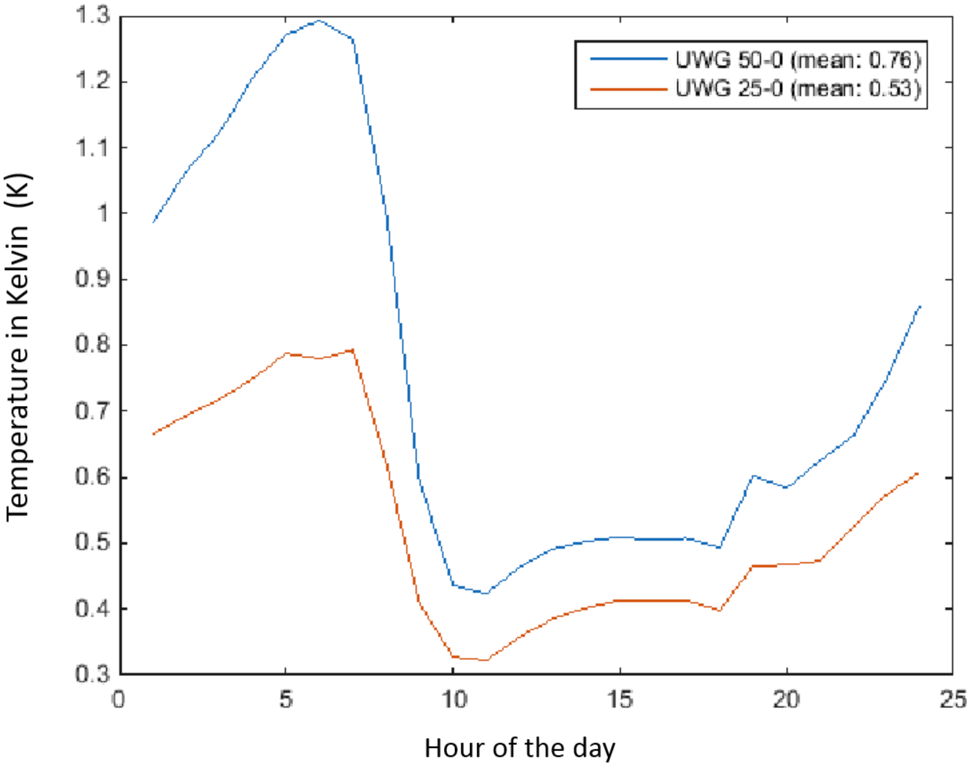


Figure 81: Temperature differential of the files generated by UWG based on the anthropogenic heat values of 0, 25 and 50 W/m^2.

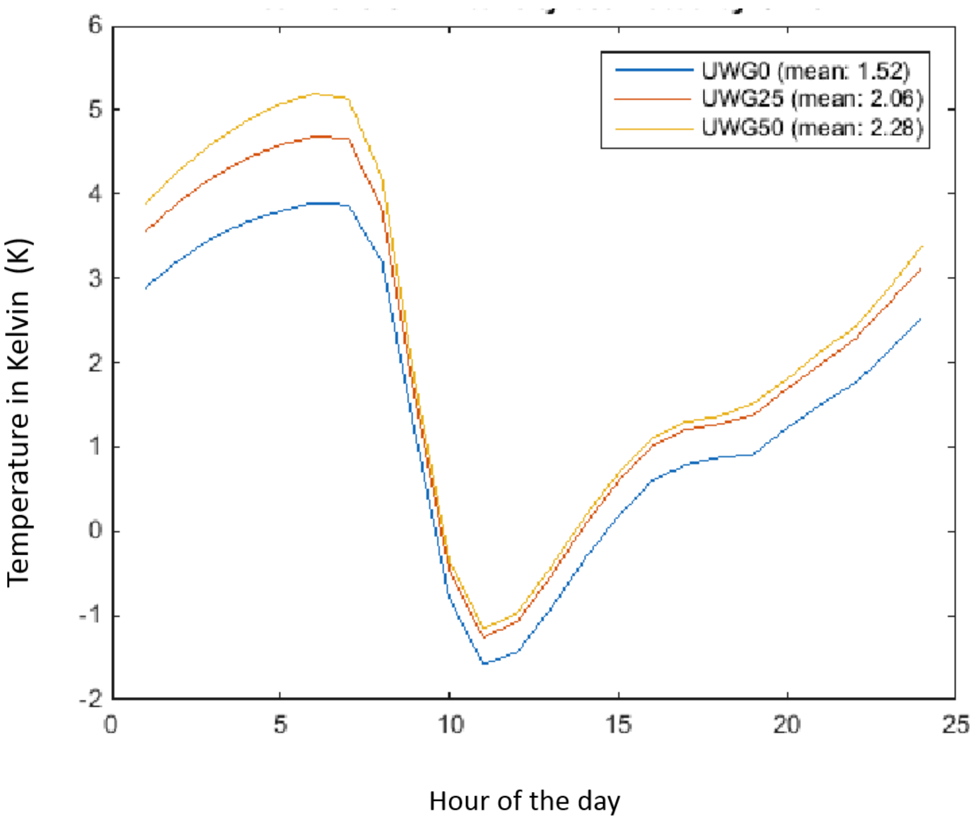


Figure 80: UHI intensity estimated by UWG based on the 2015 rural file.

Discussions

Several studies in cities such as Singapore show a large variation of anthropogenic heat during the day and the week. This is connected to the human activities during the day, the use of public transportation, and the use of the air conditions in the different districts. In Singapore the buildings are the main contributors of the Anthropogenic heat according to the latest research. [221][171]

The effect of the anthropogenic heat in the megacities of Japan can potentially increase the air temperature by 3°C. In another study conducted by Kikegawa, the increase of the temperature due to the anthropogenic heat is 1°C. However, this is related to the scale of the city and the lifestyle of the citizens. [222][223][224] However, the studies in Abu Dhabi are ongoing and more accurate data is expected to be available in the next couple of years.

The results of the previous paragraph will be expanded by including the effect of the vegetation and the impact that it might have in decreasing the air temperatures (part of the future work, gathering information campaign). The UWG software has improved and the latest version considers the impact of the vegetation. The above comparison for the spring season (the period studied in ENVI-met too) shows an increase of the air temperature by 0.53°C. The values of the anthropogenic heat are being measured for the summer, autumn and winter in order to have a yearly profile.

8.3 The temperature step

Results

Table 38: Temperature step values for spring and summer.

Indoor Air Temperature (°C)	Outdoor Measured Air Temperature (°C)	Outdoor Simulated Air Temperature Shaded (°C)	Temperature step 1 (indoor- measured outdoor) (°C)	Temperature step 2 (indoor-simulated outdoor) (°C)
Spring Hour 15.00				
19.95	31.4	29.5	11.45	9.55
22.00	31.4	29.5	9.4	7.5
26.00	31.4	29.5	5.4	3.5
Spring Hour 16.00				
19.95	29.9	27.5	9.95	7.55
22.00	29.9	27.5	7.9	5.5
26.00	29.9	27.5	3.9	1.5
Summer Hour 16.00				
19.95	41.8	40.8	21.85	20.85
22.00	41.8	40.8	19.8	18.8
26.00	41.8	40.8	15.8	14.8

The temperature step (the difference between indoor and outdoor temperatures) process is described in Chapter 3, paragraph 3.5. As per table 38 results, the temperature step changes by a minimum of 2°C from the measured case study and from the simulated one. As indoor temperature, three main air temperatures, 19.85°C, 22.00°C and 26.00°C, are considered. The first one is related to the constant air temperature considered in the ENVI-met models; the second one is the current air temperature used in the residential buildings in Abu Dhabi, and the 26.00°C is the one suggested to be used in the residential buildings. The temperature step between the first value of indoor air temperature and the second value is almost 6°C. The difference in the summer season reaches almost 22°C. The difference between the simulated air temperature and the measured one in the summer season is almost 1°C while in the spring season it is nearly 2°C. The difference between the estimated indoor value of 20°C and the outdoor simulated air temperature is 1.5°C compared to 3.9°C for the indoor and outdoor measured air temperature.

Discussion

The reduction of the temperature step is one of the positive effects that the shading devices bring into the districts. This section is an additional analysis to the outdoor thermal comfort. However, further studies have to be conducted. They will include as subjects the people leaving in the districts included in the analysis. The effect of the temperature step on human health depends mainly on the perception created from the different people included in the research. As per the latest studies, a difference of 15°C between indoor and outdoor air temperature might bring potential cardiovascular difficulties in people experiencing such temperature step. It varies on the step-in or step-out movement. In this case such a difference is noticed in the summer season. The shading devices seem to decrease such a temperature step. Higher values of temperature step might bring about difficulties in the oral and skin temperatures, blood oxygen saturation, respiration rate, hearing rate, and heart rate variability. However such difficulties are subject to the personal perception of each subject (person) considered in the study. [125][122]

8.4 Cooling load Calculations

Results

The energy consumption results shown in this chapter and the cost evaluation mentioned in the next chapter are additional positive results that this kind of proposed intervention brings to a neighbourhood. Of course, the primary positive outcome is the improvement of the PET and the reduction of the temperature step (important for the human health) as mentioned in the previously.

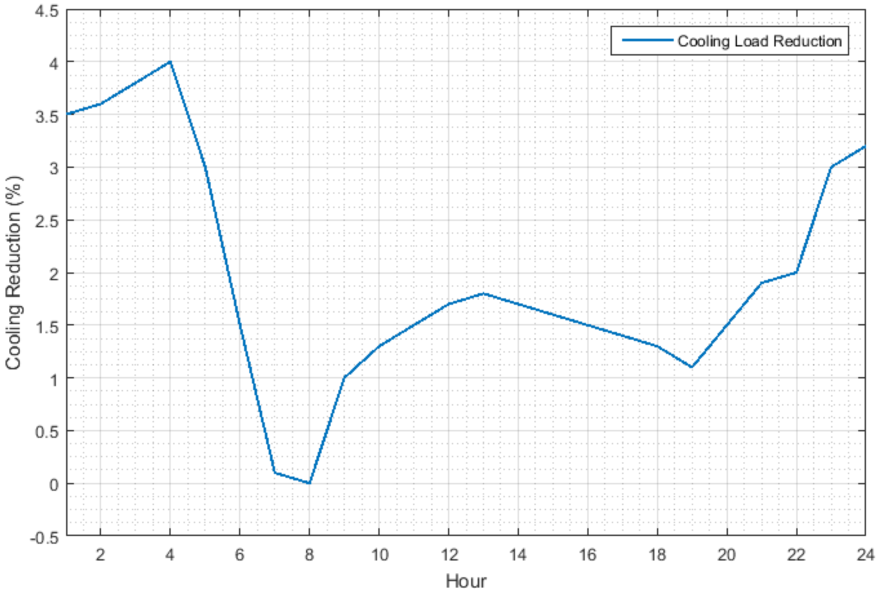


Figure 82: Average Cooling Load reduction for the first 7 floors of the E3 District

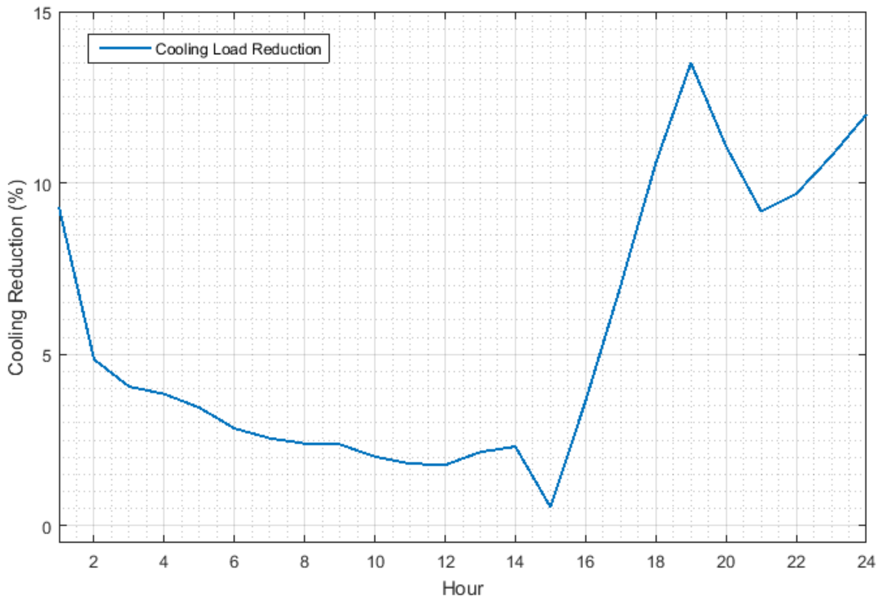


Figure 83: Average Cooling Load reduction for Villa District.

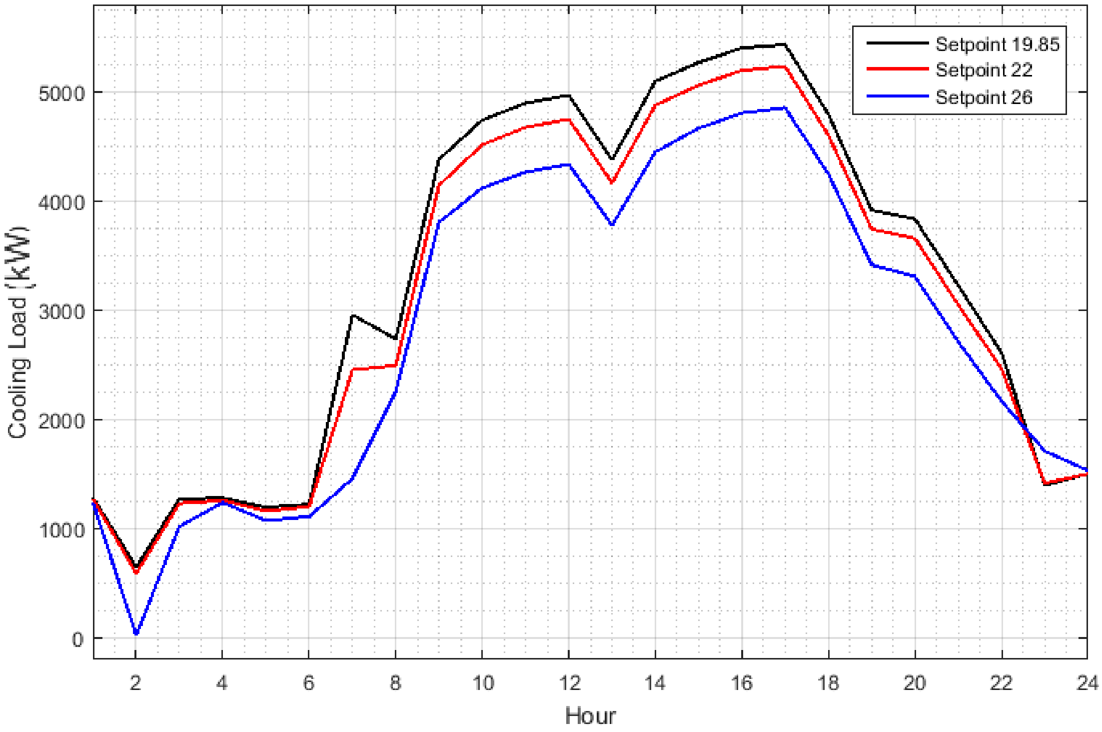


Figure 84: Cooling Load for the 21 June, E3 District Abu Dhabi. The calculation is done for the first 4 floors of all the buildings and the time of this calculation is 24hours.

As shown in figure 82-83 the cooling load reduction in the E3 district can reach up to the 4% that might not seem a considerable value but it is a saved energy. Meanwhile, on the villa district the savings reach an amount of 13%, which is an interesting result. Of course, it is connected with the height of the buildings and the type of the shading device, the height of the unit and the opening toward the north (whether is a 'cool' shading device or a 'green' shading device).
However, a second analysis is conducted in the base file of the E3 district. In this case the internal air temperatures are changed into different values. The value of 19.85 degrees is the base case scenario used in the ENVI-met models; the 22 degrees is the indoor air temperature mostly used on the main island of Abu Dhabi and the value of 26 degrees is the optimized one. As it can be seen from the graph, by only changing the internal set point of the air temperature the cooling load gets reduced 4.8% from the base case to the currently used values and 13.9% reduction from the base case to the optimized value. The outdoor–indoor temperature difference defines the energy saving.

Recent studies have shown that a change on the thermostat from 22.2°C to 25°C in an office building can bring about a 29% reduction in the cooling load. [225] In this case the set point changes from 19.85°C to 26°C and has a 14% cooling load reduction and on the second scenario from 22°C to 26°C has a 10% cooling load reduction.

Discussion

The cooling load calculations are based on the base case files and the shaded files taken from ENVI-met. The reduction of the cooling load in percentage in the E3 district is 4%, slightly low value compared to the other district. A more detailed model can potentially improve the result. The time consumption of the simulation was an initial difficulty during this study. However, the Grasshopper model used for the simulation had the gradient coefficient applied and in this calculation were considered the first four floors of all the buildings in the district. The simulation with the different internal set points of the air temperature can be improved by detailing the models more and creating different zones within the same floor.

Shading Devices Distribution

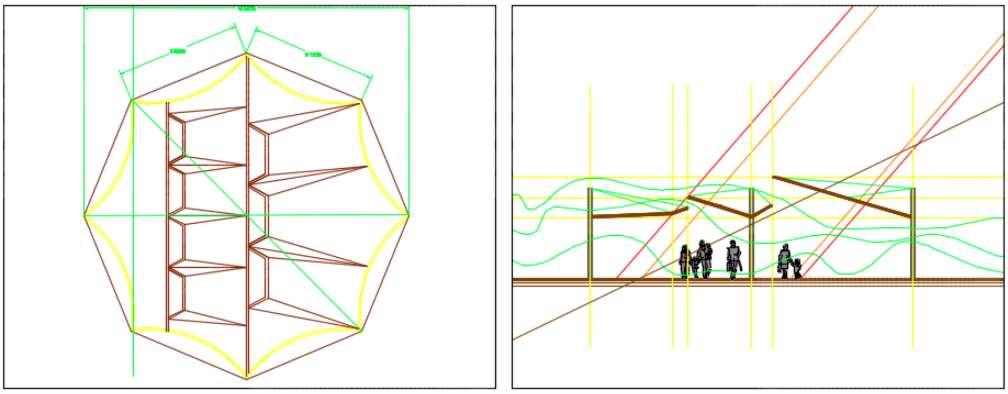


Figure 86: Shading device proposal 3, design trials.

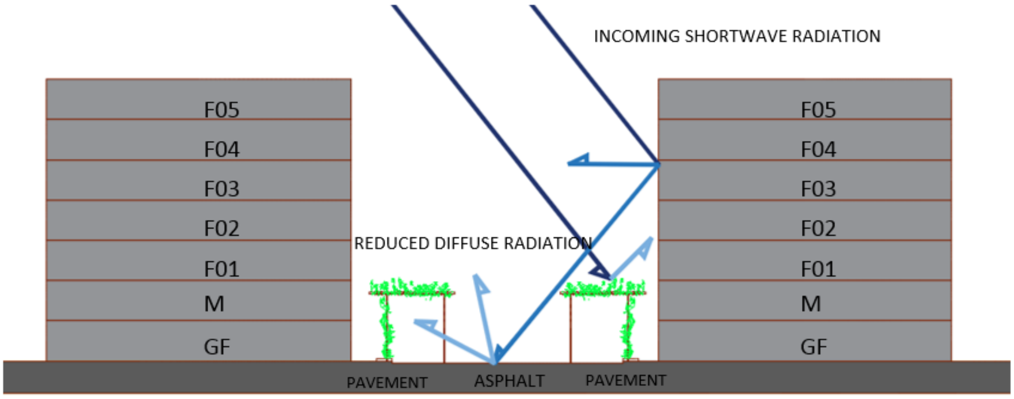


Figure 85: Section of the mid-rise/high-rise district showing the behaviour of each shading proposal ('green' shading) toward the solar radiation (analysed in chapter 5).

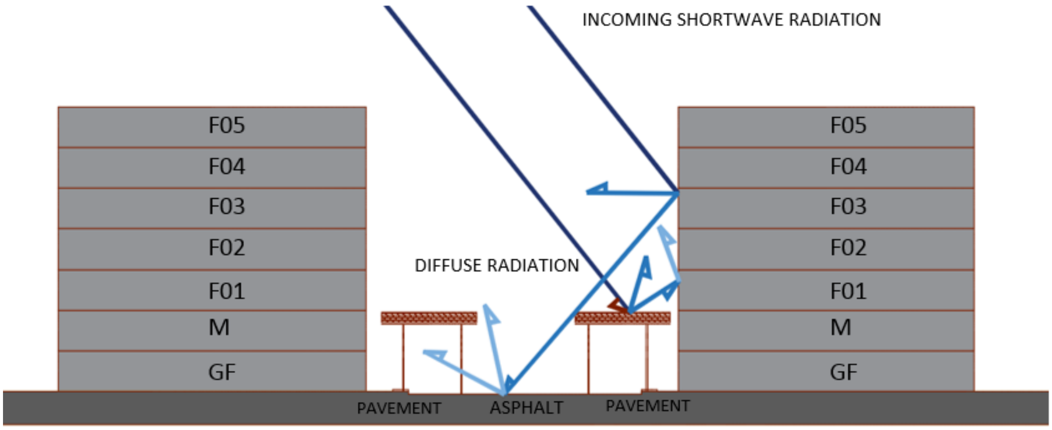


Figure 87: Section of the villas districts showing the behavior of each shading proposal ('Cool' shading) toward the solar radiation (analyzed in chapter 5).

In figure 84 one of the designs of the shading devices that were proposed for the five different district typologies is shown. That is one of the samples that is analyzed. The idea of such a strategy besides the CFD models and microclimate was to connect the city of Abu Dhabi with the Emirati heritage of the use of the traditional design and features of mashrabiya. An analysis on the local plants can be integrated with such structure. This concept can help the current generations connect with their past. The local institutions promote this kind of connection in the construction field. In figures 85 and 87 the principles of the behaviour of each shading proposal ('cool' shading and 'green' shading) toward the solar radiation are shown. In ENVI- met the models that were analyzed are based on the 'cool' shading properties. The scale varied from 100x100 to 180x180. There were several trials and the last version of the simulations is based on a better airflow of the shading devices that brought better results of the air temperature.

After analyzing each district the results of the temperature reduction in each district are shown below. Without calculating the error percentage as shown, the biggest temperature reduction is provided for in district 4 medium rise buildings, which means that the first intervention to be done in case of requalifying the neighbourhoods is the medium rise building districts. As per the ENVI-met simulations, the air temperature reductions for the different district typologies are shown in table 36. The biggest temperature reductions are achieved in district 4 (medium rise buildings) and district 1 (villas). The detailed models for the villa district and the E3 comparing the 'cool' shading devices and the 'green' shading devices showed that the biggest air temperature reductions are achieved by improving the wind flow within the district. However, the 'cool' shaded devices showed a higher impact on the air temperature by 0.1°C.

The calculation of the MSE (mean squared error) is based on the difference of the results received from the site measurements and the base file compared to the difference of both simulated files (shaded versus base) and it reached 0.1°C. The results shown in table 39 are based on the analysis shown in chapter 3. The behaviour of the cool surfaces and the vegetation toward shortwave and longwave radiation in the urban canyon of the different districts defines which kind of shading typology can be applied. This division is also based on the cost evaluation (Appendix) of different shading models. The 'cool' shading devices have a lower cost application and maintenance cost than the 'green' shading devices.

Table 39: Average air temperature reduction in each district typology.

District 5	Villas and high rise buildings
T Reduction (°C)	0.328
District 1	Villas
T Reduction (°C)	0.372
District 2	High rise buildings
T Reduction (°C)	0.112
District 3	Medium and high rise buildings
T Reduction (°C)	0.174
District 4	Medium rise buildings
T Reduction (°C)	0.393

Discussion

The design part of the shading devices in this thesis is conceptual. The focus is the ENVI-met model analysis. However, further analysis is needed to explore such a connection between the historical use of local materials and their modern adaptation since the UAE is still in transformation not only from the urban planning and construction point of view but also from the social point of view. The connection with the past is one of the main pillars of the country's foundation. A deeper study in the sociological transformation of the society and how Urban Planning might make this transition pass in different stages can be understood better by the new generations.[56]

The values of the air temperature drop are based on the ENVI-met models. Even though the average air temperature reduction seems to have low values, the PET under the shading devices has considerable high value. The average values also include the areas above the asphalt. Open parking and internal roads for the cars characterize the districts in Abu Dhabi since it is a car-oriented city. However, further studies have to be conducted in the different models by modifying the albedo of the street material and exploring the potential air temperature reduction, microclimate modification, etc. [20]

After having the site measurements, the models were validated. It is important to mention that in ENVI-met the anthropogenic heat is missing. However, the other parameters considered in the software brings the model into similar conditions as the outdoor environment. Regarding the air temperature under the shading, it can be reduced up to two degrees in the peak hours. The average value of the air temperature reduction (for the considered spring-summer season) in the first district is 0.18 degrees and in the villa district is 0.35. Based on these results the cooling load reduction for the summer (21 June) peak hours (12.00-15.00) is 4%. It is a significant value considering the massive use of the AC system during this specific time of the day.

Chapter 9: Conclusions and future work

9. Conclusions and future work

9.1 PET

Conclusions

For the E3 district the PET in the spring season drops by 4 degrees in the peak hour (13.00) after adding the shading devices. In the summer for the same district the PET gets reduced by 5°C. In both cases there is no change in the thermal stress scale although in the spring season the PET reduction is one degree above the limit between slightly warm and warm.

On the villa district the reduction of PET is almost 5°C so the thermal stress gets reduced from hot to war. In the climate of Abu Dhabi, this change is quite important since walking around the district for a longer time is connected to human health. For the same district in the summer time the reduction reached 4°C. However, the season that this study is focused on is spring. During this time of the year, the citizens tend to go out more and such PET changes can improve the outdoor quality.

As shown in tables 40-41, the difference between the site measurements and the simulation results vary from 0.1 to 0.2°C. Meanwhile, the difference between the baseline case and the shaded case is more than 3 degrees. These results show an improvement in the calculation of the PET through this CFD software. However, it was pointed out during the simulations that the mean radiant temperatures tend to be overestimated in ENVI-met.

There is no significant difference between the 'cool' shading models and the 'green' shading models in terms of PET. Therefore, the conclusions refer to the 'cool' shading device models. Based on these results it can be assumed that this strategy can potentially improve the outdoor thermal comfort in different district typologies. It can be considered as part of the different urban development in the city of Abu Dhabi. The improvement of the outdoor thermal comfort improves the health of the citizens and, therefore, their quality of life.

Table 40: Average values of the Site Measurements Spring, E3 District.

Site Measurements vs ENVI-met		
	Hour 15.00	Hour 16.00
Site Measurements PET (RayMan)	31.5	28.9
ENVI-met	31.8	29
Difference	-0.2	-0.1

Table 41: Site Measurements Summer, E3 District

Site Measurements vs ENVI-met	
	Hour 16.00
Site Measurements PET (RayMan)	43.2
ENVI-met	43.5
Difference	-0.2

The impact of the AH in the air temperature is 0.53K. Using RayMan to convert this impact into the PET, we get 0.4°C for the spring season and 0.36°C for the summer season (figure 79, figure 81)[160]. Even though the calculations and the validation of the UWG are done for the spring season, the temperature impact of the anthropogenic heat is kept the same for the summer season considering that the anthropogenic heat value is a yearly average.

Future work

Part of the future work is to prepare mode detailed models on a larger scale in order to have shading devices with different geometry. The time consumption of the simulations was the main obstacle for such simulations. However, the latest version of ENVI-met has been improved in this aspect and is subject to deeper understanding.

The trial of the 'green' shading device modelling in chapter 7, paragraph 7.2 showed results very similar to the 'cool' shading devices. ENVI-met has a limitation in building the 'green' shading geometry. Therefore, in this study only the 'cool' shading devices' out coming results from the modelling are considered. The evapotranspiration process is considered in ENVI-met; however, the soil profiles and the irrigation process modifications and changes gave results very similar to the 'cool' shading devices in the district area. The model of the detailed influence of the 'green' shading devices is part of future work exploration through scSTREAM software [21]. A part of the future work is also the expansion of the sensor network in different districts' typology in order to register more values of air temperature, relative humidity, mean radiant temperature and wind speed in order to have real data of PET. This database can be used to validate more complex model simulations analyzed in the laboratory.

Even though the impact of the increase of the anthropogenic heat in the air temperatures and the PET is kept the same for the spring and summer seasons, further studies must be conducted to analyze the changes in the mean radiant temperature and surface temperature of the models due to this AH impact. Further studies have to be carried out to calculate the anthropogenic heat values related to the seasonal effect of the traffic. Site data of car monitoring in different areas could help classify the most traffic-dense areas.

9.2 The temperature step

Conclusion

The temperature step is based on the difference of the air temperature between the indoor and outdoor environments. The perceived thermal stress is the one which defines the impact that the temperature step has on the human health of the different individuals. In this study the outdoor air temperatures are based on the base case simulation of ENVI-met.

The results were compared to the measured data from different sensors around Abu Dhabi. Since the difference between the indoor and outdoor varies up to 9 degrees, this scale has an important impact on the perceived temperature step. In this research the temperature drops in the neighbourhood scale reduce the magnitude of the temperature step, which brings down the side effects it can cause to the human health.

In Abu Dhabi the temperature in the internal areas of the buildings are kept at 22 degrees. The external temperatures might reach 50°C in the summer. This brings the temperature step to 28 degrees, creating a great stress for the human body to get adapted to the new conditions.

As per the latest research studies, the difference of more than 15°C between the indoor and the outdoor might cause cardiovascular difficulties for people. The effect of the temperature step is subject to the people's perception; however, the Air temperature reductions can improve the negative effect that the temperature step has over the people's health.

The different indoor setpoints show that the temperature step can be reduced not only from external measurements but also from internal decision-making processes. In the summer the outdoor air temperature can reach 50°C and the internal setpoint of the thermostat can be adjusted to 26°C compared to the current use of 22°C. By modifying this parameter the temperature step is reduced by 4°C. If we add to this temperature drop additional external measures, then the results will impact the citizens' health as mentioned above.

Future work

Part of the future work is to create a model that makes such a simulation and estimates the negative impact of the temperature step and the different strategies that can overcome it. In the current studies there is no such analysis in the island of Abu Dhabi. Considering the hot arid climate and the different indoor air temperature setpoints that depend on the local legislation, this type of research would be beneficial for the community and the citizens.

Since in Abu Dhabi there is a very large international community, it would be interesting how different nationalities coming from countries with different climates can react to such temperature drops.

9.3 The cooling load calculation

Conclusion

The cooling load is calculated considering the base case file and the shaded file provided from ENVI-met. For the E3 district, the base case file air temperatures measured at a 2m height compared to the site data is 0.53 degrees, while the shaded file has a difference of 0.66. The difference between both scenarios is 0.1; meanwhile, the average temperature reduction all over the district is 0.174. It is over the uncertainty level.

The main focus of this study is the reduction of the PET; however, the cooling load reduction is a positive effect that this kind of strategy can potentially bring to the district. If most of the districts in Abu Dhabi have such changes in their internal areas the microclimate can be improved much more. The drop of the air temperatures on average by 0.5-0.8 degrees in different districts can bring a cooling load reduction up to 13%.

The modification of the internal air temperature setpoints can bring further saving to the cooling load (that can reach up to 29%)[225]. The result achieved in the villa district is 13% of savings in the cooling load. These results can still be improved if additional retrofit strategies can be applied to each villa. The external shading devices placed at a 5-7 meter height in this kind of district where the villa height is 8 meters (mainly two-floor villas) has a positive impact on the energy saving process.

Future work

However, further studies have to be conducted in order to fully understand the ENVI-met principle of calculation. The simulations must run for 48 hours in order to avoid movements because of the boundary condition limits in the model. If additional UHI mitigation strategies such as cool surfaces [157]

The modification of the internal setpoints can additionally help reduce the cooling loads. The policies in the city of Abu Dhabi are under modifications and such results can improve the energy saving. Part of the future work is to develop such models and compare the different retrofit strategies with the different indoor set points.

The Abu Dhabi Municipality has a complete database for almost all the districts in Abu Dhabi. The right information about the building structure will help understand if different retrofit strategies can be applied to current buildings in addition to external changes or to internal air changes. A comparison between different strategies can show a positive impact that will improve the cooling load reduction. Currently, the energy consumption of the buildings takes 80% of the total energy consumption. Seventy percent of this energy use goes to the cooling load. [138]

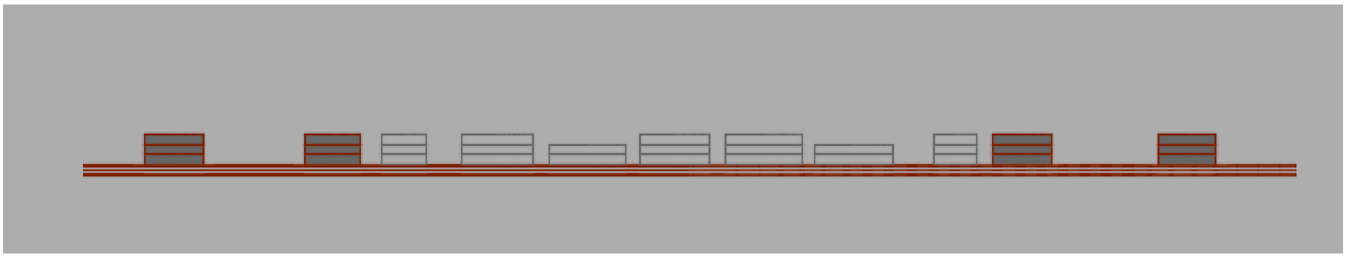
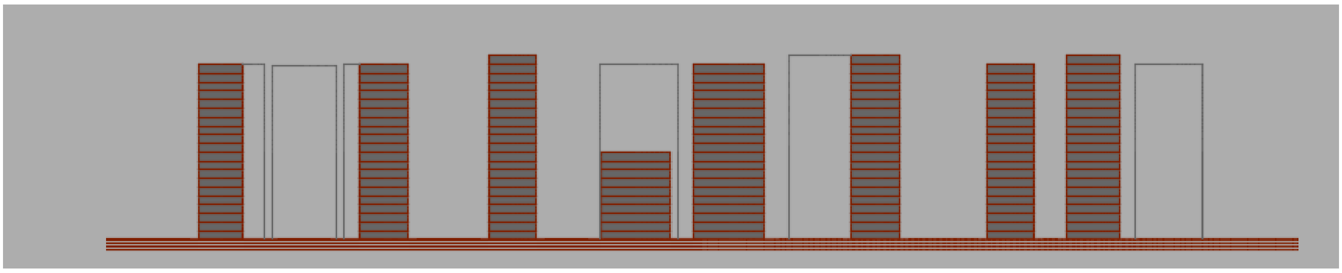
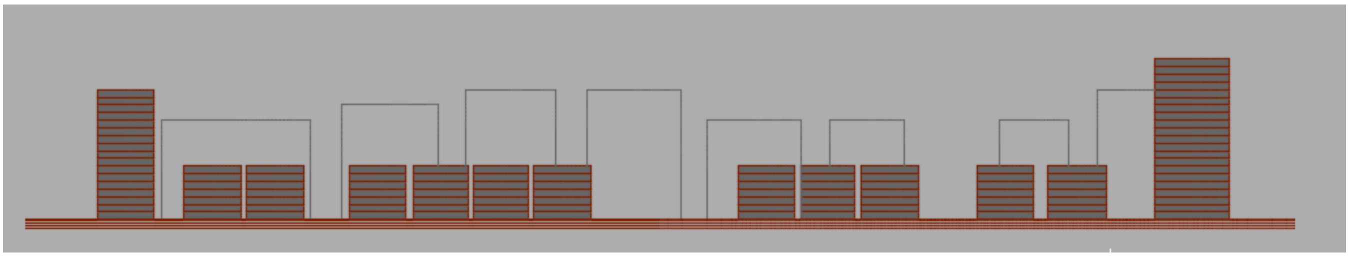
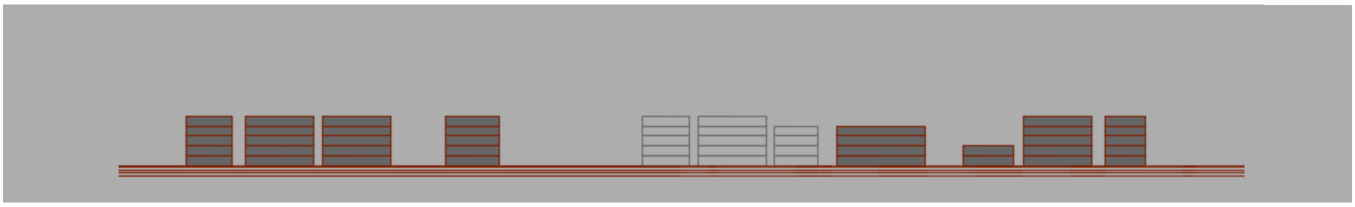
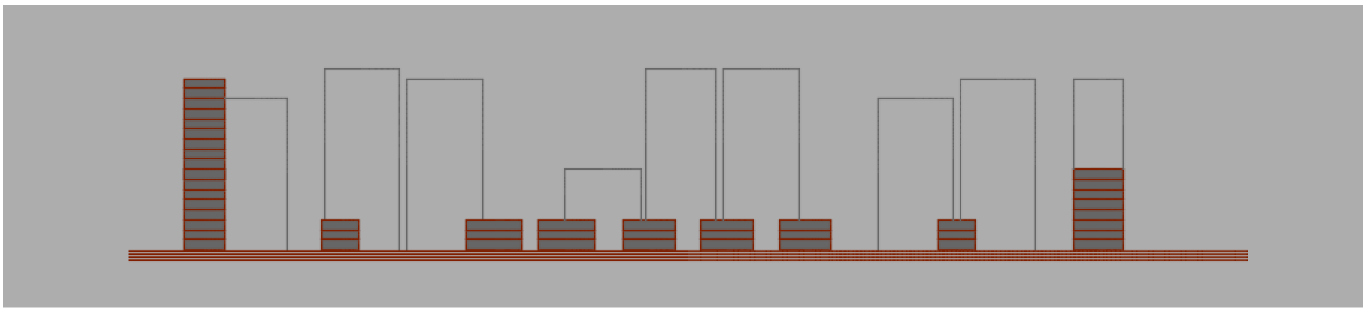
9.4 Shading devices distribution

The shading devices distribution is based on the canyon physical characteristics in each district. The geometry of the district, the height of the buildings, the width of the streets within the neighbourhoods are the one to define whether one type of shading device can be applied or not. The building characteristics have a crucial role in the selection of the shading devices that can be applied in different districts. In the Villa district, the buildings are mainly two floors, 0.3 grazing ratio, flat rooftops, AC rooftop units. In this case the proposed shading device is the 'cool' one. As specified in the annexe, the cool shading devices have a lower cost of implementation and maintenance. Therefore, their application, wherever possible, would bring the benefits of reducing the air temperature and improving the outdoor thermal comfort. However, their use is connected to the height of the building. As per different studies, the cool surfaces have the tendency to reduce the air temperature below them but increase the cooling load of the building floors above them due to the multiple reflections. A similar effect is also achieved from cool pavements. [157]
The second district analyzed is the E3. The buildings in this district are a mix between the high-rise and midrise. The high-rise buildings are placed in the surroundings of the district and the midrise ones are placed in the centre. The grazing ratio is 0.4, the high-rise buildings are built in the last 20 years; therefore, their energy performance is better than the midrise buildings built almost 40 years ago. In this district the proposed shading device is the 'green' one. As mentioned in the previous paragraph, the 'cool' shading devices have a lower implementation and maintenance cost. However, after an analysis of the different local plants growing in the Middle East region and after inspecting different areas in Abu Dhabi/Al Ain, the green shading devices are the second proposal as a UHI mitigation strategy. In such a district where the height of the buildings is at least 20meters above the shading structures, the vegetation behaviour towards the shortwave radiation is the most suitable proposal. The green part of the shadings absorbs the shortwave radiation and has enough openings (leaf structure) [43] to help the longwave radiation go toward the sky by not increasing the cooling load of the upper floor of the buildings. The local plants do not need an excessive amount of water for the irrigation process (calculations done in the annexe section) and they can climb the wooden structures creating shading in the streets of the urban canyon.

Table 42: Proposed urban shading device for each district typology.

DISTRICT TYPOLOGY	PROPOSED UHI MITIGATION STRATEGY
VILLAS	'COOL' SHADING DEVICES
HIGH RISE BUILDINGS	'GREEN' SHADING DEVICES
HIGH RISE/ MID RISE BUILDINGS	'GREEN' SHADING DEVICES
MID- RISE BUILDINGS	'GREEN' SHADING DEVICES 'COOL' SHADING DEVICES
HIGH RISE BUILDINGS AND VILLAS	'GREEN' SHADING DEVICES 'COOL' SHADING DEVICES

Table 43: District typology, building height and shading typology

District Section	
District 1 - Villas	'COOL' SHADING DEVICES
	
District 2 – High Rise Buildings	'GREEN' SHADING DEVICES
	
District 3 – High Rise and Mid-Rise Buildings	'GREEN' SHADING DEVICES
	
District 4 – Mid-Rise Buildings	'GREEN'/ 'COOL' SHADING DEVICES
	
District 5 – High Rise Buildings and Villas	GREEN'/ 'COOL' SHADING DEVICES
	

The shading device application in the different urban areas and different district typologies can modify the air temperature, wind speed, relative humidity, mean radiant temperature, longwave radiation, and shortwave radiation; therefore, it can improve and modify the microclimate of the district. In this study five different district typologies, villas and high-rise building, villas, high-rise buildings, high-rise and mid-rise buildings, and mid-rise buildings were considered. Among them the villa district, and the high-rise/mid-rise district were the ones to be detailed and analyzed deeper. However, the reduction of the air temperature shows that the urban shading devices can be a potential UHI mitigation strategy. The typology of the shading device is defined by the H/W value of the district. The 'cool' shading devices are applied in districts with a low value of H/W and the 'green' shading devices are applied in districts with high H/W value. This value varies from one canyon to another within the same district.

Future work

The 'green' shading devices are subject to a deeper study in order to understand the evapotranspiration process and the relation that it has with different neighbourhood physiognomy. A combination of green walls and green roofs and their effect into the urban microclimate is ongoing. Even though the cost of maintenance might be higher than other mitigation strategies, the feedback and the impact that such intervention has on the PET and the cooling load of the buildings are much higher. The ENVI-met simulations can be expanded in the different district typologies not included in this research. The main island of Abu Dhabi has different district typologies at the entrance, the middle part and the downtown area. The five district typologies taken into consideration in this study are the most representative one (table 42-43).

References

References:

[1] "World's population increasingly urban with more than half living in urban areas | UN DESA | United Nations Department of Economic and Social Affairs." [Online]. Available: http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html. [Accessed: 25-Jan-2017].

[2] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy Build.*, vol. 40, no. 3, pp. 394–398, 2008.

[3] "Welcome to The Municipality of Abu Dhabi City." [Online]. Available: http://www.adm.gov.ae/en/home/index.aspx. [Accessed: 01-Feb-2017].

[4] "UAE State of Energy Report 2016 | Dubai Carbon l Green Economy Enabler." [Online]. Available: http://dcce.ae/state-of-energy-report-2016/. [Accessed: 01-Feb-2017].

[5] "Fact sheets - 7. Energy efficiency and demand side management." [Online]. Available: http://financialresults.co.za/2012/eskom_ar2012/fact-sheets/007.php. [Accessed: 01-Feb-2017].

[6] "Abu Dhabi Urban Planning Council - Abu Dhabi Vision 2030." [Online]. Available: http://www.upc.gov.ae/abu-dhabi-2030.aspx?lang=en-US. [Accessed: 01-Feb-2017].

[7] F. Bruno, "The Walled City of Multan: Characters of the Settlement Structure and GIS as an Instrument of Urban Analysis," 2014, pp. 163–180.

[8] M. Boriani, M. Giambruno, and S. Pistidda, "Guidelines for the Walled City of Multan: Knowledge, Conservation, and Relationship Ancient/New for a Sustainable Rehabilitation," 2014, pp. 211–223.

[9] A. Del Bo, "Introduction and Approach: Sharing Culture and Knowledge of the Core of Multan," 2014, pp. 3–15.

[10] R. Moya Castro, D. Prohasky, S. Watkins, Y. Ding, J. Burry, and M. Burry, "Aerodynamic strategy applied in an urban shelter design - Simulation and analysis of aerodynamic phenomena in an urban context," *eCAADe 2014 Fusion - data Integr. its best*, pp. 137–144, 2014.

[11] "Grasshopper - algorithmic modeling for Rhino." [Online]. Available: http://www.grasshopper3d.com/.

[12] S. Gracik, M. Heidarinejad, J. Liu, and J. Srebric, "Effect of urban neighborhoods on the performance of building cooling systems," *Build. Environ.*, vol. 90, pp. 15–29, 2015.

[13] V. Dorer, J. Allegrini, K. Orehounig, P. Moonen, G. Upadhyay, J. Kämpf, and J. Carmeliet, "Modelling the urban miscroclimate and its impact on the energy demand of buildings and buildings clusters."

[14] B. B. Unzeta, L. K. Norford, and R. Britter, "An urban weather generator coupling building simulations with a physically based urban model."

[15] Y. Arima, R. Ooka, H. Kikumoto, and T. Yamanaka, "Near Future Weather Data for Building Energy Simulation in Summer/Winter Seasons in Tokyo Developed by Dynamical Downscaling Method."

[16] B. Jérémy, M. Marjorie, C. Isabelle, B. Erwan, and K. Pascal, "Urban heat island and inertial effects : analyse from field data to spatial analysis," 2015.

[17] Y. Zheng, C. Ren, E. Ng, K. Ka, -Lun Lau, Y. Shi, and J. Ho, "Temporal and Spatial Structure of Urban Heat Island in Subtropical City of Hong Kong."

[18] B. Blocken and J. Persoon, "Pedestrian wind comfort around a large football stadium in an urban environment: CFD simulation, validation and application of the new Dutch wind nuisance standard," *J. Wind Eng. Ind. Aerodyn.*, vol. 97, no. 5–6, pp. 255–270, Aug. 2009.

[19] D. Hii Jun Chung and L. Choo Malone-lee, "Computational fluid dynamics for urban design."

[20] S. Huttner, M. Bruse, and P. Dostal, "Full 3D editor Numeriacl Modelling of the Urban Microclimate – a preview on ENVI-MET 4.0."

[21] "CFD| Software Cradle Co., Ltd." [Online]. Available: http://www.cradle-cfd.com/. [Accessed: 31-Jan-2017].

[22] Y. Makido, V. Shandas, M. S. Ferwati, and D. J. Sailor, "Exploring the Spatial and Temporal Variation of Air Temperature in the Extreme Desert Climate of Doha, Qatar."

[23] A. E. Thomas and A. Elizabeth, "Sustainable landscapes for residential neighborhoods in

Dubai: An analysis of the relationship between ambient temperature and water requirements of landscape," 2013.
[24] E. Erell, "The Application of Urban Climate Research in the Design of Cities," *Adv. Build. Energy Res.*, vol. 2, no. 1, pp. 95–121, Jan. 2008.
[25] I. D. Stewart, "A systematic review and scientific critique of methodology in modern urban heat island literature," *Int. J. Climatol.*, vol. 31, no. 2, pp. 200–217, Feb. 2011.
[26] R. Hamdi and G. Schayes, "Sensitivity study of the urban heat island intensity to urban characteristics," *Int. J. Climatol.*, vol. 28, no. 7, pp. 973–982, Jun. 2008.
[27] J. Lu, C. Li, C. Yu, M. Jin, and S. Dong, "Regression Analysis of the Relationship between Urban Heat Island Effect and Urban Canopy Characteristics in a Mountainous City, Chongqing," *Indoor Built Environ.*, vol. 21, no. 6, pp. 821–836, Dec. 2012.
[28] M. Santamouris, "On the energy impact of urban heat island and global warming on buildings," *Energy Build.*, vol. 82, pp. 100–113, 2014.
[29] M. Santamouris, C. Cartalis, A. Synnefa, and D. Kolokotsa, "On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review," *Energy Build.*, vol. 98, pp. 119–124, 2015.
[30] V. Diogo and E. Koomen, "Simulating future changes in the urban heat island effect based on an integration of socio-economic and climate scenarios."
[31] M. Mohan, Y. Kikegawa, B. R. Gurjar, S. Bhati, A. Kandya, and K. Ogawa, "Urban Heat Island Assessment for a Tropical Urban Airshed in India," *Atmos. Clim. Sci.*, vol. 2, no. 2, pp. 127–138, 2012.
[32] B. Stone and M. O. Rodgers, "Urban Form and Thermal Efficiency: How the Design of Cities Influences the Urban Heat Island Effect," *J. Am. Plan. Assoc.*, vol. 67, no. 2, pp. 186–198, Jun. 2001.
[33] K. Giannopoulou, I. Livada, M. Santamouris, M. Saliari, M. Assimakopoulos, and Y. G. Caouris, "On the characteristics of the summer urban heat island in Athens, Greece," *Sustain. Cities Soc.*, vol. 1, no. 1, pp. 16–28, 2011.
[34] K. Setaih, N. Hamza, M. A. Mohammed, S. Dudek, and T. Townshend, "CFD modeling as a tool for assessing outdoor thermal comfort conditions in urban settings in hot arid climates," *J. Inf. Technol. Constr.*, vol. 19, no. 19, pp. 248–269, 2014.
[35] A. Matzarakis and B. Amelung, "Physiological Equivalent Temperature as Indicator for Impacts of Climate Change on Thermal Comfort of Humans."
[36] W. T. L. Chow, D. Brennan, and A. J. Brazel, "Urban heat island research in phoenix, Arizona," *Bull. Am. Meteorol. Soc.*, vol. 93, no. 4, pp. 517–530, Apr. 2012.
[37] J. S. Golden, "The Built Environment Induced Urban Heat Island Effect in Rapidly Urbanizing Arid Regions – A Sustainable Urban Engineering Complexity," *Environ. Sci.*, vol. 0, no. 0, pp. 0–0, 2004.
[38] T. R. Oke and T. R., "Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations," *J. Climatol.*, vol. 1, no. 3, pp. 237–254, Jul. 1981.
[39] R. G. (Roger G. Barry and P. Blanken, *Microclimate and local climate*. .
[40] D. S.-K. Ting, "Heat Islands – Understanding and Mitigating Heat in Urban Areas," *Int. J. Environ. Stud.*, vol. 69, no. 6, pp. 1008–1011, Dec. 2012.
[41] I. Ozkeresteci, K. Crewe, A. J. Brazel, and M. Bruse, "Use and evaluation of the ENVI-met model for environmental design and planning. An Experiment on Lienar Parks," *South Africa*, pp. 10–16, 2003.
[42] F. Yuan and M. E. Bauer, "Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery."
[43] S. Sakai, M. Nakamura, K. Furuya, N. Amemura, M. Onishi, I. Iizawa, J. Nakata, K. Yamaji, R. Asano, and K. Tamotsu, "Sierpinski's forest: New technology of cool roof with fractal shapes," *Energy Build.*, vol. 55, pp. 28–34, 2012.
[44] R. Paolini, A. G. Mainini, T. Poli, and L. Vercesi, "Assessment of Thermal Stress in a Street Canyon in Pedestrian Area with or without Canopy Shading," *Energy Procedia*, vol. 48, pp. 1570–1575, 2014.
[45] R.-L. Hwang, T.-P. Lin, and A. Matzarakis, "Seasonal effects of urban street shading on long-term outdoor thermal comfort," *Build. Environ.*, 2010.
[46] T. Susca, S. R. Gaffin, and G. R. Dell'osso, "Positive effects of vegetation: urban heat island

and green roofs.," *Environ. Pollut.*, vol. 159, no. 8–9, pp. 2119–26.
[47] S. Saneinejad, P. Moonen, and J. Carmeliet, "Comparative assessment of various heat island mitigation measures."
[48] H. Akbari, M. Pomerantz, and H. Taha, "Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas," *Sol. Energy*, vol. 70, no. 3, pp. 295–310, 2001.
[49] T. Karlessi, M. Santamouris, A. Synnefa, D. Assimakopoulos, P. Didaskalopoulos, and K. Apostolakis, "Development and testing of PCM doped cool colored coatings to mitigate urban heat island and cool buildings," *Build. Environ.*, vol. 46, no. 3, pp. 570–576, Mar. 2011.
[50] A. Synnefa, A. Dandou, M. Santamouris, M. Tombrou, N. Soulakellis, A. Synnefa, A. Dandou, M. Santamouris, M. Tombrou, and N. Soulakellis, "On the Use of Cool Materials as a Heat Island Mitigation Strategy," *J. Appl. Meteorol. Climatol.*, vol. 47, no. 11, pp. 2846–2856, Nov. 2008.
[51] "WAN:: Urban Shade by WAN Editorial in Holon, Israel." [Online]. Available: http://www.worldarchitecturenews.com/project/2014/24759/wan-editorial/urban-shade-in-holon.html.
[52] M. Fahmy, H. Mokhtar, and A. Gira, "Adaptive urban form design on a climate change basis A case study in Nubia, Egypt (PDF Download Available)." [Online]. Available: https://www.researchgate.net/publication/280732627_Adaptive_urban_form_design_on_a_climate_change_basis_A_case_study_in_Nubia_Egypt. [Accessed: 28-Jan-2017].
[53] L. Shashua-Bar and M. E. Hoffman, "Vegetation as a climatic component in the design of an urban street An empirical model for predicting the cooling effect of urban green areas with trees," *Energy Build.*, vol. 31, pp. 221–235, 2000.
[54] "Middle East Sustainable Cities." [Online]. Available: http://www.carboun.com/sustainable-design/passive-cooling-responding-to-uae%25E2%2580%2599s-soaring-electricity-demand/Journal.
[55] "Estidama." [Online]. Available: http://estidama.upc.gov.ae/.
[56] "Abu Dhabi Public Realm Design Manual." [Online]. Available: http://www.upc.gov.ae/prdm/index.asp.
[57] *Cities : architecture and society : 10. Mostra internazionale di architettura, la Biennale di Venezia.* Rizzoli, 2006.
[58] J. Montgomery, "Making a city: Urbanity, vitality and urban design," *J. Urban Des.*, vol. 3, no. 1, pp. 93–116, Feb. 1998.
[59] P. Pinho and V. Oliveira, "Different approaches in the study of urban form," *J. Urban. Int. Res. Placemaking Urban Sustain.*, vol. 2, no. 2, pp. 103–125, Jul. 2009.
[60] M. KII and S. Hanaoka, "Comparison of sustainability between private and public transport considering urban structure.," 2003.
[61] D. Robinson, "Urban morphology and indicators of radiation availability," 2006.
[62] M. Tadi, G. Lobaccaro, and S. Vahabzadeh Manesh, "Sustainable urban morphology for a greener city: An integrated approach for the energy-efficiency of neighbourhoods," *GreenAge Symp.*
[63] F. Ali-Toudert and H. Mayer, "Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate," *Build. Environ.*, vol. 41, no. 2, pp. 94–108, 2006.
[64] S. Lenzholzer, "A city is not a building – architectural concepts for public square design in Dutch urban climate contexts," *J. Landsc. Archit.*, vol. 3, no. 1, pp. 44–55, Mar. 2008.
[65] M. Radfar, "Urban Microclimate, Designing the Spaces Between Buildings," *Hous. Stud.*, vol. 27, no. 2, pp. 293–294, Mar. 2012.
[66] C. Yuan and L. Chen, "Mitigating urban heat island effects in high-density cities based on sky view factor and urban morphological understanding: a study of Hong Kong," *Archit. Sci. Rev.*, vol. 54, no. 4, pp. 305–315, Nov. 2011.
[67] "Solar Energy at Urban Scale - Google Books." [Online]. Available: https://books.google.ae/books?id=GAOnjP4k7SQC&printsec=frontcover&dq=editions:iTbtV2V6_vcC&hl=en&sa=X&ved=0ahUKEwi6jcCTwuLQAhVBWxQKHeQADY4Q6AEIGTAA#v=onepage&q&f=false.
[68] M. Morganti, "Sustainable density: form, built environment, energy."
[69] S. Grimmond, "Urbanization and global environmental change: local effects of urban

warming," *Geogr. J.*, vol. 173, no. 1, pp. 83–88, Mar. 2007.
[70] G. Mills, "Cities as agents of global change," *Int. J. Climatol.*, vol. 27, no. 14, pp. 1849–1857, Nov. 2007.
[71] M. G. Lawrence, T. M. Butler, J. Steinkamp, B. R. Gurjar, and J. Lelieveld, "Regional pollution potentials of megacities and other major population centers," *Atmos. Chem. Phys. Atmos. Chem. Phys.*, vol. 7, pp. 3969–3987, 2007.
[72] Mazria and E., "Passive Solar Energy Book." Rodale Press,Emmaus, PA, 1979.
[73] S. Macmillan, "Added value of good design," *Build. Res. Inf.*, vol. 34, no. 3, pp. 257–271, May 2006.
[74] *An Urban Approach To Climate Sensitive Design: Strategies for the Tropics: Rohinton Emmanuel: 9780415334105: Amazon.com: Books*. .
[75] D. Pearlmutter, P. Berliner, and E. Shaviv, "Urban climatology in arid regions: current research in the Negev desert," *Int. J. Climatol.*, vol. 27, no. 14, pp. 1875–1885, Nov. 2007.
[76] "Fez Morocco - Fes Medina Maroc: Travel, Tours, History, Culture, Architecture, Hammam, Restoration." [Online]. Available: http://fesmedina.com/info-renaissance.htm.
[77] "Isfahan x. Monuments (3) Mosques – Encyclopaedia Iranica." [Online]. Available: http://www.iranicaonline.org/articles/isfahan-x3-mosques.
[78] A. Soncini, D. Bocchiola, R. Rosso, S. Meucci, F. Pala, and G. Valé, "Water and Sanitation in Multan, Pakistan," 2014, pp. 149–162.
[79] "About Esfahan | Isfahan Venus Hotel." [Online]. Available: http://venushotelesfahan.ir/about-isfahan?lang=en.
[80] "building in old sana'a - Picture of Sanaa, Yemen - TripAdvisor." [Online]. Available: https://www.tripadvisor.com/LocationPhotoDirectLink-g294015-i25424550-Sanaa.html.
[81] "Professor S. Roaf: Badgir (Iran's Ancient Air Conditioning System) | Kaveh Farrokh." [Online]. Available: http://kavehfarrokh.com/iranica/learning-knowledge-medicine/professor-s-roaf-badgir-irans-ancient-air-conditioning-system/.
[82] "Architectural Provision against Heat in the Orient on JSTOR." [Online]. Available: https://www.jstor.org/stable/542618?seq=1#page_scan_tab_contents.
[83] D. Beacco, "An Architectural Analysis of the Walled City: A 'Pilot Experiment' of Collaboration with the Building and Architectural Engineering Department of Bahauddin Zakariya University," 2014, pp. 281–288.
[84] "Yemen Maps - Perry-Castañeda Map Collection - UT Library Online." [Online]. Available: http://www.lib.utexas.edu/maps/yemen.html.
[85] "Photographs from Yemen: What's at Stake | beirutmabitmoot." [Online]. Available: https://beirutmabitmoot.wordpress.com/2015/05/13/photographs-from-yemen-whats-at-stake/.
[86] "ISFAHAN ii. Historical Geography – Encyclopaedia Iranica." [Online]. Available: http://www.iranicaonline.org/articles/isfahan-ii-historical-geography.
[87] "Multan Fort : Qila Kohna Qasim Bagh." [Online]. Available: http://www.pakimag.com/tourism/multan-fort-qila-kohna-qasim-bagh.html.
[88] "Ancient cities of Pakistan." [Online]. Available: http://oldcitiesofworld.blogspot.ae/2015/07/blog-post.html.
[89] "Looking at water in Fez, Morocco." [Online]. Available: http://www.wfsj.org/news/news.php?id=115.
[90] "Buildings Sana Yemen Stock Photos & Buildings Sana Yemen Stock Images - Alamy." [Online]. Available: http://www.alamy.com/stock-photo/buildings-sana-yemen.html.
[91] "نسخه متنی: آشنایی با کنیسه های اصفهان:" [Online]. Available: http://www.tebyan-zn.ir/news-papers/tourism/travel_turism_in_iran/Isfahan_Province/2013/7/21/117241.html.
[92] "Photographers, Cities and Projects on Pinterest." [Online]. Available: https://www.pinterest.com/pin/288723026086073350/.
[93] "List of places in Multan - Wikipedia." [Online]. Available: https://en.wikipedia.org/wiki/List_of_places_in_Multan.
[94] "About Morocco | Cities of Morocco : Fès." [Online]. Available: http://www.labelvoiture.com/guide-du-maroc/villes.php?lang=en&ville=5.
[95] "Fes City And Market Royalty Free Stock Photos - Image: 15438648." [Online]. Available: https://www.dreamstime.com/royalty-free-stock-photos-fes-city-market-image15438648.
[96] http://www.f-in-d.com/stories/abu-dhabi-guide-2014-introduction, "Introduction." [Online].

Available: http://www.f-in-d.com/stories/abu-dhabi-guide-2014-introduction.
[97] "As the UAE celebrates its 42nd National Day, Abu Dhabi celebrates its past, present and future | The National." [Online]. Available: http://www.thenational.ae/uae/heritage/on-the-uaes-42nd-national-day-abu-dhabi-celebrates-its-past-present-and-future. [Accessed: 02-Feb-2017].
[98] "Abu Dhabi, la perle jaillie des sables - Itinera-magica.com." [Online]. Available: http://www.itinera-magica.com/abu-dhabi-la-perle-des-sables/. [Accessed: 13-Dec-2016].
[99] "The man behind Abu Dhabi's master plan | The National." [Online]. Available: http://www.thenational.ae/uae/heritage/the-man-behind-abu-dhabis-master-plan#page3.
[100] "Old and Rare Pictures of Dubai and Abu Dhabi - 1966, 1954 |Living Life in UAE | Life in UAE, Dubai, Abu Dhabi, Sharjah, Universities,college,education,banks,jobs,business,expats life, working in dubai." [Online]. Available: http://blog.idubai.info/2012/11/old-and-rare-pictures-of-dubai-and-abu.html. [Accessed: 13-Dec-2016].
[101] "Memories of the old days | The National." [Online]. Available: http://www.thenational.ae/thenationalconversation/feedback/memories-of-the-old-days. [Accessed: 13-Dec-2016].
[102] E. Gómez-Baggethun and D. N. Barton, "Classifying and valuing ecosystem services for urban planning," *Ecol. Econ.*, vol. 86, no. C, pp. 235–245, 2013.
[103] "Planning World Cities - P. Newman|Andy Thornley - Palgrave Higher Education." [Online]. Available: https://he.palgrave.com/page/detail/planning-world-cities-peter-newman/?sf1=barcode&st1=9780230247314.
[104] P. Newman and A. Thornley, "Urban Planning in Europe: International Competition, National Systems and Planning Projects."
[105] S. Cassano, C. Francisco, P. M. Ganglani, A. Sathish, and Z. Pinto, "Atlas Environmental Abu Dhabi Emirate of."
[106] "masdar." [Online]. Available: http://www.masdar.ae/.
[107] R. Capello and R. Camagni, "Beyond Optimal City Size: An Evaluation of Alternative Urban Growth Patterns," *Urban Stud.*, vol. 37, no. 9, pp. 1479–1496, Aug. 2000.
[108] M. Salama and A. P. Habib, "Investigating the causes of variatiorn within the construction projects in UAE.," pp. 949–57, 2009.
[109] "Improving Building Industry Results through Integrated Project Delivery and Building Information Modeling."
[110] "Sustainability Challenges of Residential Reinforced-Concrete Panel Buildings | A. Ciutina - Academia.edu." [Online]. Available: http://www.academia.edu/23793562/Sustainability_Challenges_of_Residential_Reinforced-Concrete_Panel_Buildings.
[111] J. L. M. Hensen and R. Lamberts, "Building Performance Simulation for Design and Operation."
[112] A. Llordés, G. Garcia, J. Gazquez, and D. J. Milliron, "Tunable near-infrared and visible-light transmittance in nanocrystal-in-glass composites," *Nature*, vol. 500, no. 7462, pp. 323–326, Aug. 2013.
[113] "Masdar Institute of Abu Dhabi, MIT and African Agribusiness Knowledge Centers team-up to bring renewable energy solutions to African agribusiness zone/city planning." [Online]. Available: https://www.masdar.ac.ae/about-us/item/6221-masdar-institute-of-abu-dhabi-mit-and-african-agribusiness-knowledge-centers-team-up-to-bring-renewable-energy-solutions-to-african-agribusiness-zone-city-planning/?templatedirectory=10.
[114] P. Höppe, "The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment," *Int. J. Biometeorol.*, vol. 43, no. 2, pp. 71–75, Oct. 1999.
[115] M. Nikolopoulou and K. Steemers, "Thermal comfort and psychological adaptation as a guide for designing urban spaces," *Energy Build.*, vol. 35, no. 1, pp. 95–101, 2003.
[116] A. C. Carfan, E. Galvani, and J. T. Nery, "Study of thermal comfort in the City of São Paulo using ENVI-met model Estudio del confort térmico en la ciudad de São Paulo utilizando el modelo ENVI-MET," *Núm*, vol. 78, pp. 188–4611, 2012.
[117] F. Yang, S. S. Y. Lau, and F. Qian, "Thermal comfort effects of urban design strategies in high-rise urban environments in a sub-tropical climate," *Archit. Sci. Rev.*, vol. 54, no. 4, pp. 285–304, Nov. 2011.

[118] L. Peng and C. Jim, "Green-Roof Effects on Neighborhood Microclimate and Human Thermal Sensation," *Energies*, vol. 6, no. 2, pp. 598–618, Jan. 2013.
[119] N. Gaitani, M. Santamouris, and G. Mihalakakou, "Thermal comfort conditions in outdoor spaces."
[120] A.-T. Fazia and M. Helmut, "Thermal Comfort in Urban Streets with Trees under Hot Summer Conditions."
[121] E. Johansson, "Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco," *Build. Environ.*, vol. 41, no. 10, pp. 1326–1338, 2006.
[122] H. Kan, S. J. London, H. Chen, G. Song, G. Chen, L. Jiang, N. Zhao, Y. Zhang, and B. Chen, "Diurnal temperature range and daily mortality in Shanghai, China.," *Environ. Res.*, vol. 103, no. 3, pp. 424–31, Mar. 2007.
[123] Y. Luo, Y. Zhang, T. Liu, S. Rutherford, Y. Xu, X. Xu, W. Wu, J. Xiao, W. Zeng, C. Chu, and W. Ma, "Lagged effect of diurnal temperature range on mortality in a subtropical megacity of China.," *PLoS One*, vol. 8, no. 2, p. e55280, 2013.
[124] B. Cao, Q. Shang, Z. Dai, and Y. Zhu, "The Impact of Air-conditioning Usage on Sick Building Syndrome during Summer in China," *Indoor Built Environ.*, vol. 22, no. 3, pp. 490–497, Jun. 2013.
[125] J. Xiong, Z. Lian, X. Zhou, J. You, and Y. Lin, "Potential indicators for the effect of temperature steps on human health and thermal comfort," *Energy Build.*, vol. 113, pp. 87–98, 2016.
[126] J. Xiong, Z. Lian, and X. Zhou, "Investigation of Subjectively Assessed Health Symptoms and Human Thermal Perceptions in Transient Thermal Environments," *Procedia Eng.*, vol. 121, pp. 212–216, 2015.
[127] "Estidama." [Online]. Available: http://estidama.upc.gov.ae/. [Accessed: 28-Jan-2017].
[128] G. Chiri and I. Giovagnorio, "Gaetano Vinaccia's (1881–1971) Theoretical Work on the Relationship between Microclimate and Urban Design," *Sustainability*, vol. 7, no. 4, pp. 4448–4473, Apr. 2015.
[129] C. Rosenzweig, W. Solecki, S. A. Hammer, and S. Mehrotra, "Cities lead the way in climate–change action," *Nature*, vol. 467, no. 7318, pp. 909–911, Oct. 2010.
[130] C. G. Collier, "The impact of urban areas on weather," *Q. J. R. Meteorol. Soc.*, vol. 132, no. 614, pp. 1–25, Jan. 2006.
[131] C. S. B. Grimmond, M. Roth, T. R. Oke, Y. C. Au, M. Best, R. Betts, G. Carmichael, H. Cleugh, W. Dabberdt, R. Emmanuel, E. Freitas, K. Fortuniak, S. Hanna, P. Klein, L. S. Kalkstein, C. H. Liu, A. Nickson, D. Pearlmutter, D. Sailor, and J. Voogt, "Climate and More Sustainable Cities: Climate Information for Improved Planning and Management of Cities (Producers/Capabilities Perspective)," *Procedia Environ. Sci.*, vol. 1, pp. 247–274, 2010.
[132] G. Mills, H. Cleugh, R. Emmanuel, W. Endlicher, E. Erell, G. McGranahan, E. Ng, A. Nickson, J. Rosenthal, and K. Steemer, "Climate Information for Improved Planning and Management of Mega Cities (Needs Perspective)," *Procedia Environ. Sci.*, vol. 1, pp. 228–246, 2010.
[133] C. Ratti, D. Raydan, and K. Steemers, "Building form and environmental performance: archetypes, analysis and an arid climate," *Energy Build.*, vol. 35, no. 1, pp. 49–59, 2003.
[134] T. R. Oke, "Street design and urban canopy layer climate," *Energy Build.*, vol. 11, no. 1, pp. 103–113, 1988.
[135] P. Kastner-Klein, R. Berkowicz, and R. Britter, "The influence of street architecture on flow and dispersion in street canyons," *Meteorol. Atmos. Phys.*, vol. 87, no. 1–3, pp. 121–131, Sep. 2004.
[136] N. H. Wong and S. K. Jusuf, "Study on the microclimate condition along a green pedestrian canyon in Singapore," *Archit. Sci. Rev.*, vol. 53, no. 2, pp. 196–212, May 2010.
[137] M. Jin and J. M. Shepherd, "Inclusion of Urban Landscape in a Climate Model: How Can Satellite Data Help?," *Bull. Am. Meteorol. Soc.*, vol. 86, no. 5, pp. 681–689, May 2005.
[138] Ministry of Environment and Water of UAE, "UAE State of Green Economy 2014," 2014.
[139] "3ds Max | 3D Modeling, Animation & Rendering Software | Autodesk." [Online]. Available: http://www.autodesk.com/products/3ds-max/overview. [Accessed: 06-Feb-2017].
[140] "fez morocco old pictures internal courts - Google Search." [Online]. Available: https://www.google.ae/search?q=fez+morocco+old+pictures+internal+courts&espv=2&biw=

1366&bih=662&source=lnms&tbm=isch&sa=X&ved=0ahUKEwij5bbrwM_PAhUDrRoKHReTAOkQ_AUIBigB#imgrc=mwX8zKeJtsJ3gM%253A.
[141] W. Samuels and William, "Performance and Permeability: An investigation of the Mashrabiya for Use within the Gibson Desert," 2011.
[142] J. Mohamed and M. Rosenberg, "The tradiational arts and crafts of turnery or mashrabiya.," 2015.
[143] "Saudi Aramco World : The Magic of The Mashrabiyas." [Online]. Available: http://archive.aramcoworld.com/issue/197404/the.magic.of.the.mashrabiyas.htm. [Accessed: 20-Dec-2016].
[144] Chenyang Li, "Modernizing the Mashrabiya: Smart-skinned Al Bahar Towers," *2013*. [Online]. Available: http://scholar.googleusercontent.com/scholar?q=cache:7ilzp3hv5HcJ:scholar.google.com/+mashrabiya+use&hl=en&as_sdt=0,5. [Accessed: 20-Dec-2016].
[145] "Jeddah Saudi Historical Stock Photos & Jeddah Saudi Historical Stock Images - Alamy." [Online]. Available: http://www.alamy.com/stock-photo/jeddah-saudi-historical.html.
[146] M. Santamouris, "Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments," *Sol. Energy*, vol. 103, pp. 682–703, 2014.
[147] C. Yu and W. N. Hien, "Thermal benefits of city parks," *Energy Build.*, vol. 38, no. 2, pp. 105–120, Feb. 2006.
[148] H. Akbari, D. M. Kurn, S. E. Bretz, and J. W. Hanford, "Peak power and cooling energy savings of shade trees," *Energy Build.*, vol. 25, no. 2, pp. 139–148, 1997.
[149] D. M. Kurn, S. E. Bretz, B. Huang, and H. Akbari, "The potential for reducing urban air temperatures and energy consumption through vegetative cooling," Berkeley, CA, May 1994.
[150] M. Tjernstr�m, "Some tests with a surface energy balance scheme, including a bulk parameterisation for vegetation, in a mesoscale model," *Boundary-Layer Meteorol.*, vol. 48, no. 1–2, pp. 33–68, Jul. 1989.
[151] M. Boukhabl and D. Alkam, "Impact of Vegetation on Thermal Conditions Outside, Thermal Modeling of Urban Microclimate, Case Study: The Street of the Republic, Biskra," *Energy Procedia*, vol. 18, pp. 73–84, 2012.
[152] "Home | envimet." [Online]. Available: http://www.envi-met.com/.
[153] M. Bruse, "ENVI-met 3.0: Updated Model Overview," 2004.
[154] A. Fanchiotti, "Impact of cool materials on urban heat island and on building comfort and energy consumption."
[155] A. H. Rosenfeld, H. Akbari, S. Bretz, B. L. Fishman, D. M. Kurn, D. Sailor, and H. Taha, "Mitigation of urban heat islands: materials, utility programs, updates," *Energy Build.*, vol. 22, no. 3, pp. 255–265, 1995.
[156] R. Emmanuel, H. Rosenlund, and E. Johansson, "Urban shading—a design option for the tropics? A study in Colombo, Sri Lanka," *Int. J. Climatol.*, vol. 27, no. 14, pp. 1995–2004, Nov. 2007.
[157] N. Yaghoobian and J. Kleissl, "Effect of reflective pavements on building energy use," *Urban Clim.*, vol. 2, pp. 25–42, 2012.
[158] A. Gros, E. Bozonnet, and C. Inard, "Cool materials impact at district scale—Coupling building energy and microclimate models," *Sustain. Cities Soc.*, vol. 13, pp. 254–266, 2014.
[159] "Autodesk Student Community | Free Software & Resources for Education." [Online]. Available: http://www.autodesk.com/education/home. [Accessed: 09-Feb-2017].
[160] "RayMan - Modelling Mean Radiant Temperature and Thermal Indices." [Online]. Available: http://www.mif.uni-freiburg.de/rayman/intro.htm. [Accessed: 12-Feb-2017].
[161] "testo 435-3 multi-function climate measuring instrument | Pressure measurement - Filter | Pressure measurement | Air-conditioning systems maintenance | Operations/ maintenance and service | Applications | Testo® India." [Online]. Available: https://www.testo.com/en-IN/Applications/Operations-maintenance-and-service/Air-conditioning-systems-maintenance/Pressure-measurement/Pressure-measurement---Filter/testo-435-3/p/0560 4353. [Accessed: 12-Feb-2017].
[162] "Onset HOBO and InTemp Data Loggers." [Online]. Available: http://www.onsetcomp.com/.
[163] B. Bueno, J. Hidalgo, G. Pigeon, L. Norford, V. Masson, B. Bueno, J. Hidalgo, G. Pigeon, L.

Norford, and V. Masson, “Calculation of Air Temperatures above the Urban Canopy Layer from Measurements at a Rural Operational Weather Station,” *J. Appl. Meteorol. Climatol.*, vol. 52, no. 2, pp. 472–483, Feb. 2013.
[164] B. Bueno Unzeta, “Study and prediction of the energy interactions between buildings and the urban climate,” 2012.
[165] B. Bueno, M. Roth, L. Norford, and R. Li, “Computationally efficient prediction of canopy level urban air temperature at the neighbourhood scale,” *Urban Clim.*, vol. 9, pp. 35–53, 2014.
[166] W. T. L. Chow and M. Roth, “Temporal dynamics of the urban heat island of Singapore,” *Int. J. Climatol.*, vol. 26, no. 15, pp. 2243–2260, Dec. 2006.
[167] T. R. Oke and G. B. Maxwell, “Urban heat island dynamics in Montreal and Vancouver,” *Atmos. Environ.*, vol. 9, no. 2, pp. 191–200, Feb. 1975.
[168] M. (Matheos) Santamouris and D. N. (Demosthenes N. . Asimakopoulos, *Energy and climate in the urban built environment*. James X James, 2001.
[169] S. M. Khan and R. W. Simpson, “Simulation of mixing depths incorporating the urban heat island effect,” *Environ. Model. Assess.*, vol. 6, no. 3, pp. 183–193, 2001.
[170] S. I. Bohnenstengel, I. Hamilton, M. Davies, and S. E. Belcher, “Impact of anthropogenic heat emissions on London’s temperatures,” *Q. J. R. Meteorol. Soc.*, vol. 140, no. 679, pp. 687–698, Jan. 2014.
[171] A. K. L. Quah and M. Roth, “Diurnal and weekly variation of anthropogenic heat emissions in a tropical city, Singapore,” *Atmos. Environ.*, vol. 46, pp. 92–103, 2012.
[172] “https://btrl.masdar.ac.ae/index.php/about-us/people/item/11-afshin-afshari.” [Online]. Available: https://btrl.masdar.ac.ae/index.php/about-us/people/item/11-afshin-afshari. [Accessed: 26-Jan-2017].
[173] X. Yang, L. Zhao, M. Bruse, and Q. Meng, “An integrated simulation method for building energy performance assessment in urban environments,” *Energy Build.*, vol. 54, pp. 243–251, 2012.
[174] “Analysis and diagnosis of the energy performance of buildings and districts: Methodology, validation and development of Urban Energy Maps | rosa de masi - Academia.edu.” [Online]. Available: http://www.academia.edu/20973595/Analysis_and_diagnosis_of_the_energy_performance_of_buildings_and_districts_Methodology_validation_and_development_of_Urban_Energy_Maps.
[175] J. A. Fonseca and A. Schlueter, “Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts,” *Appl. Energy*, vol. 142, pp. 247–265, 2015.
[176] T. S. Saitoh, T. Shimada, and H. Hoshi, “Modeling and simulation of the Tokyo urban heat island,” *Atmos. Environ.*, vol. 30, no. 20, pp. 3431–3442, 1996.
[177] A. H. Ghoreishi and M. M. Ali, “Contribution of Thermal Mass to Energy Performance of Buildings: A Comparative Analysis,” *Int. J. Sustain. Build. Technol. Urban Dev.*, 2011.
[178] R. Giridharan, S. Ganesan, and S. S. . Lau, “Daytime urban heat island effect in high-rise and high-density residential developments in Hong Kong,” *Energy Build.*, vol. 36, no. 6, pp. 525–534, 2004.
[179] C. de Munck, G. Pigeon, V. Masson, F. Meunier, P. Bousquet, B. Tréméac, M. Merchat, P. Poeuf, and C. Marchadier, “How much can air conditioning increase air temperatures for a city like Paris, France?,” *Int. J. Climatol.*, vol. 33, no. 1, pp. 210–227, Jan. 2013.
[180] M. Santamouris, N. Papanikolaou, I. Livada, I. Koronakis, C. Georgakis, A. Argiriou, and D. . Assimakopoulos, “On the impact of urban climate on the energy consumption of buildings,” *Sol. Energy*, vol. 70, no. 3, pp. 201–216, 2001.
[181] D. B. Crawley, “Estimating the impacts of climate change and urbanization on building performance,” *J. Build. Perform. Simul.*, vol. 1, no. 2, pp. 91–115, Jun. 2008.
[182] J. Allegrini, V. Dorer, and J. Carmeliet, “Influence of the urban microclimate in street canyons on the energy demand for space cooling and heating of buildings,” *Energy Build.*, vol. 55, pp. 823–832, 2012.
[183] T. Denes-Bejat, E. Bozonnet, and I. . Calmet, “Modeling the global warming effect on indoor temperature peaks and cooling systems consumption,” 2009.
[184] H. Akbari and S. Konopacki, “Calculating energy-saving potentials of heat-island reduction

strategies," *Energy Policy*, vol. 33, no. 6, pp. 721–756, 2005.
[185] H. Taha, H. Akbari, A. Rosenfeld, and J. Huang, "Residential cooling loads and the urban heat island—the effects of albedo," *Build. Environ.*, vol. 23, no. 4, pp. 271–283, 1988.
[186] T. R. Oke, "The energetic basis of the urban heat island," *Q. J. R. Meteorol. Soc.*, vol. 108, no. 455Oke, T. R. (1982). The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society, 108(455), 1–24. https://doi.org/10.1002/qj.49710845502, pp. 1–24, Jan. 1982.
[187] "Today's Global Flâneuse."
[188] "Low-energy design in the United Arab Emirates- Building design principles - Google Search." [Online]. Available: https://www.google.ae/search?q=Low-energy+design+in+the+United+Arab+Emirates-+Building+design+principles&oq=Low-energy+design+in+the+United+Arab+Emirates-+Building+design+principles&aqs=chrome..69i57.487j0j4&sourceid=chrome&ie=UTF-8.
[189] "Challenging the Supremacy of Airconditioning."
[190] Y. Sun, Y. Heo, M. Tan, H. Xie, C. F. Jeff Wu, and G. Augenbroe, "Uncertainty quantification of microclimate variables in building energy models," *J. Build. Perform. Simul.*, vol. 7, no. 1, pp. 17–32, Jan. 2014.
[191] C. Willmott and K. Matsuura, "Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance," *Clim. Res.*, vol. 30, no. 1, pp. 79–82, 2005.
[192] *Boundary Layer Climates: T. R. Oke: 9780415043199: Amazon.com: Books*. .
[193] M. Bruse, "Simulating microscale climate interactions in complex terrain with a high-resolution numerical model: A case study for the Sydney CBD Area (Model Description)."
[194] R. Giridharan, S. S. Y. Lau, S. Ganesan, and B. Givoni, "Lowering the outdoor temperature in high-rise high-density residential developments of coastal Hong Kong: The vegetation influence," *Build. Environ.*, vol. 43, no. 10, pp. 1583–1595, 2008.
[195] D. J. Sailor, "A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment," *Int. J. Climatol.*, vol. 31, no. 2, pp. 189–199, Feb. 2011.
[196] H. Taha, "Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat," *Energy Build.*, vol. 25, no. 2, pp. 99–103, 1997.
[197] P. Rajagopalan, K. C. Lim, and E. Jamei, "Urban heat island and wind flow characteristics of a tropical city," *Sol. Energy*, vol. 107, pp. 159–170, 2014.
[198] S. Rafailidis, "Influence of Building Areal Density and Roof Shape on the Wind Characteristics Above a Town," *Boundary-Layer Meteorol.*, vol. 85, no. 2, pp. 255–271, 1997.
[199] A. Zhang, C. Gao, and L. Zhang, "Numerical simulation of the wind field around different building arrangements," *J. Wind Eng. Ind. Aerodyn.*, vol. 93, no. 12, pp. 891–904, 2005.
[200] G. Ferguson and A. D. Woodbury, "Subsurface heat flow in an urban environment," *J. Geophys. Res. Solid Earth*, vol. 109, no. B2, Feb. 2004.
[201] Qihao Weng and Dengsheng Lu, "A sub-pixel analysis of urbanization effect on land surface temperature and its interplay with impervious surface and vegetation coverage in Indianapolis, United States," 2008.
[202] Q. Weng, D. Lu, and J. Schubring, "Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies," *Remote Sens. Environ.*, vol. 89, no. 4, pp. 467–483, 2004.
[203] K. D. Hage and K. D. Hage, "Urban-Rural Humidity Differences," *J. Appl. Meteorol.*, vol. 14, no. 7, pp. 1277–1283, Oct. 1975.
[204] M. Aida, "Urban albedo as a function of the urban structure ? A model experiment," *Boundary-Layer Meteorol.*, vol. 23, no. 4, pp. 405–413, Aug. 1982.
[205] R. A. Memon, D. Y. C. Leung, and L. Chunho, "A review on the generation, determination and mitigation of urban heat island.," *J. Environ. Sci. (China)*, vol. 20, no. 1, pp. 120–8, 2008.
[206] M. Bruse, "Modelling and straetgies for improved urban climates."
[207] M. Bruse and H. Fleer, "Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model," *Environ. Model. Softw.*, vol. 13, no. 3, pp. 373–384, 1998.
[208] "Tutorials - Grasshopper." [Online]. Available: http://www.grasshopper3d.com/page/tutorials-1.

[209] C. F. Reinhart, “Tutorial on the Use of Daysim Simulations for Sustainable Design,” 2006.
[210] J. A. Jakubiec and C. Reinhart, “DIVA 2.0: Integrating the daylight and energy simulation.”
[211] “Ecotect Analysis Discontinuation FAQ | Ecotect Analysis | Autodesk Knowledge Network.” [Online]. Available: https://knowledge.autodesk.com/support/ecotect-analysis/troubleshooting/caas/sfdcarticles/sfdcarticles/Ecotect-Analysis-Discontinuation-FAQ.html.
[212] “R2011b - Updates to the MATLAB and Simulink product families - MATLAB & Simulink.” [Online]. Available: https://www.mathworks.com/products/new_products/release2011b.html.
[213] T. Toppi, P. Zangheri, and R. Paolini, “Simplified Method for Modification of Weather Data File for Energy Simulations within Urban Areas.”
[214] R. M. T. Priyadarsini, “Microclimatic modeling of the urban thermal environment of singapore to mitigate the Urban Heat Island.”
[215] J. Bouyer, C. Inard, and M. Musy, “Microclimatic coupling as a solution to improve building energy simulation in an urban context,” *Energy Build.*, vol. 43, no. 7, pp. 1549–1559, 2011.
[216] M. Roth, C. Jansson, and E. Velasco, “Multi-year energy balance and carbon dioxide fluxes over a residential neighbourhood in a tropical city,” *Int. J. Climatol.*, Sep. 2016.
[217] “honeybee example files - Grasshopper.” [Online]. Available: http://www.grasshopper3d.com/group/ladybug/forum/topics/honeybee-example-files?xg_source=activity. [Accessed: 16-Feb-2017].
[218] A. Martilli, A. Clappier, and M. W. Rotach, “An urban surface exchange parametrisation for mesoscale models.”
[219] “Ladybug Analysis Tools - Grasshopper.” [Online]. Available: http://www.grasshopper3d.com/group/ladybug. [Accessed: 16-Feb-2017].
[220] S. Attia and S. Carlucci, “Impact of different thermal comfort models on zero energy residential buildings in hot climate,” *Energy Build.*, vol. 102, pp. 117–128, 2015.
[221] D. J. Sailor, “Anthropogenic Heat and Moisture Emissions in the Urban Environment.”
[222] H. Kondo and Y. Kikegawa, “Temperature Variation in the Urban Canopy with Anthropogenic Energy Use,” in *Air Quality*, Basel: Birkhäuser Basel, 2003, pp. 317–324.
[223] Y. Ohashi, Y. Genchi, H. Kondo, Y. Kikegawa, H. Yoshikado, and Y. Hirano, “Influence of Air-Conditioning Waste Heat on Air Temperature in Tokyo during Summer: Numerical Experiments Using an Urban Canopy Model Coupled with a Building Energy Model,” *J. Appl. Meteorol. Climatol.*, vol. 46, no. 1, pp. 66–81, Jan. 2007.
[224] D. Narumi, A. Kondo, and Y. Shimoda, “Effects of anthropogenic heat release upon the urban climate in a Japanese megacity,” *Environ. Res.*, vol. 109, no. 4, pp. 421–431, May 2009.
[225] T. Hoyt, E. Arens, and H. Zhang, “Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings,” *Build. Environ.*, vol. 88, pp. 89–96, 2015.
[226] “New water and electricity tariffs structure.” [Online]. Available: http://rsb.gov.ae/en/sector/new-water-and-electricity-tariffs-structure.
[227] “Multan, the walled city - Photo-essays - Domus.” [Online]. Available: http://www.domusweb.it/en/photo-essays/2013/03/12/multan-the-walled-city.html. [Accessed: 25-Jan-2017].
[228] “Urban Energy Modeling.” [Online]. Available: https://btrl.masdar.ac.ae/index.php/research/item/69-urban-energy-modeling. [Accessed: 26-Jan-2017].
[229] “Workshop 13w » Blog.” [Online]. Available: https://iam.tugraz.at/workshop13w/blog/.
[230] “Middle east, Middle and Architecture on Pinterest.” [Online]. Available: https://www.pinterest.com/pin/368098969514586425/.
[231] “Abu Haleem Al Yemeni.” [Online]. Available: http://www.abuhaleem.com/.
[232] S. Sakai, I. Iizawa, M. Onishi, M. Nakamura, K. Kobayashi, M. Mitsunaga, and K. Furuya, “Fractial geometry of the ground surface and urban heat island.”

Table Content

Figure Content:

Annex

Annex

1. *Temperature measurements from the sensor network downtown Abu Dhabi (Chapter 6)*

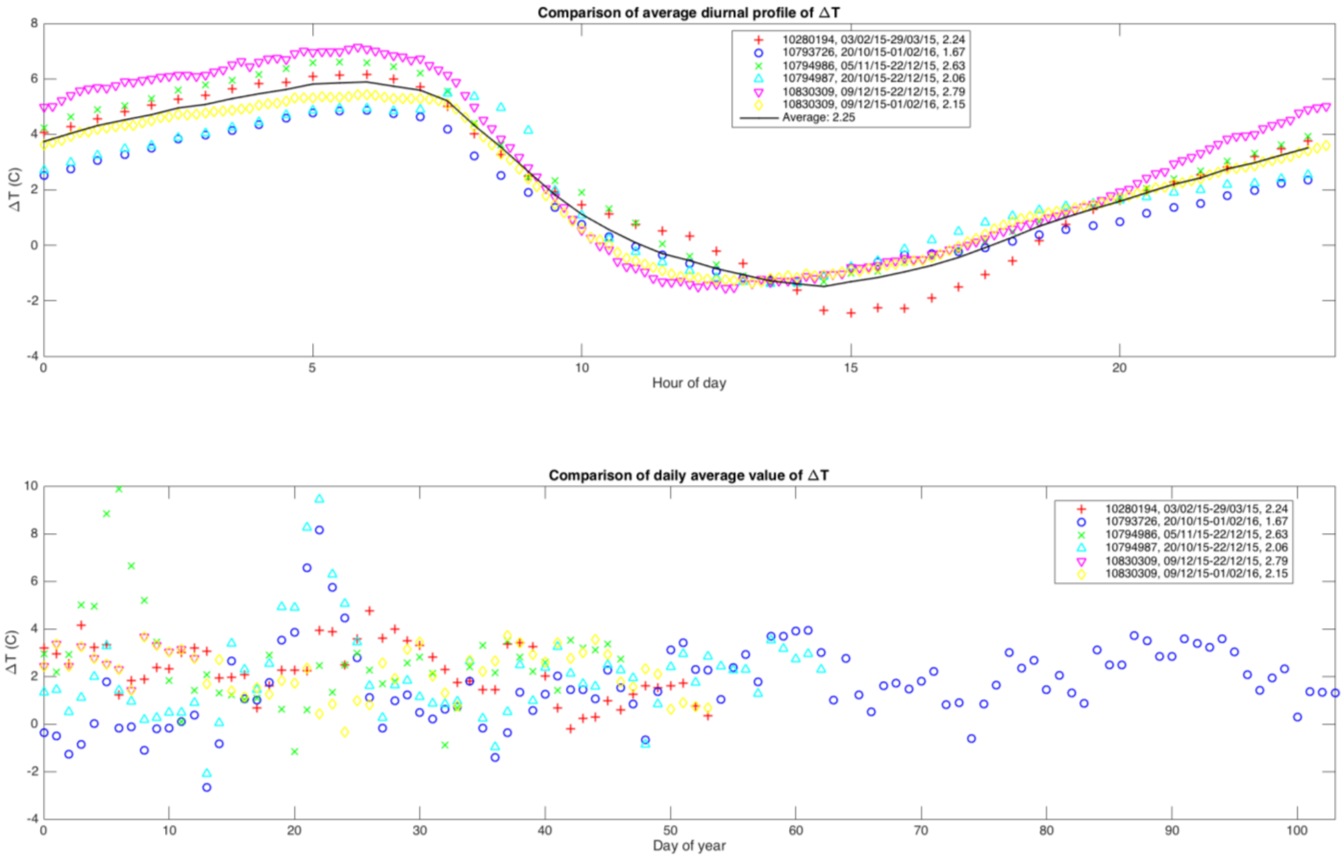


Figure 88: Sensors (H01, H02, H03, H04 and H05) measurements during the winter season.

2. *Table of the building typology included in the UWG simulation (Chapter 7)*

Table 44: Building Typologies used in UWG

	Residential 01	**Residential 02**	**Office**	**Hotel**
Distribution	38%	34%	11%	27%
Glazing ratio	0.43	0.3	0.43	0.43
Window U-value	2.4 W/m^2	3.88 W/m^2	2.4 W/m^2	2.4 W/m^2
Cooling set point	19.85°C	19.85°C	19.85°C	19.85°C
Cooling COP	2.5	2.5	2.5	2.5

3. *Table of the ENVI-met initial conditions for the spring simulation (Chapter 7)*

Table 45: ENVI-met Initial Conditions

Start Simulation at Day (DD.MM.YYYY):	21.03.2012
Start Simulation at Time (HH:MM:SS):	00:00:00
Total Simulation Time in Hours:	48
Wind Speed in 10 m ab. Ground [m/s]	3.55
Wind Direction (0:N..90:E..180:S..270:W..)	210.89
Roughness Length z0 at Reference Point [m]	0.01
Initial Temperature Atmosphere [K]	298.95
Specific Humidity in 2500 m [g Water/kg air]	7.0
Relative Humidity in 2m [%]	56
[SOILDATA] ____	
Initial Temperature Upper Layer (0-20 cm) [K]	301.15
Initial Temperature Middle Layer (20-50 cm) [K]	297.50
Initial Temperature Deep Layer (below 50 cm)[K]	293.00
Relative Humidity Upper Layer (0-20 cm)	95.00
Relative Humidity Middle Layer (20-50 cm)	90.00
Relative Humidity Deep Layer (below 50 cm)	85.00
[SIMPLEFORCE] ____	
Hour 00h [Temp, rH]	296.80, 63.94
Hour 01h [Temp, rH]	296.30, 65.82
Hour 02h [Temp, rH]	296.08, 66.19
Hour 03h [Temp, rH]	295.73, 67.45
Hour 04h [Temp, rH]	295.13, 70.70
Hour 05h [Temp, rH]	295.00, 71.45
Hour 06h [Temp, rH]	295.29, 69.85
Hour 07h [Temp, rH]	297.17, 62.39
Hour 08h [Temp, rH]	298.97, 54.64
Hour 09h [Temp, rH]	300.60, 46.61
Hour 10h [Temp, rH]	301.88, 41.58
Hour 11h [Temp, rH]	302.62, 40.00
Hour 12h [Temp, rH]	303.18, 38.56
Hour 13h [Temp, rH]	302.79, 39.57
Hour 14h [Temp, rH]	302.54, 41.99
Hour 15h [Temp, rH]	302.39, 41.75
Hour 16h [Temp, rH]	301.73, 45.07
Hour 17h [Temp, rH]	300.75, 48.72
Hour 18h [Temp, rH]	299.68, 53.33
Hour 19h [Temp, rH]	299.04, 57.02
Hour 20h [Temp, rH]	298.46, 59.95
Hour 21h [Temp, rH]	297.82, 62.28
Hour 22h [Temp, rH]	297.61, 62.61
Hour 23h [Temp, rH]	297.16, 63.89

4. Cost estimation of ‘cool’ and ‘green’ urban shading devices (Chapter 9)

As per the request of the different stakeholders involved in this research, the cost evaluation analysis was based on the local market. The contractors are from the city of Abu Dhabi and the materials are brought produced in China. Since the beginning of the research, the same materials used in the case study are taken and exposed to the outdoor conditions in one of the laboratories rooftop. The lifecycle analysis of this materials is part of a separate ongoing research. Below are listed some points that this research is related to Cost Estimation, Stakeholders, Local Community, Environmental Impact, Sustainable City.

The cost estimation of the three types of shading devices was done according to an existing applied case study for the traditional and the tent type. For the calculation of the cost of the green shading devices, the online resources from the AD Municipality were used. In order to get the real prices, the process evolves as below. The design of this shading devices went through a long process of revisions. The client had several requests to the areas that were covered with the traditional shading devices and the areas that had the modern or the tent one. The design phase went to four revisions according to the comments of the owner and according to the budget modifications. This part followed the models that were initially built and analyzed in the lab. Even though the initially covered area was bigger, the last approved design has a good combination between the traditional tent and the modern one. In this way the children will have a connection with the past and a vision of the future. In the cost estimation below, the photovoltaic cells that were initially planned to be installed are not placed. In the quotation the specifications below are mentioned: All materials used are the highest specifications and high quality of manufacture. DESIGN: as per your proposed Louvre (type 1 to 7) and sail (type A8, A10 and A11) design. All the steel structure will be design to withstand fabrics given load. As per drawing #: (G.2). MATERIALS: Fabric options: HDPE fabric Commercial 95, 340 gsm, made in Australia; Steel Structure: MS plate for base, stiffener, cleats and wall bracket. G.I. wire rope. G.I. accessories and fittings. Paint Specification: powder coated paint system. Foundation: steel bracket to the concrete wall (figure 90-91).

The procurement phase.

The procurement process went through several revisions; the initial budget was 250000 aed. After several discussions, at a much lower quotation was finalized. The procurement phase had several revisions. From an initial budget estimation of 250000 aed, the budget went down to 75000 aed. This was due to the owner’s request. In real conditions the last negotiations are very important, as the quality of the work that will be executed depends on the conditions mentioned in the contract. In this case the change of the tent typology made a big difference in the quotation. The current selection has a warranty of 15 years. The bamboo or traditional one has a warranty of 10 years.

The execution phase

During the execution there was a different approach from both contractors. One of them was from Abu Dhabi and the other one from Al Ain. The traditional shading devices were installed within 20 days. On the other hand the other contractor brought up some delays due to the paint used in the metallic parts. The execution was divided into two main phases. The first one was the traditional shading device installation. The contractor started with the first layer of shading. Then he added the second layer, creating the estimated difference of 50 cm between the layers. The difficulties noticed in this case were the connection points with the wall. This kind of bamboo taken from the local market has a limited length. With the locally made ropes, it was possible to establish the connections and finalize the work within 20 days. On the other side, the modern tents has not yet started to be installed as there were

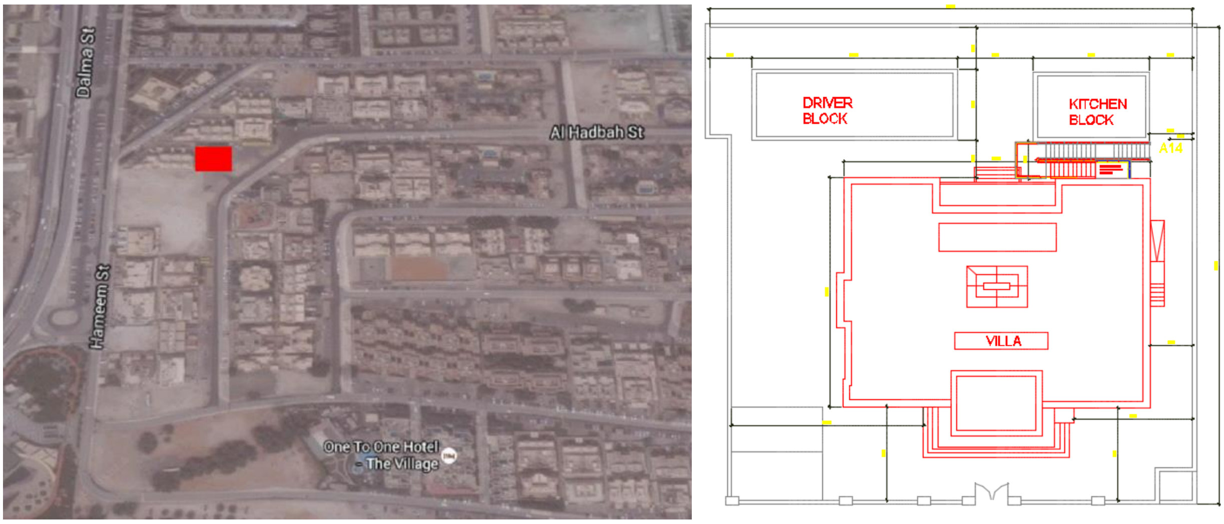


Figure 89: The unit location.

Figure 90: Design proposal 1.

Figure 91: Applied shading device.

The district hypothesis

In this point is done some estimation in order to have a general idea of how much a similar intervention might cost at a district level. It is important to have an idea of the costs and the possibility of application as the models done at the laboratory don't estimate this part. As showed below, the aim of this research is to make an estimation of the cost and time frame of such intervention in this district typology. This means more work for the local community beside of the life quality improvement. All of this job could be done in 4 months with several contractors working in the same time. The warranty of such investment varies from 10 to 15 years. The cost and the timeline depend on the type of the design and the material of course. In this case the proposed materials were two types. Based on this unit information was possible to extract the prices per unit and therefore to be used for the full district calculation. Regarding the Green Shading devices, the main plant typologies suggested to be used in this cost analysis was based on the Realm Design Manual and a reference project done in Dubai. According to the UAE policies, the prices of recycled water used to irrigate the vegetation are almost 0. The local government facilitates the appliances of such intervention (figure 92, table 46-51).

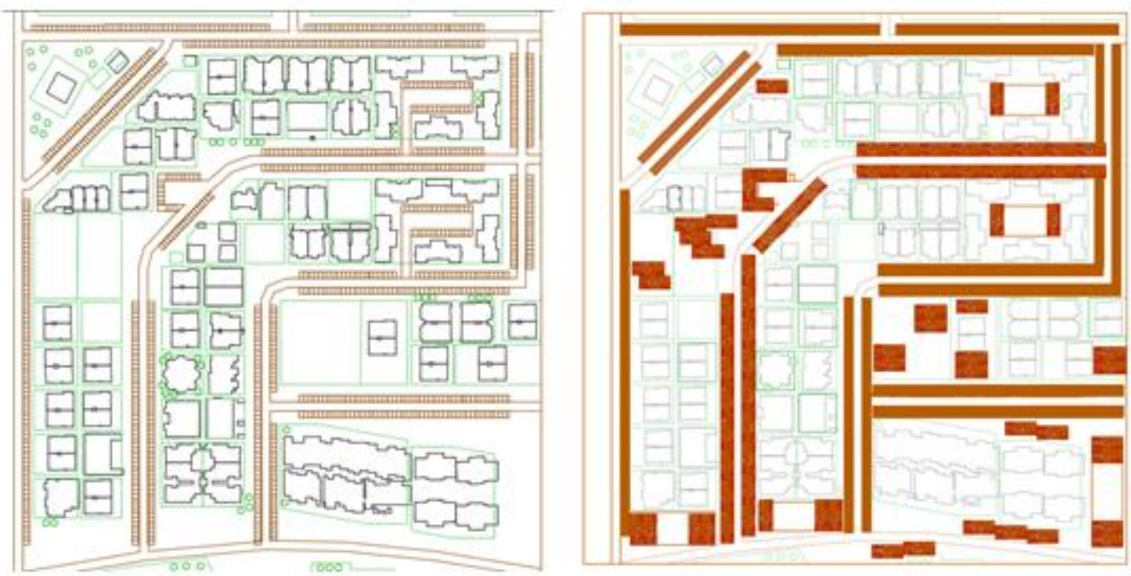


Figure 92: District comparison before and after the proposal.

Table 46: Vegetation Properties.

PLANT LIST BASED ON PUBLIC_REALM_DESIGN_MANUAL							
No.	**Species Botanic Name**	**Common Name**	**Local Name**	**Size**	**Water requirements**	**Type**	**Planting Density**
1	Phoenix Dactylifera	Date palm	Nakhil al balah	18-25m high, 12m spread	low	tree	avg
2	Azadirachta indica	Neem tree		6-8m spreading crown	low	tree	high
3	Adenim Obesum	Desert rose	adanah	5m high, 3m spread	low	shrub	low
4	Caesalpina Pulcherrima	Red bird of paradise, pride of barbadous	Zahrat Al Tawose, Abu Shawarib	3m high, 3m spread	medium	shrub	low

Table 47: Cost evaluation1.

TRADITIONAL SHADING DEVICES				
DISTRICT	**SHADED AREA**	**PERSENTAGE**	**COST M2 (eur)**	**TOTAL COST (eur)**
Villas	41,692.00	34.87	18.40	0.7M
High Rise Buildings	28,250.00	18.61	18.40	0.5M
Medium and High Rise Buildings	32,702.00	16.87	18.40	0.6M
Medium Rise Buildings.	20,426.00	14.94	18.40	0.4M
Villas and High Rise Buildings.	37,384.00	23.01	18.40	0.7M

Table 48: Cost evaluation2.

TENT SHADING DEVICES				
DISTRICT	**SHADED AREA**	**PERSENTAGE**	**COST M2 (eur)**	**TOTAL COST (eur)**
Villas	41,692.00	35	32.2	1,3M
High Rise Buildings	28,250.00	19	32.2	0.9M
Medium and High Rise Buildings	32,702.00	17	32.2	1M
Medium Rise Buildings	20,426.00	15	32.2	0.6M
Villas and High Rise Buildings	37,384.00	23	32.2	1.2M

Table 49: Cost evaluation 3.

GREEN SHADING DEVICES					
DISTRICT	**SHADED AREA**	**PERSENTAGE**	**STRUCTURE COST COST (eur)**	**GREEN COST (eur)**	**TOTAL COST (eur)**
Villas	41,692.00	35	0.6M	0.9M	1,5M
High Rise Buildings	28,250.00	19	0.4M	0.6M	1,03M
Medium and High Rise Buildings	32,702.00	17	0.5M	0.7M	1,19M
Medium Rise Buildings.	20,426.00	15	0.3M	0.4M	0,7M
Villas and High Rise Buildings.	37,384.00	23	0.6M	0,8M	1,3M

Table 50: Cost evaluation 4.

ENERGY SAVING				
TEMPERATURE DROP	**KW /m2 year**	**COST/KW (eur)**	**FOOTPRINT M2**	**TOTAL SAVING/ YEAR (eur)**
0.5	600	0.05	38,052.00	1,1M
0.5	900	0.05	27,256.00	1,2M
0.5	900	0.05	46,651.00	2,1M
0.5	900	0.05	31,878.00	1,4M
0.5	900	0.05	27,033.00	1,2M

Table 51: Cost evaluation 5 [226] [56][23].

TIME	**CASH FLOW (eur)**				
	Villas	**High Rise Buildings**	**Medium and High Rise Buildings**	**Medium Rise Buildings.**	**Villas and High Rise Buildings.**
0	(1,5M)	(1,03M)	(1,19M)	(0,74M)	(1,36M)
1	1,14M	1,22M	2,09M	1,43M	1,21M
2	1,14M	1,22M	2,09M	1,43M	1,21M
3	1,14M	1,22M	2,09M	1,43M	1,21M
4	1,14M	1,22M	2,09	1,43M	1,21M
5	1,14M	1,22M	2,09M	1,43M	1,21M
6	1,14M	1,22M	2,09M	1,43M	1,21M
7	1,14M	1,22M	2,09M	1,43M	1,21M
8	1,14M	1,22M	2,09M	1,43M	1,21M
9	1,14M	1,22M	2,09M	1,43M	1,21M
10	1,14M	1,22M	2,09M	1,43M	1,21M
11	1,14M	1,22M	2,09M	1,43M	1,21M
12	1,14M	1,22M	2,09M	1,43M	1,21M
13	1,14M	1,22M	2,09M	1,43M	1,21M
14	1,14M	1,22M	2,09M	1,43M	1,21M
15	1,14M	1,22M	2,09M	1,43M	1,21M
NPV	**5,15M**	**6,1M**	**11,08M**	**7,64M**	**5,7M**
IRR	**75%**	**119%**	**176%**	**192%**	**89%**

Stakeholders

The main stakeholders in this project are the Abu Dhabi Municipality, Abu Dhabi Urban Planning Council, and Dubai Municipality. Since the release of the ABU Dhabi Plan 2030, the different institutions are committed to achieving the requirements defined in the maul in order to make Abu Dhabi a more sustainable city. This research project is part of an ongoing collaboration among the above institutions.

Partners and research communities:

Politecnico di Milano, Italy.
Masdar Institute of Science and Technology.
Massachusetts Institute of Technology.
Abu Dhabi Municipality.

Local Community

The different proposals shown in the second chapter aim to involve the local community in the design of the Urban Shading devices. Presenting several options in 3D and consulting the different communities living in the area, the citizens will be able to participate in the decision-making and, therefore, be part of the new interventions.

Environmental Impact

As mentioned in the previous chapters, a combination between 'cool' shading devices and 'green' shading devices can reduce the outdoor air temperatures. The citizens would be more stimulated to use the cars less in order to circulate within the district. Including the vegetation in the different districts beside the evapotranspiration process and the impact in the outdoor thermal comfort, the level of the CO2 decreases.

Sustainable City

Emerging countries have an urgent need of sustainable construction guidelines. While innovative solutions in energy efficiency have become a common feature in many mature economies, the developing ones are still facing many challenges, mostly related to the complicated relationship between traditional architecture and new technologies.

The Middle East area is a good example in this sense. Indeed, new architecture features, technologies and materials are rapidly replacing traditional architecture. This is usually done without taking the country's architectural heritage, which may itself already offer sustainable solutions, into sufficient consideration. In simpler words, innovation may come from a complete rethinking/reusage of traditional architectures combined with the latest technologies. This would be a great opportunity for many developing countries, as they could still preserve their architectural heritage but at the same time moving along the path of more advanced building technologies. However, the actual implementation of such an opportunity needs to be carefully tested before entering the market. Indeed, a too early deployment of advanced technologies to traditional architecture may easily have more risks than gains.

Innovation in architecture and construction comes as an opportunity that needs to be studied and tested before entering the market. The innovation risks walk along with the opportunity for a sustainable solution. Evaluation of the risks has to be done as an overview of the transformation and evolution that brings out this innovation. Among all urban features, a focus on residential buildings will make this evaluation take place.[168]

Thank you.