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SCHOOL OF ENVIRONMENTAL ENGINEERING
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**Doctoral Thesis**

# Introducing environmental principles, methodology and tools for bioclimatic urban open space design of Mediterranean cities

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## Contents

## Abstract

While comfort conditions of the indoor environment have been extensively analysed during the last decades, increasing interest has been given towards the influence of the outdoor environment to sustainable use of urban open spaces by citizens of cities. The scope of this study is to introduce an integrated approach to urban open space design by following a refined design process and proposing a new palette of decision-making tools.

The study quantifies the effect of the most common parameters that affect the comfort conditions of urban open spaces in cities with a Mediterranean climate. The analysed parameters are addressed mostly on existing open spaces and can be easily adjusted through open space regeneration. The studied parameters are height to width ratio of an urban canyon, sky view factor, greenery coverage percentage and paving material properties. Each parameter is investigated individually and in relation to the others. The obtained results indicate that there is a significant correlation between certain parameters which produce approximately the same amount of influence to the design. In the same time, other parameters influence the whole area cumulatively. This study also offers a complete methodological tool which allows a simplified and accurate analysis that takes into consideration the most crucial microclimatic parameters and can provide the necessary information to the design team to develop sustainable outdoor urban open spaces especially for the summer season in cities with a Mediterranean climate. The proposed tool provides to stakeholders, a set of comparable data of certain bioclimatic indexes that will speed-up and guide the decision process on the basic issues regarding the new area design.

if a design team working on an urban area regeneration project, use specific bioclimatic criteria as basic directions for the design concept will achieve good results with improved microclimate comfort conditions for the space users. The study proposes a methodology that combines a literature review, simulation and evaluation of different case scenarios and implementation on existing areas of Crete, Greece. This methodology reflects the evidence-based design principles for the bioclimatic regeneration of urban open spaces in cities with a Mediterranean climate and it has been already applied and evaluated in several architectural projects in Greece.

**Published research within the PhD study**

| | |
|---|---|
| **06/2017** | **Μ. Τσίτουρα, Μ. Μιχαηλίδου «Επιλύοντας θέματα προσβασιμότητας σε αναπλάσεις δημόσιου χώρου στο Ν. Χανίων, Μελέτη περίπτωσης για πλατεία στον Πλατανιά και την κεντρική πλατεία Σούδας» 8ο Συνέδριο p public, Χανιά 2017** |
| **06/2017** | M. Tsitoura, M. Michailidou, T. Tsoutsos **"A bioclimatic outdoor design tool in urban open space design"** special issue entitled "Climatic Adaptation of Building Energy Performance" of the Energy & Buildings journal 153, (2017) pp.368–381 |
| **05/2016** | M. Tsitoura, M. Michailidou, T. Tsoutsos "**Achieving sustainability through the management of microclimate parameters in Mediterranean urban environments during summer**" Sustainable Cities and Society 26 (2016) 48–64 |
| **04/2015** | M. Tsitoura, M. Michailidou, T. Tsoutsos "**Achieving sustainability through management of microclimate parameters in urban environments during summer"** article in Multi. Vol set on Environment Science and Engineering (In 12 vols set) by Studium Press LLC, USA. ISBN 978-1-62699-061-6 |
| **07/2014** | M. Tsitoura, T. Tsoutsos, T. Daras **"Evaluation of comfort conditions in urban open spaces. Application in the island of Crete"** Energy Conversion and Management 86 (2014) 250–258 |
| **06/ 2011** | M. Tsitoura, M. Michailidou, T. Tsoutsos «Evaluation of comfort conditions and sustainable design of urban open spaces in Crete» Conference PLEA 2011, Louvain la neuve, Belgium |
| **05/2011** | Μ. Μιχαηλίδου, Μ. Τσίτουρα «Χρήση της προσομοίωσης και των μετρήσεων του μικροκλίματος για την ανάπλαση αστικού πάρκου στην Κρήτη» , Συνέδριο ΑΡΕΝΕΠ 2011, Αθήνα |
| **09/ 2010** | M. Tsitoura, T. Tsoutsos, D. Kolokotsa **«Comfort conditions in urban open spaces in Crete»** Palenc 2010 Conference, Rhodes |
| **02/ 2010** | N. Papamanolis, M. Tsitoura **«A comparative approach to the energy and environmental behaviour of contemporary urban buildings in Greece»** Conference Portugal SB10 2010, Conference publication «Sustainable Building affordable to all, low cost sustainable solutions» |

## Abbreviation list

| | |
|---|---|
| $C_{sa}$ | Mediterranean hot-summer climate (Köppen climate classification) |
| PA | Partnership agreement |
| $DH_T$ | Degree-hours of $T_a > 26℃$ |
| $DH_{UTCI}$ | Degree-hours of $UTCI > 26℃$ |
| H/W | Height/Width ratio of a canyon |
| MRT | Mean radiant temperature [°C] |
| °C | Degree Celsius |
| p | Air pressure [Pa] |
| RH | Relative Humidity [%] |
| RMSE | Root Mean Square Error |
| NRMSD | Normalised Root Mean Square Deviation |
| $T_a$ | Air Temperature [°C] |
| $T_m$ | Mean Maximum Air Temperature [°C] |
| $T_{mm}$ | Regional Mean Maximum Air Temperature for each zone [°C] |
| $T_{ms}$ | Mean Maximum Surface Temperature [°C] |
| $T_{mms}$ | Regional Mean Maximum Surface Temperature for each zone [°C] |
| THA | Mean maximum UTCI index |
| $THA_m$ | Regional mean maximum UTCI index for each zone [°C] |
| $T_r$ | Radiant Temperature [°C] |
| $V_a$ | Air velocity [m/s] |
| UHI | Urban Heat Island Phenomenon |
| UTCI | Universal Thermal Climate Index |

## Introduction

As an architect, I have participated in every phase of urban design projects starting from capturing the basic concept until the detailed design and documentation. This complex procedure is based on a decision-making process, evaluating certain criteria that will guide the transformation of open spaces in sustainable and functional forms.

The architecture studies introduced me to a complex framework of organising each phase of the design process by analysing the requirements and constraints through the aid of the principles of synthesis and symmetry, to design open spaces that correspond to the initial objectives.

In most cases, the typical urban design principals are relevant to the usability of open space, while the stakeholders base their views primarily on the general concept of aesthetics.

Architects and urban planners usually work in such design projects with the aid of an obsolete framework containing mainly technical and regulative manuals. It is crucial to enhance this standard toolbox with scientific knowledge and contemporary tools relevant to the environment in order not only to deliver viable solutions but also to define the full dimensions of the problem.

In my experience, the successful design often derives out of investigating complex alternative design scenarios and is achieved when the restrictions are more intense than the architect's freedom in design. The subjective criteria of aesthetics are not sufficient to guide the design process to successful results. Consequently, it is imperative need to elaborate quantitative goals related to user comfort and perception. This PhD research targets these issues with the introduction of goals related to thermal comfort, naturalness and health conditions in urban open spaces using the proposed methodology and the corresponding tools to implement during the design phase of the project. Scientific research should be the initial step of the design process and its results will assist stakeholders to adopt the design and embrace it in their everyday lives.

The research structure is combined by the following chapters:

**Chapter 1** analyses the urban design problem and its relation to environmental factors as well as the perception in combination with urban climatic structure and energy equilibrium. This chapter is more focused on "research on design" as mentioned by Lenzholzer (2010) meaning that it is a review of the urban planning research methods which describes the way to implement on city planning procedures.. Areas of interest are presented through the basic typology of urban open spaces analysis specifically focused on the Mediterranean zone. The city growth and current planning methods derive from the wide spreading urbanization problems such as unusable open areas, the urban heat island phenomenon and pollution that are noted even in smaller cities.

**Chapter 2** analyses the research methodology and the research steps that have been followed to optimize the design of urban open spaces by introducing a variety of tools and environmental factors.

**Chapter 3** consists of a detailed “research on design” (Lenzholzer 2010) where all the crucial parameters that influence open urban space sustainability and comfort conditions are analysed. This analysis includes a literature review in relation to interviews in certain urban open spaces in Crete and on-site microclimatic measurements. The aim of this chapter is to quantify the perception of people and to introduce design guidelines for perception in areas of the Mediterranean zone that could be furthermore investigated. Through this “research on design” phase have concluded that there is a necessity for more useful guidelines in design. Following the analysis of specific parameters that influence the urban tissue and the quality of applications in Mediterranean urban environments research, the next chapter proceeds to the configuration of tools controlling the influence of these parameters.

**Chapter 4** reviews existing microclimatic models and the simulation principles that define energy fluxes within a city. ENVI-met software has been selected for the implementation of the following methodology to parametrize the urban microclimate. Further validation and sensitivity analysis of the selected software is performed for the classification of the described microclimate factors through simulation analysis.

**Chapter 5** introduces an innovative bioclimatic decision-making tool that stakeholders can use in the phase of selecting the initial design principles in a project, as it is simple to use and does not demand complicated calculations. The tool is initially parameterized for the hot summer Mediterranean climates ($C_{sa}$) and provides accurate quantification of the alternative scenarios including key bioclimatic indexes, ensuring the achievement of the initial goals.

**Chapter 6** is focused on the analysis of a bioclimatic urban design methodology as a space regeneration strategy. The first step of this analysis includes the use of the proposed tool and the following steps of case-specific analysis with the use of microclimatic measurements, outdoor and indoor simulation models and bioclimatic index calculations.

The proposed methodology and case-specific analysis have already been implemented in a series of urban open spaces in Crete, some of them have already been constructed, and some of them will be constructed in the following years. **Chapter 7** analyses some of these applications and the bioclimatic details that led to the architectural design proposals.

Apart from the main benefits of the case-specific methodology that are the improved thermal comfort conditions and the extended use of the urban open space, next chapters analyse additional benefits relevant to energy savings and air pollution reduction. **Chapter 8** analyses the final part of the proposed methodology that is related to energy savings from the surrounding buildings.

The analysis includes all the buildings facing the selected area and defines the level of detail of the input information to obtain valid results.

Finally, **Chapter 9** describes the results of the study and the innovative aspects of the research, consisting mainly that the proposed tools combine design, implementation and continuous onsite measurements of the site before and after construction.

## 1. Urban microclimate in open spaces

### 1.1. Typology of urban open spaces in Mediterranean areas

The urban open space can be divided into certain groups according to its geometry, open sides, materials, and use. Stanley et al. (2012) divide the urban open space into 7 categories the type of which is dependent on the urban scale that is placed such as city centre, intermediate zone or residence areas as shown in Table 1.

Table 1: Transdisciplinary topology of urban open spaces (Sandalac & Uribe 2010).

| | | SCALE | | |
|---|---|---|---|---|
| | | City | Intermediate | Residence |
| FORM | **Transport facilities** | Harbours, Airport and Train stations, Parking | Transit stations, City Gate areas | Driveways, Parking Areas |
| FORM | **Streets** | Central Boulevards | Street space | Pedestrian Alleys, Paths |
| FORM | **Plazas** | Large Formal Plazas | Smaller Neighbourhood Plazas | Interior Courtyards |
| FORM | **Recreational Space** | Stadiums, Greenbelts, Beaches | Sports Facilities, Playgrounds | Houseyard Playspace |
| FORM | **Incidental Space** | Natural Features and Semi-Wild Areas | Empty Lots, Transit Borders | Marginalized Space Between Buildings |
| FORM | **Parks and Gardens** | Major Formal Park and Garden Space | Institutional Gardens, Small Parks, Cemeteries | Household Gardens |
| FORM | **Food production** | Orchards, Agricultural Fields | Grazing Commons, Community Gardens | Kitchen Gardens, Small Horticulture |

| | |
|---|---|
| (grey) | Grey Space |
| (green) | Green Space |

Each type is combined with certain functional requirements and aesthetic considerations. This typology accommodates another division according to the level of greenery possibilities they have. It is obvious that regarding the existing urban open space the vegetation parameter is quite often neglected and sacrificed for the use of cars and stores. While history has proven that when it comes to open space the quality of life is dependent on the quality of greenery, large urbanization needs in the city center brought car movement, parking and consumerism on the first raw of importance (Stanley et al. 2012; Sandalack & Uribe 2010).

Urban open spaces in Greece follow this pattern as well. During the previous decades, the city centres were urbanised rapidly without sustainable planning. Around 80% of the urban population of Greece lives in the 18 largest cities, all of which have a population of over 50.000 inhabitants, while the remaining 20% live in another 66 cities, with populations ranging between 10,000 and 50,000 inhabitants (Papamanolis 2015b). All interest shifted on private properties and public urban open space degenerated while becoming private, commercial or abandoned. According to data held on the Urban Atlas database of the European Environment Agency, Greece, 60% of the urban open space of Greece has less than 20% green areas.

However, this phenomenon did not always dominate the meaning of urban open space in Greek towns. Before World War II the meaning of urban open space was different for the traditional Greek community. The main square of a village or a city was a place of association, collectivity, and communication. The neighbourhood connections were strong, and the public space was extended within the private. In all the urban open spaces the lack of greenery was evident. The public urban open space of the Greek traditional cities can be categorized according to its place and importance to the following:

- Main urban squares with a growing town around them. Usually, the town main roads start there, and all the secondary roads follow the earth paths and routes. In the old castle towns of the islands, these squares were on the top of the town not in the middle. In a densely populated urban fabric, usually they were connected with high importance buildings like city halls or churches and it was the place where all the public relations took place. These squares were found in the core of the center of the old town and are surrounded by buildings. Their size is relatively small and quite often they had a large tree placed as a landmark in the middle of its surface.

- Larger squares that are formed on the edge of the old and new towns next to the surrounding fortresses. As the town extended beyond the castle the old fortress area is used for creating natural squares with greenery and several uses.
- Smaller urban squares scattered within the neighbourhoods to encourage social communication. These areas were usually covered with planted nets and were used as an extension of the private and very small courtyards.
- Main boulevards from 5to 8 meters wide that were and the basic axis of the town.
- Smaller roads from 0.85 to 2.20 meters wide that usually followed the constructed buildings or the soil inclination. These streets had occasionally wider parts that formed small openings in the dense urban fabric.

**1.2. Urban design principles**

Urbanisation describes the physical growth of urban areas and refers to the increasing number of people living in them.  Over 50% of the world's population lives in urban areas while in Europe the share of the population living in urban areas is expected to rise up to 80% by 2050 (Figure 1) (EuroStat 2016). Urbanization is not merely a modern phenomenon, but a rapid and historic transformation of human social roots on a global scale and has been observed that the urban culture is rapidly replacing the rural culture. Cities' development is synonymous with human development, and *Homo sapiens* has become *Homo Urbanus* (Grimond 2007).

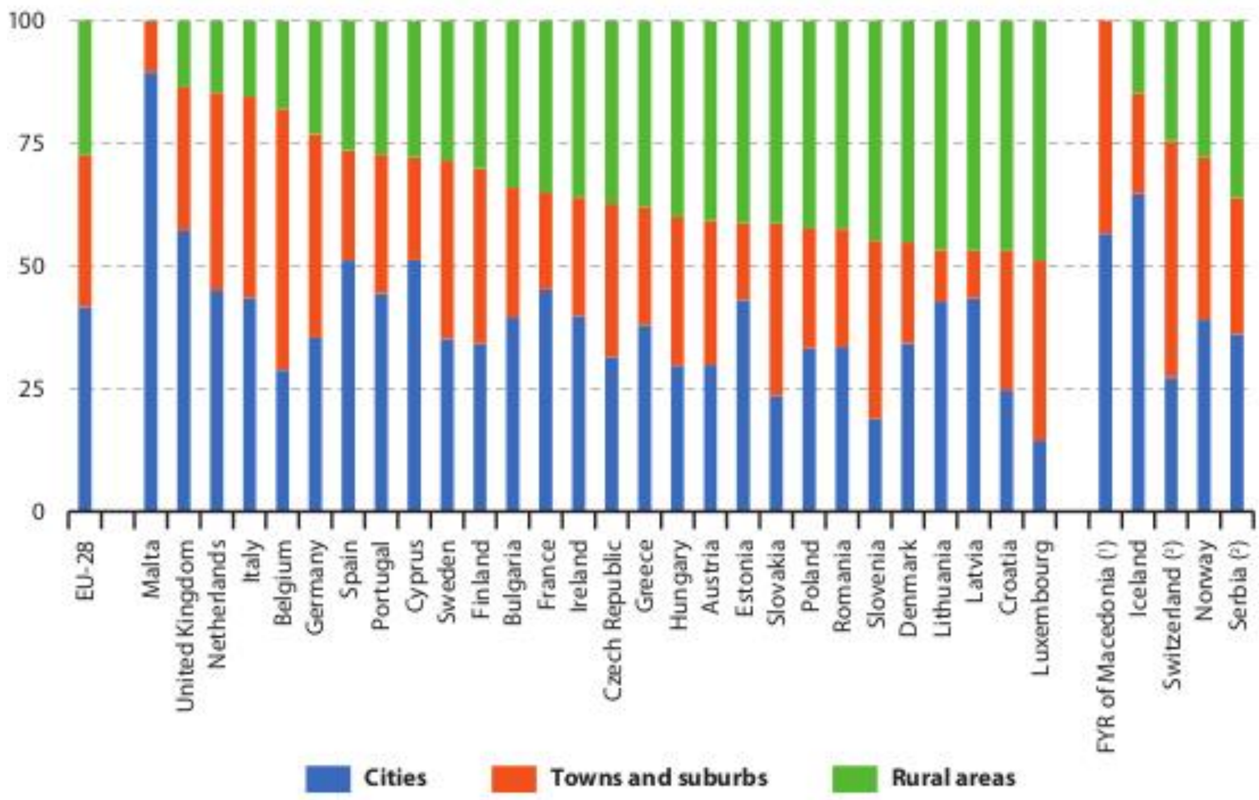



Figure 1: Distribution of population, by the degree of urbanization (EuroStat 2016)

The rapidly growing urbanisation rates impose evaluation and analysis of the urban form and implementation of the sustainable urban design. The definition of urban design and the successful implementation to achieve a higher quality of living in cities has many aspects. Though the urban design has a typical methodology of planning, it lacks cohesive theoretical foundations. Much writings take the form of guidebooks or manuals, which rely on rules, analytical techniques, and architectural ideas, however, the organization of the public realm requires more scientific approaches. At a time of declining natural resources, where pollution and the greenhouse effect are taking place, the urban design methodologies and tools have to take into consideration the environmental issues of the selected area. As a consequence of urbanization and industrialization, environmental and ecological issues have become increasingly critical in any urban design decision. Landscape architecture is far more than just a simplified empirical design process. Typically, the method includes evidence-based design principles combining perception with aesthetics and embraces traditional design paradigms with the public realm in its wider context. There are several areas of landscape architecture that already implement evidence-based paradigms such as soil drainage, transplanting of trees, microclimate modification, materials engineering, and visual preference. In fact, this encompasses many of the physical, several of the biological, and a few of the human components of the landscape (Bahrainy & Bakhtiar 2016).

The urban planning process has a very broad range of issues encompassed by the urban atmosphere in its literally and metaphorically meaning (Radfar et al. 2012).

These include:

- Optimization of land use patterns in relation to the different activities that are carried out;
- Identification and development of suitable microclimates for various activities, such as parks and recreation activities;
- Identification of adverse microclimatic factors likely to affect the detailed design of urban systems, such as high local winds;
- Optimization of building form in relation to external climatic inputs, such as solar radiation and wind and in relation to the microclimatic modification of the immediate exterior domain of the building such as the high winds induced near ground level by tall buildings;
- Selection of appropriate building materials for all urban surfaces;
- Structural safety and process planning for an assessment of building running costs (HVAC, lighting);
- Optimization of the operating environment of transport systems with respect to air pollution.

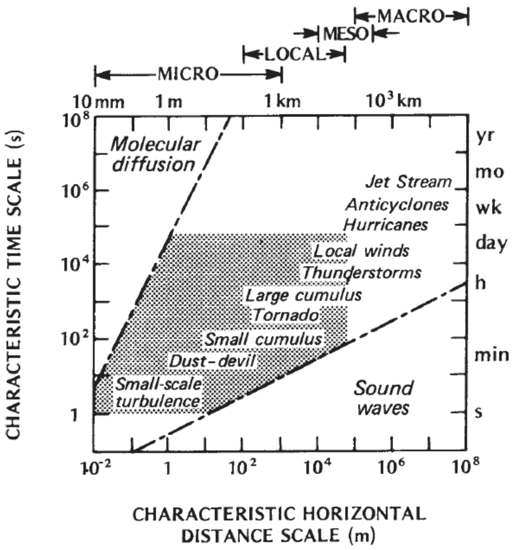
### 1.3. Urban microclimate and urban energy balance

Climate plays an important role in our perception of the environment. It is the way that we describe and parameterize our senses with the use of specific meteorological parameters like temperature, humidity, atmospheric pressure precipitation, wind speed and direction sun radiance etc.

Urban climate differs from the climatic conditions of the surrounding rural areas mainly because of the physical structure of the city that can be modified by urban design. The variation is caused by changes in the radiant balance of the urban space, the convective heat exchange between the ground and the buildings and by the heat generation within the city.

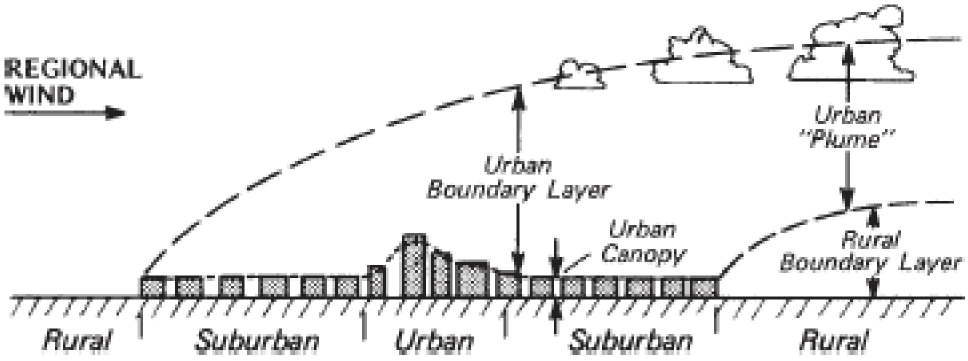
It is important to understand the local climate within the built-up area and the atmosphere above and beyond its boundaries to obtain sustainability in the urban design. As suggested by Oke (1978), the atmosphere can be divided into certain space scales by using the characteristic horizontal distance scale as a criterion. These scales and their limits as appear in Picture 1 are:

- Micro-scale $10^{-2}$ to $10^{3}$ m.
- Local-scale $10^{2}$ to $5x10^{4}$ m.
- Meso-scale $10^{4}$ to $2x10^{5}$ m.
- Macro-scale $10^{5}$ to $10^{8}$ m.




Picture 1 : Time and space scales of various atmospheric phenomena ( Oke 1978).

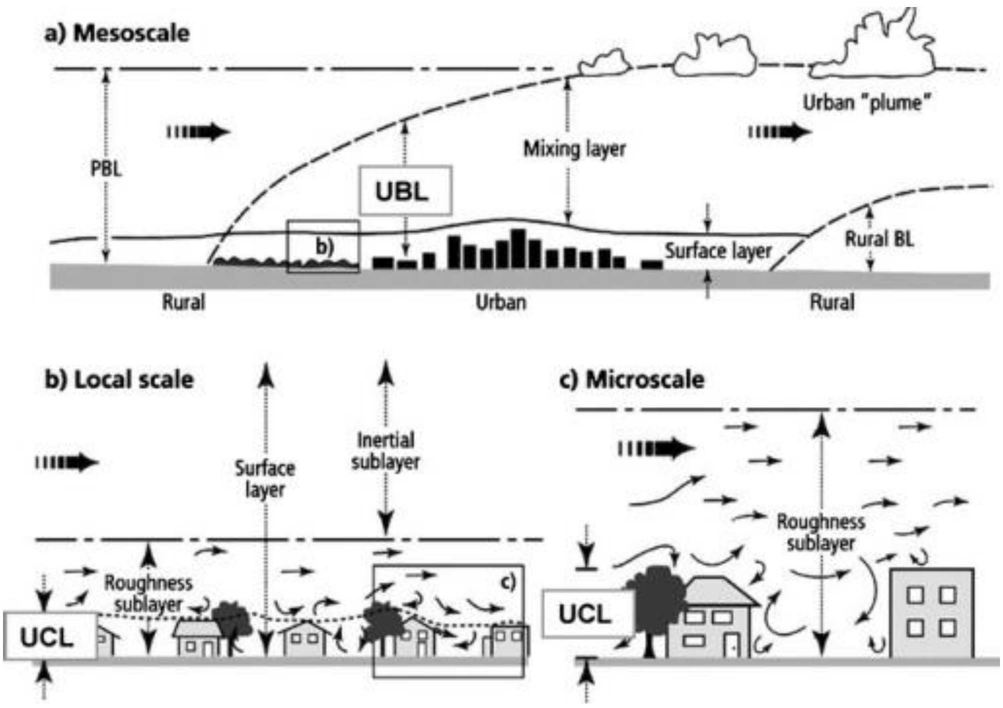
Oke points that the layers defining the city atmosphere and are decisively affected by the nature of the built-up terrain is known as Urban Boundary Layer (UBL) (Lazaridis 2011). The UBL is the entire volume of air above the city that is influenced by its surface characteristics and by activities within it as shown in Picture 2. It generally extends upward to about ten times the height of the buildings and beyond the urban area in the wind direction.




Picture 2: Schematic section of the urban atmosphere (Oke 1978).

The UBL is composed of a series of zones, each one of them has different characteristics and dependencies (Picture 3). These zones are:

1) The upper part of UBL is a **"mixed" layer** that its height varies according to the atmospheric stability and magnitude.
2) Up to a height of about 4-5 times of the average building is a **surface layer** that is entirely conditioned by the 3d geometry. Its properties are not affected by individual urban elements such as single buildings or trees rather than the texture of the urban surface as a whole.
3) The zone between the building height and two times up there is a highly variable **roughness sub-layer**, in which the airflow consists of interacting wakes and plumes introduced by individual roughness elements.
4) The lowest zone is the **Urban Canopy Layer (UCL)** that is a microscale area which extends from ground level to the height of the buildings, trees and other objects. It is the lowest part of the urban atmosphere and is characterized by a high level of heterogeneity, since conditions vary widely from point to point within the canopy volume.




Picture 3: Different sub-layers of the urban boundary layer (https://openi.nlm.nih.gov).

According to Oke (1976), the energy balance of an urban air-volume (bounded at about the roof-level of buildings) as illustrated in Picture 4 is given by the following equation:

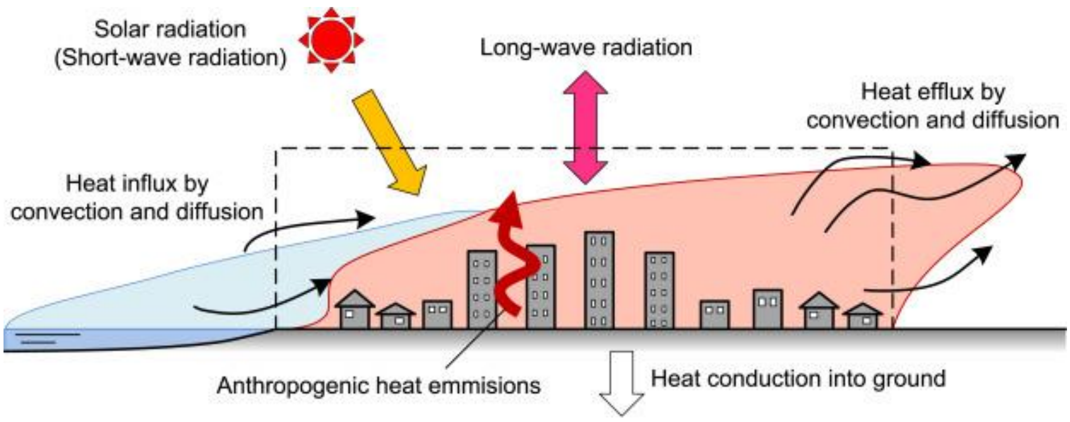
$$Q^{*} + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

Where:

- $Q^{*}$ is the net radiation;
- $Q_F$ is anthropogenic heat from heat sources in the city that are associated with combustion;
- $Q_H$ is the sensible heat flow;
- $Q_E$ is the latent heat exchange from plants;
- $\Delta Q_S$ is the heat storage changes in the ground, the buildings and the air contained within the volume;
- $\Delta Q_A$ is the net horizontal transfer of sensible and latent heat, through the sides of the urban-air volume.

To sum up it is important to underline that the urban microclimate strongly depends on the urban surface layer. The energy balance determines the latter between the received net radiation (both short-wave and long-wave), the sensible and latent heat fluxes transferred to the air, the heat storage in urban structures and the ground, and the anthropogenic heat sources, as shown in Picture 4. The energy-balance characteristics may vary according to certain parameters, such as:

- City location;
- City size;
- Density of the built-up area;
- Land coverage;
- Height to Width ratio that is the height of buildings to the width of streets;
- Orientation;
- Subdivision of the building lots;
- Special design details that affect outdoor conditions such as building overhanging, glare control treatments, etc.




Picture 4: The urban heat balance (Mao et al. 2017).

**1.4. Urban Heat Island phenomenon in Greek cities**

One of the factors that contribute to the formation of the air temperature in Greek cities is the Urban Heat Island (UHI) phenomenon, the existence of which had already been confirmed by relevant climatological studies and is described as the temperature difference between the urban and suburban areas. During summer the phenomenon is mainly caused by the stored thermal energy of urban cover materials that is conducted on the ambient air after sunset.

Since then, the characteristics of the UHI in Greek cities have been the object of a variety of studies as appear inTable 2 (Charalampopoulos et al. 2013; Gago et al. 2013; Papamanolis et al. 2015a; Papamanolis 2015b;).

As indicated in the studies the methods for identifying the intensity of the UHI is either by ground measurements or satellite images. The phenomenon is observed in many Greek cities depending on the density of the urban fabric. The greater differences are found a few hours after sunset and the lowest in the morning hours regardless of the season. As shown in Table 2 the temperature difference between urban and suburban areas can reach very high values in many cities in Greece. The causes of such difference according to the references are:

- The population growth rate has the best correlation with the UHI intensity;
- Urban cover materials. The materials that are used in the cities store a large amount of thermal energy that conducts when the ambient temperature drop. Research has shown that within a typical Greek city, 77% of the area is covered by buildings and concrete, 19% by asphalt roads and only 4% by green open areas;
- Urban sprawl that is formed by the several been urban canyons between the buildings. The urban canyons encourage sun radiation reflectance and prevent the heat transfer to the upper layers;
- The anthropogenic heat caused by buildings and transportation. This cause is more evident when the sky is cloudy;
- The greenhouse effect that traps the sun's heat in the lower atmosphere, due to increased air pollution;
- Reduced evaporation surfaces caused by the lack of greenery;
- Weather parameters like wind speed, humidity, and cloud coverage while the most important seems to be the radiation level of the previous day.

The mitigation of the UHI phenomenon is a crucial need of the cities and affects the quality of life, the health and living conditions (Stathopoulou et al. 2009).

Table 2: Studies of UHI in Greek cities.

| City | Temperature difference (°C) | Notes | Reference |
|---|---|---|---|
| Heraklion | 1.9 | Research from satellite images in July | (Stathopoulou & Cartalis 2007) |
| | 8 | The larger differences were measured on the coastal zone and airport | (Stathopoulou et al. 2005) |
| Chania | 3 | Larger differences in June | (Kolokotsa et al. 2009) |
| Volos | 0.4 – 0.8 | Research from satellite images | (Stathopoulou & Cartalis 2007) |
| | 1.8 | the mixed urban areas that include industrial units are hot spots and appear to be warmer than the surrounding rural area | (Stathopoulou et al. 2005) |

| | | | |
|---|---|---|---|
| | 3.4-3.1 | A similar difference in winter and summer. During both seasons the daily maximum hourly UHI intensity is positively correlated with solar radiation and with previous day's maximum hourly UHI intensity and negatively correlated with wind speed | (Papanastasiou & Kittas 2012) |
| Patra | 3 | The difference in May, Research from satellite images | (Stathopoulou & Cartalis 2007) |
| | 7 | Research from satellite images NOAA/ AVHRR | (Stathopoulou et al. 2005) |
| Thessaloniki | 2.7 | The larger differences were measured in the coastal zone. Landsat 7 daytime thermal images | (Stathopoulou & Cartalis 2007) |
| | 8 | Research from satellite images NOAA/ AVHRR | (Stathopoulou et al. 2004) |
| Athens | 3.3 | Measured in May, south-west areas were hotter | (Stathopoulou & Cartalis 2007) |
| | 10 | During daytime | (Papanikolaou et al. 2001) |
| | 2.1-5.4 | An intelligent ''data-driven'' method is used in the present study for investigating, analyzing and quantifying the UHI | (Mihalakakou et al. 2004) |
| | 4.3 | In October the UHI is minimized, Elliniko airport had the lowest temperatures | (Stathopoulou et al. 2009) |
| | 4 | Measured in Eleusina | (Kassomenos & Katsoulis 2006) |
| | 3-5.3 | During daytime, during nighttime, these differences were smaller 1.3 – 2.3 ºC | (Giannopoulou et al. 2011) |
| | 9-10 | Difference between the hotspots and the suburban areas | (Keramitsoglou et al. 2011) |
| | >4 | The difference in the night, it minimized in the morning | (Giannaros et al. 2013) |

### 1.5. Urban pollution

Air pollution environment in cities is a major determinant of the quality of life and health of the citizens. The main causes of air pollution in urban environments are transportations, human activities and nature (sea salt aerosol or dust) (Papamanolis 2015c). The basic city pollutants and their boundaries have been defined by EU Standards (European Union law 2011) and their health effects (WHO 2005) appears in Table 3. The aerosol concentrations in microclimatic scale can be affected by the temperature, wind speed and humidity. Also, urban transportation is responsible for about a quarter of $CO_2$ emissions. Research in Mediterranean cities showed that sulfate ($SO_4^{2-}$), and ammonium ($NH_4^{+}$) have been identified as the main ionic components of the submicronic aerosol fraction, with $SO_4^{2-}$ accounting for up to 38% of the total fine mass and up to 65% of the total ionic mass during summer and winter (Bardoukia et al. 2003; Lazaridis et al. 2008; Colbeck & Lazaridis 2010).

An environmental urban design at first focuses on minimizing the pollution sources, and, as a secondary approach, the management of the aerosol particles through bioclimatic design solutions. The reduction of city pollution levels from industrial uses is made by urban planning decisions regarding the city used per area and from transportation sources is achieved by urban planning decisions that take into account the zones of cities and the main transportation channels. The optimal transportation planning processes arise through the implementation of Sustainable Urban Mobility Planning (SUMP). SUMP is a strategic document designed to contribute to meeting European targets. It builds on existing planning practices and takes due consideration of integration, participation and evaluation principles. It is the result of a structured process that comprises status analysis, vision building, objective and target setting, policy and measure selection, active communication, monitoring and evaluation and the review of lessons learned (Wefering et al. 2013).

The microclimatic determination of the air pollutants in certain city area can be made through the application of the proposed methodology and management of microclimatic factors like wind speed, temperature and humidity. The methodology with the use of simulation models of the ENVI-met software allows the simultaneous release, dispersion and deposition of up to 6 different pollutants including particles and gases. Sometimes, the naturalness of the area and the implementation of water-sensitive design principles can provide pollutant free areas for public use.

Table 3: Averaged concentrations of the most basic pollutants and their effects (WHO 2005).

| Compound | Mean Time | Level (μg/m$^3$) | Health Effect |
|---|---|---|---|
| $PM_{2.5}$ | annual<br>24-hour | 10<br>25 | higher mortality percentages, lug cancer |
| $PM_{10}$ | annual<br>24-hour | 20<br>50 | higher mortality percentages, lug cancer |
| $NO_2$ | annual<br>1-hour | 40<br>200 | bronchitis and reduced lung function growth |
| $O_3$ | 8-hour | 100 | breathing problems, trigger asthma, reduce lung function and cause lung diseases |
| $SO_2$ | 24-hour<br>10-minute | 20<br>500 | affect the respiratory system and the functions of the lungs, coughing, mucus secretion, aggravation of asthma, chronic bronchitis, makes people more prone to infections of the respiratory tract, and causes irritation of the eyes |

## 2. Research Methodology

This chapter describes the research methodology and the validation process of the produced results as shown in Figure 2. After having reviewed the existing bibliography and the achieved goals in urban regeneration projects following bioclimatic open space design principles, this study will proceed with the investigation of comfort conditions on existing, recently regenerated urban open spaces in Crete; taking into account user's perception.

During this study, the thermal comfort conditions of recently regenerated urban open spaces were captured to examine the relation between microclimatic conditions, the applied design decisions and user's comfort votes. The methodology included on-site measurements of the microclimatic parameters and face-to-face interviews based on a suitable questionnaire. The research carried out in four cities in Crete and the obtained conclusions include the basic principles and guidelines to ensure successful sustainable design in cities with the same Mediterranean climate. These principles and guidelines include:

- The definition of the climate parameters to calculate their contribution to the overall comfort levels;
- The determination of the comfort levels of every microclimate parameter according to the answers given both in winter and summer periods;
- The determination of the basic human parameters that affect the comfort levels;
- Suggestions for beneficial interventions of future designs based on the geospatial characteristics of open spaces such as location, orientation and elevation.

Each of the selected case-studies represents an area with different geographical characteristics based on certain parameters such as elevation, location (coastal or inland) and terrain morphology. The conclusions of this research are used to examine the outdoor comfort conditions of areas with the same Mediterranean climate. The field surveys involved detailed microclimatic monitoring with the use of a portable weather station, with sensors conforming to ISO 7726, while people were studied in their natural environment through structured interviews and observations, to evaluate the comfort conditions they experience and their perception of the environment. The selection of interviewees has been conducted with special care in order to include representative samples of different ages and different use patterns of the open space. The field surveys began in February 2009 and were completed in July 2009, covering both extreme seasons; summer and winter. Each site was observed for a representative day of each season. The research focused on issues related to the use of space, as opposed to the user's evaluation of comfort conditions. The users were studied in their natural environment taking into account factors affecting the use of space, such as user classification, social activities and patterns of use within the area.

This preliminary research as presented in the next chapter revealed the main problems occurred when designing the urban realm. The low percentage of comfort votes in relation with a large number of hours that the microclimatic conditions exceed the acceptable boundaries leads us to the conclusion that the existing open spaces cannot be used for a large part of the day during summer. Regardless of aesthetic criteria of the area, the lack of thermal comfort conditions prevents the users from including the open space in their everyday route or destination, resulting to its abandonment. Therefore, the public space, as it is not claimed by the citizens, it is slowly converted into private space.

The basic causes of this phenomenon are:

- The lack of environmental design parameters in the urban design prerequisites palette;
- Devaluation of the comfort percentage votes importance that leads to the minimization of use of the urban open space during summer;
- The false treatment of public space as being the "leftover" that should be exploited by the private sector;
- The duplication of successful urban open space design from areas with a different climate that cannot be adjusted to the Mediterranean climate demands.

In order to design using a brand new tool palette for bioclimatic urban open space design, this study will proceed into the research and evaluation of innovative urban open space features that can adjust microclimate to the certain needs of comfort. These features as appear in Figure 2 include:

- Materials such as cool and photocatalytic coatings that can modify the surface temperatures and the heat exchange between the material and the ambient air;
- The selection of suitable sensors that can measure the necessary parameters for the bioclimatic indexes calculation. Research on their configuration and data logging, and also on the way the data will be managed and recorded in order to produce microclimatic heat-maps;

- Environmental design solutions and methods that have been applied and evaluated. This study includes both bibliographic research on studies and applied designs, including configurations and tests for the Mediterranean climate.

As mentioned above, the conducted research has led to the formation of a new methodology of designing considering crucial bioclimatic criteria. This methodology selects the appropriate bioclimatic indexes and proposes sustainable design principles that can be implemented in areas with a Mediterranean climate. Additionally, it proposes a weather station with suitable sensors that can be used for such studies according to the proposed ISO standards for monitoring the on-site microclimate conditions. The desired outcome of all this research is the creation of bioclimatic design guidelines for the Mediterranean climate. These guidelines can ensure the bioclimatic design approach on the urban open space. The described research has emphasized the complexity of environmental design regarding urban open space, where microclimatic conditions are difficult to determine demanding specific scientific knowledge. However, in most of the cases, the design team is not qualified to perform complex calculations and to evaluate bioclimatic indexes in 3D environments. Therefore, it is imperative need to introduce a tool which allows a simplified and accurate analysis that considers the most crucial microclimatic parameters and provides the necessary guidelines to develop sustainable open spaces. This is the main reason for the creation of the bioclimatic tool that can guide the stakeholders to better design decisions. This tool can only provide comparative results according to certain design patterns. Furthermore, the study proposes a case-specific methodology that can calculate the bioclimatic indexes and simulate all the microclimate parameters of the final design scenario.

The opportunity to implement the case-specific methodology was obtained within a funded Partnership Agreement (PA) competition for bioclimatic outdoor design. The city of Rethymnon in Crete assigned me the modification of a competition awarded design plan and the preparation of a bioclimatic outdoor study according to the competition guidelines (the proposal was awarded and selected to be funded). An area of 25,000m$^2$ in the western part of Rethymno had been designed with bioclimatic principles, simulated, constructed and measured. This first implementation allowed the validation of the research methodology, software and models in areas with a Mediterranean climate. This funded competition was used as a pilot guide for introducing environmental parameters on the public space design in

Greece. During the following years, bioclimatic aspects have been included in the prerequisite legacy and from now on the bioclimatic design with a microclimate analysis and evaluation is demanded for every new urban open space regeneration project.

In years following the first projects construction, I have completed numerous new open space regeneration projects being responsible for both, architectural and bioclimatic study of the area. With this work, I had the opportunity to validate the case-specific methodology which has been embraced by local authorities in many municipalities of Crete. Some of these projects are:

1. Western coastal zone in the city of Rethymnon, Crete, Greece (constructed project);
2. Melissinou street in Rethymnon, Crete, Greece (under construction);
3. Playground and sports area in the village Platanias, Chania, Crete, Greece
4. New design of the central square of Souda, Chania, Crete, Greece (funded for construction);
5. New design of Agelou Sikelianou street and square of Saint George Rethymno (funded and under construction) that additionally included playground and parking area;
6. New design of central roads within the centre of Chania city (roads Tzanakaki, Giannari, Skalidi) (funded for construction);
7. Playground and schoolyard area in the village Kalives, Chania (under construction)
8. Apostolaki street in Rethymnon, Crete, Greece (under construction);
9. Kolokotroni street in Rethymnon city (under design);
10. Several streets within the Rethymnon city center (under design).

More details and other case studies can be found in the annex. In the following chapters, many implementation examples will be further analysed.

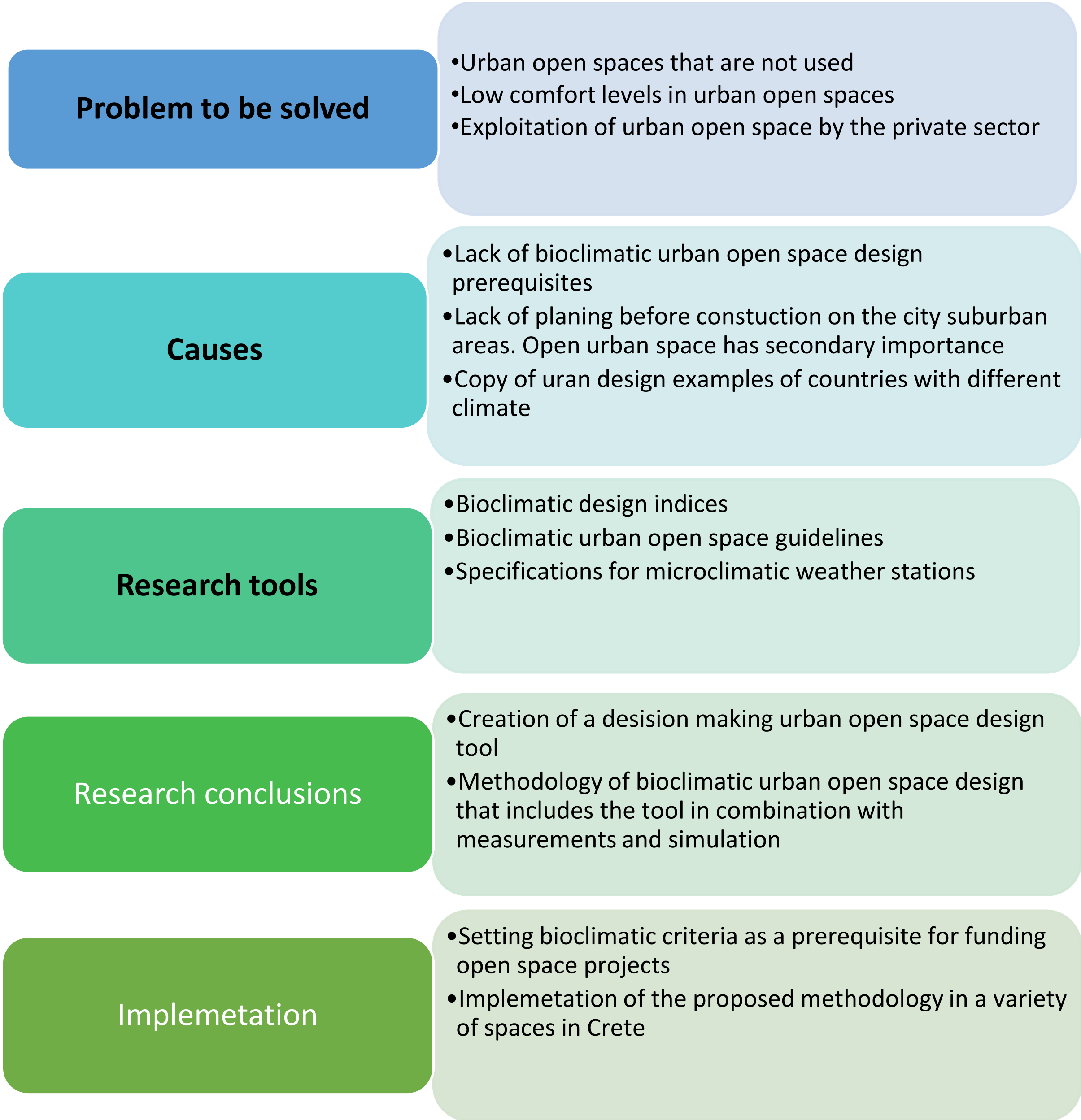



Figure 2: Research Methodology.

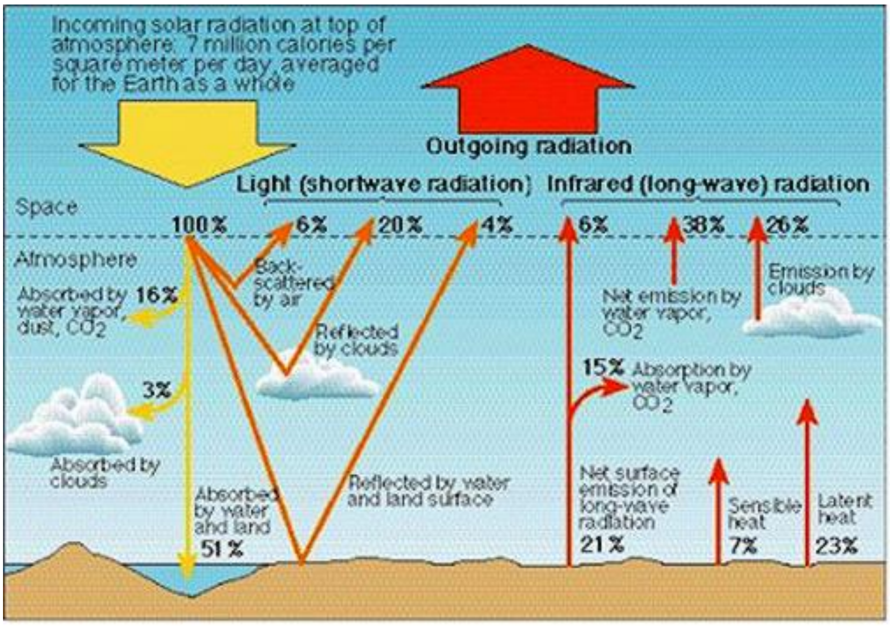
## 3. Sustainability in urban open spaces

### 3.1. Parameters that determine microclimate in urban open spaces

As analysed in the previous chapter the urban open space is directly affected by the habitats and vice versa the habitats' quality of life and social status is related to the open urban space design (Andrade & Alcoforado 2008). The major determinants of the use and viability of an open place, that are analysed during the design phase, are the climate conditions in the micro-scale environment (Tsitoura et al. 2011; Moonen et al. 2012; Santamouris 2001). These are:

1) Radiation Environment and mean radiant temperature

Solar radiation received at the surface of the Earth is the main source of energy in the UCL. The radiation balance in the urban environment is the sum of the incoming absorbed short and long-wave radiation minus the longwave radiation emitted by the components of the Earth's surface. According to recent measurements the solar constant, which is the solar energy per unit time per unit area perpendicular to the mean Earth-Sun distance, is about 1,365-1,372 W/m$^2$. Picture 5 gives a schematic representation of the energy balance of the Earth. As shown in Picture 5, 30% of the incoming radiation is reflected by clouds, particles of the air and Earth's surface. The other 70% is absorbed by water vapour, dust, ozone and clouds.




Picture 5: Energy balance of the Earth (http://earthguide.ucsd.edu).

2) Surface temperature

The temperature of the external surfaces in a canyon is governed by its thermal balance. Surfaces absorb short-wave radiation as a function of their absorptivity and their exposure to solar radiation. They absorb and emit long-wave radiation as a function of their temperature, emissivity and view factor, they transfer heat to or from the surrounding air through convection and exchange heat through conduction with the lower material layers.

3) Relative humidity

Humidity levels, especially in hot climates and coastal regions is a crucial parameter of the determination of microclimate within an urban canyon. Relative humidity turns a percentage of the total radiation flow into latent heat flow through evapotranspiration.

4) Ambient air temperature

The distribution of the ambient air temperature in a canyon influences microclimatic conditions. The temperature distribution is mainly dependent on the other microclimatic parameters such as surface temperatures and humidity. Air temperature distribution in the canyon during the daytime is not significant. Higher temperatures are measured on the ground level and the temperature decreases as a function to the height. Also, ambient temperatures in the middle of the canyon are higher than that of the air film close to the facades of the canyon.

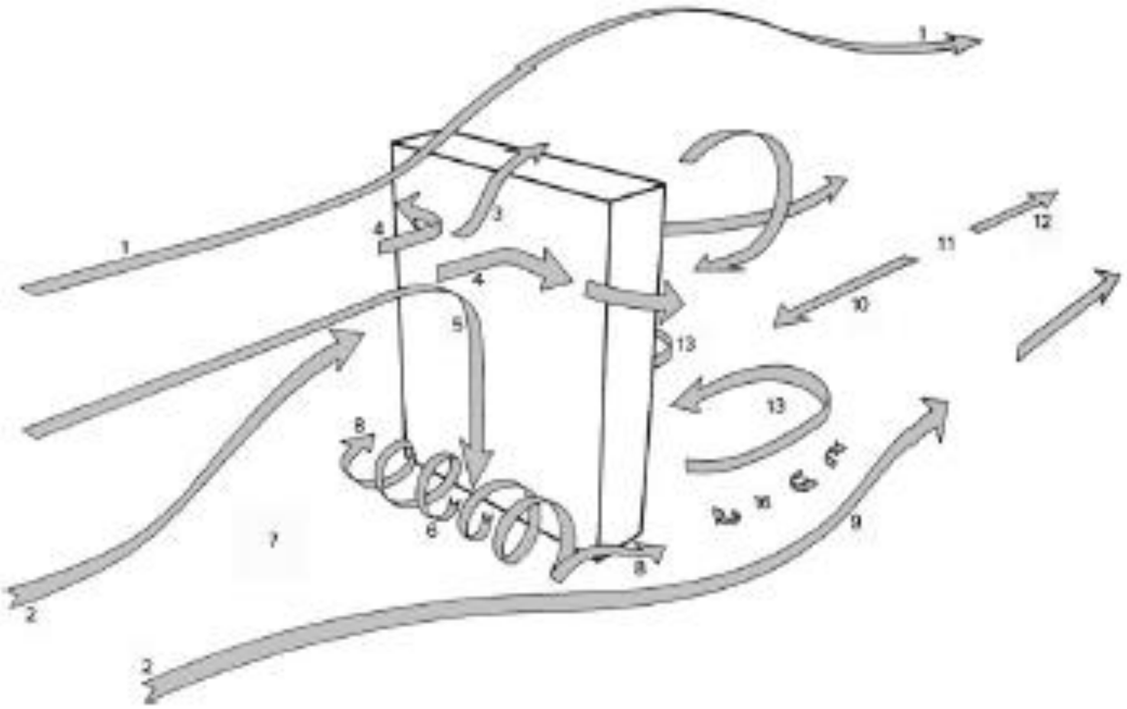
5) Wind speed and direction

The air flow affects thermal comfort relative to air temperature in the following ways:

a) It increases the heat loss through convection as the air temperature is lower than the skin temperature.
b) It accelerates evaporation by providing a cooling sensation.

The high wind speed conditions at the pedestrian level are caused by the fact that high-rise buildings deviate the wind towards the pedestrian level. The wind-flow pattern around a building is schematically indicated in Picture 6 (Bouresearch 1979). The wind is partly guided over the external shell of the building (1,3), partly around the vertical edges (2,4), but the largest part deviates to the ground-level, where a standing vortex develops

(6) that subsequently wraps around the corners (8) and joins the overall flow around the building at ground level (9). The problematic areas where high wind speed is observed are the standing vortex and the corner streams. Further upstream, a stagnation region with low wind speed is present (7). Downstream of the building shell, complex and strongly transient wind-velocity patterns develop, but these are generally associated with lower wind speed values and are of less concern (10–16).



Picture 6: Schematic representation of wind flow pattern around high rise buildings (Bouresearch 1979).

All these features have multiple results not only in the health and well-being of the citizens, tourism and local market but also the residences and the energy consumption of the surrounding buildings. Especially in islands, this relationship is more evident because the majority of the open spaces is in the form of a large central square in the city centre, as described in the previous chapter. In this way every intervention to the open space may have beneficial results in the sustainability of the whole urban system; obviously, a large-scale integration of solar applications in urban areas could improve this sustainability and self-efficiency dramatically (Lund 2012).

The study of the microclimatic factors of urban open spaces in relation with the thermal comfort factors of people using them could define the basic parameters of sustainable design (Giatrakos et al. 2009; Lin et al. 2010; Nikolopoulou & Lykoudis 2007).

Using these parameters,  a variety of bioclimatic indexes can be calculated to evaluate the subjective perception of the urban outdoor environment from the users (Chatzidimitriou & Yannas 2016; McGregor et al. 2002; Thorsson et al. 2004).

Further chapters focus on the way microclimatic conditions, such as air temperature, solar radiation, relative humidity and wind speed and direction affect the use of urban open spaces in the Mediterranean zone, with the use of field surveys conducted in four different cities in Crete, Greece. The influence of these factors can be measured and quantitatively evaluated whereas in the results are not included psychological factors and non-measurable parameters like architectural aesthetics and subjective preferences.

The aim of the research is to provide rules and guidelines, crucial for sustainable design of open urban spaces in areas with a Mediterranean climate, such as:

- Classification based on the hierarchy of the climate parameters to calculate their contribution to the overall comfort levels;
- Determination of the comfort levels of every microclimate parameter according to the answers given both in winter and in summer periods;
- Determination of the basic human parameters that affect the comfort levels;
- Valuation of these parameters depending on the different uses of the areas.

Given the prior experience, this research implements the findings into a particular type of climate, the hot-summer Mediterranean climate (Caliskan 2013). Through this way the basic indices can be validated and if possible recalculated in a different scale that is constructed by votes and real data. The parameterization of the model to track the existing conditions requires adjustments of the basic characteristics for every case individually.

### 3.2. Perception in urban open spaces of Crete

Previous chapters have concluded that the perception of the design team is an important parameter of the urban design guidelines which determines whether users will embrace the applied design. The human being is a bodily multi-sensory being whose conceptions of the world are based on sensory experiences.

In order to examine the variety of the different microclimate types and their parameters for both coastal and inland areas, field surveys have been conducted in four urban open spaces in Crete. (Tsitoura and Tsoutsos 2006; Tsitoura et al. 2014; Tsitoura et al. 2011). On-site measurements were taken, and a questionnaire was used to estimate the perception of the users. All selected sites have different characteristics considering their vegetation, location and main use while their design has been totally regenerated within the last 10 years. The first one is on the coastal zone within the historical center of Chania, the second one is between the shopping center and the port in Rethymnon the third one is a nearly constructed square within the shopping center area of Heraklion and finally, the fourth is located on a mountainous village near Heraklion called Archanes.

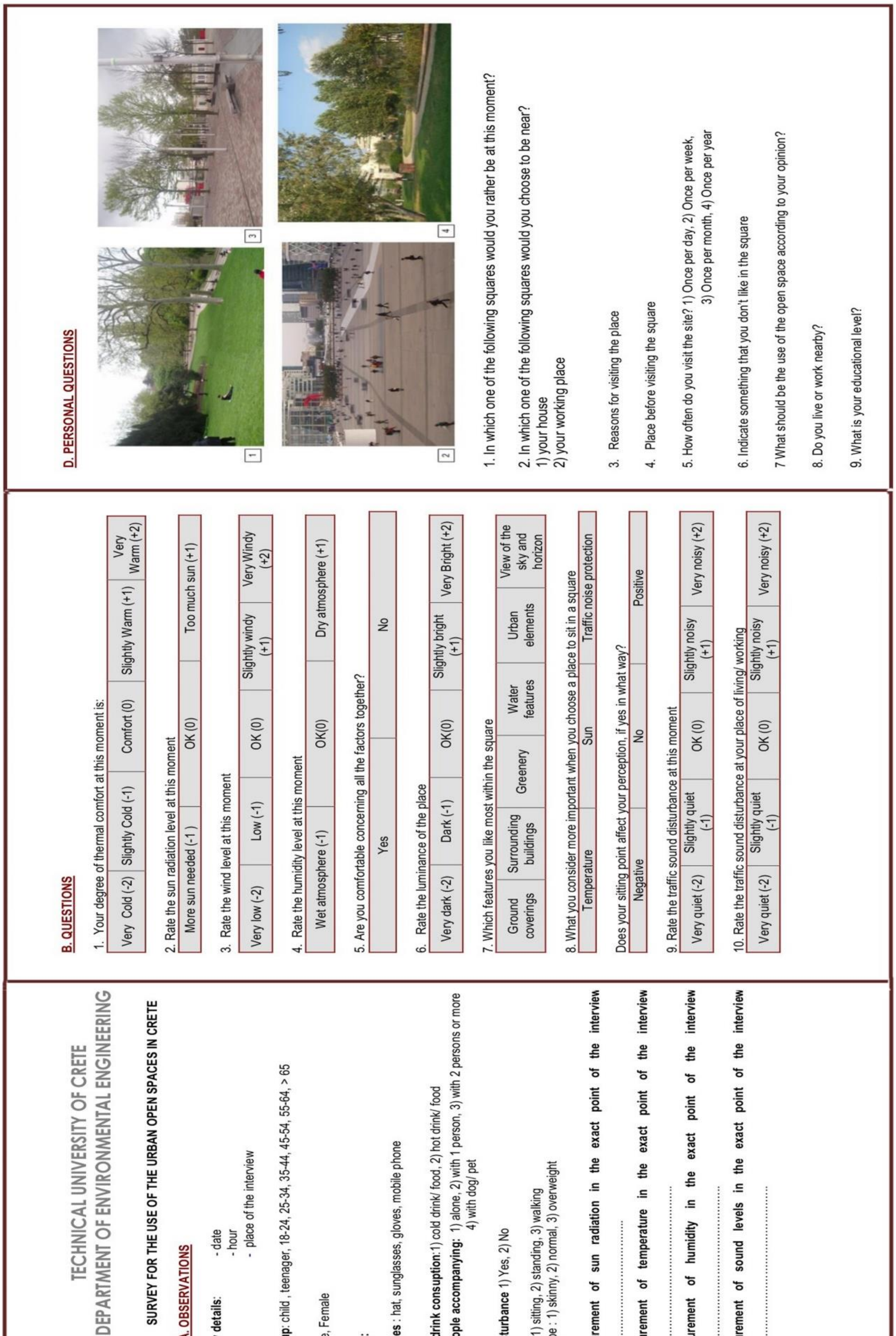
In every square two case studies have been examined, one in the winter (February 2009) and one in the summer (July 2009), for a time period between 10 a.m. and 4 p.m., and 200 questionnaires were carried out, 100 each period, meaning about 25 in each square. This number of responses is minimally sufficient to conduct valid and reliable conclusions and it was pre-calculated by tests of significance level ($a = 0.05$). The dates for the diurnal field survey, have been selected based on detailed observations of the general climatic conditions in each city during the selected month, in order to obtain realistic typical data related to microclimate of each area.

The comfort votes were approached through questions for the evaluation of all microclimatic parameters using a 3 to 5 scale voting system in relation with complementary questions regarding their total state of comfort. The scale included the comfort votes in the middle (0), and two levels of discomfort, tolerable discomfort (±1) and intolerable discomfort (±2). The parameters of thermal comfort and wind tolerance are studied in a 5-point scale while the parameters of sun tolerance, humidity tolerance and annoyance level from noise pollution are studied in a 3-point scale.

The questionnaire also included personal questions about the user's subjective preferences in general and additional opinions about the meaning and type of the ideal open urban space. All the answers were afterwards linked to the on-site microclimatic data measurements. As shown in Picture 7 the questionnaires included information about:

- Observations such as apparel; consumption of cold drinks; kinetic status -at rest or in motion; residence time in the square;

- Questions criteria for comfort in the heat, wind, sun, moisture, acoustic environment.
- Other criteria such as naturalness of the area; expectations based on proposed changes pictured; experience - impressions from their stay in the square; reasons for visiting and using; aesthetics of the area.



TECHNICAL UNIVERSITY OF CRETE
DEPARTMENT OF ENVIRONMENTAL ENGINEERING

SURVEY FOR THE USE OF THE URBAN OPEN SPACES IN CRETE

**A. OBSERVATIONS**

1. **interview details**: - date
   - hour
   - place of the interview

2. **Age group**: child , teenager, 18-24, 25-34, 35-44, 45-54, 55-64, > 65

3. **Sex**: Male, Female

4. **Clothing:**

5. **Accesories** : hat, sunglasses, gloves, mobile phone

6. **Food or drink consuption**:1) cold drink/ food, 2) hot drink/ food
7. **No of people accompanying:** 1) alone, 2) with 1 person, 3) with 2 persons or more
   4) with dog/ pet

8. **Light Disturbance** 1) Yes, 2) No

9. **Activity** 1) sitting, 2) standing, 3) walking
10. Body type : 1) skinny, 2) normal, 3) overweight

10. **Measurement of sun radiation in the exact point of the interview**
..................................................

11. **Measurement of temperature in the exact point of the interview**
:..........................................................

12. **Measurement of humidity in the exact point of the interview**
:..........................................................

13. **Measurement of sound levels in the exact point of the interview**
:..........................................................

**B. QUESTIONS**

1. Your degree of thermal comfort at this moment is:

| | | | | |
|---|---|---|---|---|
| Very Cold (-2) | Slightly Cold (-1) | Comfort (0) | Slightly Warm (+1) | Very Warm (+2) |

2. Rate the sun radiation level at this moment

| | | |
|---|---|---|
| More sun needed (-1 ) | OK (0) | Too much sun (+1) |

3. Rate the wind level at this moment

| | | | | |
|---|---|---|---|---|
| Very low (-2) | Low (-1) | OK (0) | Slightly windy (+1) | Very Windy (+2) |

4. Rate the humidity level at this moment

| | | |
|---|---|---|
| Wet atmosphere (-1) | OK(0) | Dry atmosphere (+1) |

5. Are you comfortable concerning all the factors together?

| | |
|---|---|
| Yes | No |

6. Rate the luminance of the place

| | | | | |
|---|---|---|---|---|
| Very dark (-2) | Dark (-1) | OK(0) | Slightly bright (+1) | Very Bright (+2) |

7. Which features you like most within the square

| | | | | | |
|---|---|---|---|---|---|
| Ground coverings | Surrounding buildings | Greenery | Water features | Urban elements | View of the sky and horizon |

8. What you consider more important when you choose a place to sit in a square

| | | |
|---|---|---|
| Temperature | Sun | Traffic noise protection |

Does your sitting point affect your perception, if yes in what way?

| | | |
|---|---|---|
| Negative | No | Positive |

9. Rate the traffic sound disturbance at this moment

| | | | | |
|---|---|---|---|---|
| Very quiet (-2) | Slightly quiet (-1) | OK (0) | Slightly noisy (+1) | Very noisy (+2) |

10. Rate the traffic sound disturbance at your place of living/ working

| | | | | |
|---|---|---|---|---|
| Very quiet (-2) | Slightly quiet (-1) | OK (0) | Slightly noisy (+1) | Very noisy (+2) |

**D. PERSONAL QUESTIONS**

1 3
2 4

1. In which one of the following squares would you rather be at this moment?

2. In which one of the following squares would you choose to be near?
1) your house
2) your working place

3. Reasons for visiting the place

4. Place before visiting the square

5. How often do you visit the site? 1) Once per day, 2) Once per week,
   3) Once per month, 4) Once per year

6. Indicate something that you don't like in the square

7 What should be the use of the open space according to your opinion?

8. Do you live or work nearby?

9. What is your educational level?

Picture 7: The questionnaire of the study.

Within the limitations of the survey other anthropogenic parameters are included that may affect thermal sensation like health issues, alcohol consumption, consumption of food or cold drinks before the interview etc.

The on-site measurements were afterwards compared to the mean climatic conditions at every city for this season, to confirm their quality (Figure 3). The monitoring equipment included the use of a weather station with suitable sensors were calibrated to conform to ISO 7726 and 7730 (International Standard 2008). The weather station, which was located in the middle of every square, measured values of air temperature ($^oC$), air velocity (m/s), relative humidity (%) and direct solar radiation ($W/m^2$) whereas the additional portable equipment such as hand pyranometer and sound level meter that could easily be transported around in the exact place of the interview; measured values of direct and diffuse solar radiation ($W/m^2$) , air temperature ($^oC$), humidity (%) and sound levels (dB). The data logging software of the weather station was configured to log data every five minutes to have sufficient amount of measurements whereas the data from the interviews were collected in the exact place of the interview about every fifteen minutes, depending on the free time between the interviews.

All the thermal indexes calculated were based on the values measured and the answers given by every person separately. The questionnaires were completed only by the people who actually used the squares and stayed in them for a minimum time of 5 min. The subject is thermal sensation and comfort vote were recorded by face-to-face interview while the subject’s demographic background, clothing and activities were recorded by observation. The interviewees were conducted in the exact spot where they sat or stood, to be investigated in relation with the actual microclimatic factors that contributed to their subjective answers.

During the questionnaire survey, people involved were carefully selected to include all different age groups and gender present, and also special characteristics such as main use of the square and number of interviews as shown in Figure 4.

The study focuses on issues related to the use of space, as opposed to people’s evaluation of comfort conditions. All the interviews considered not only comfort votes but also other physical characteristics that may affect these votes.

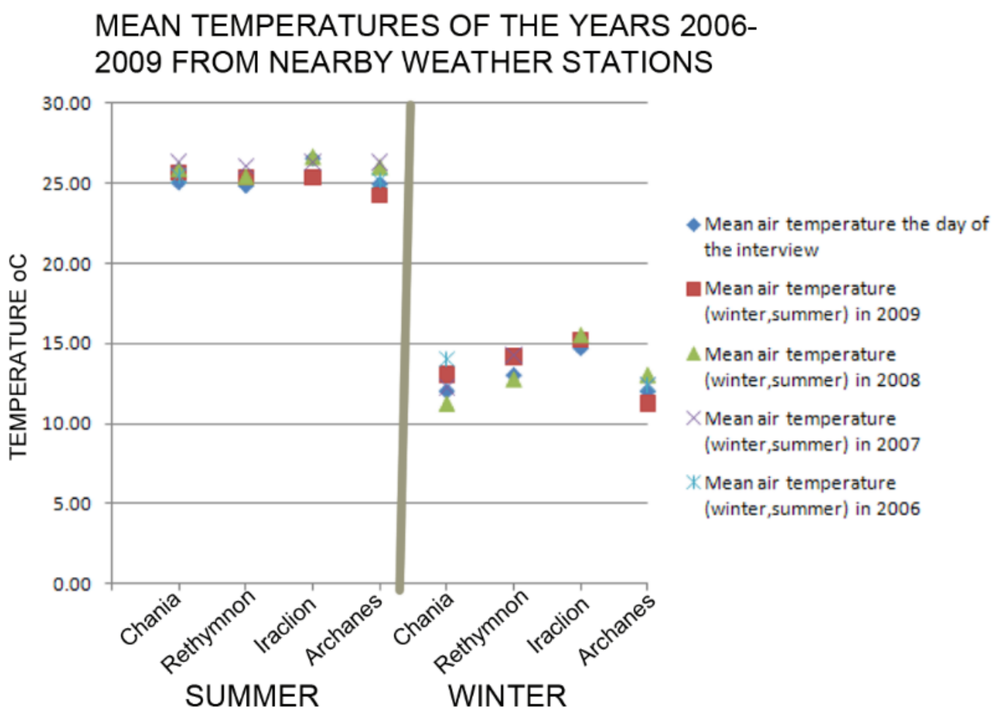



Figure 3: Mean air temperatures in the survey cities for the years 2006-2009.

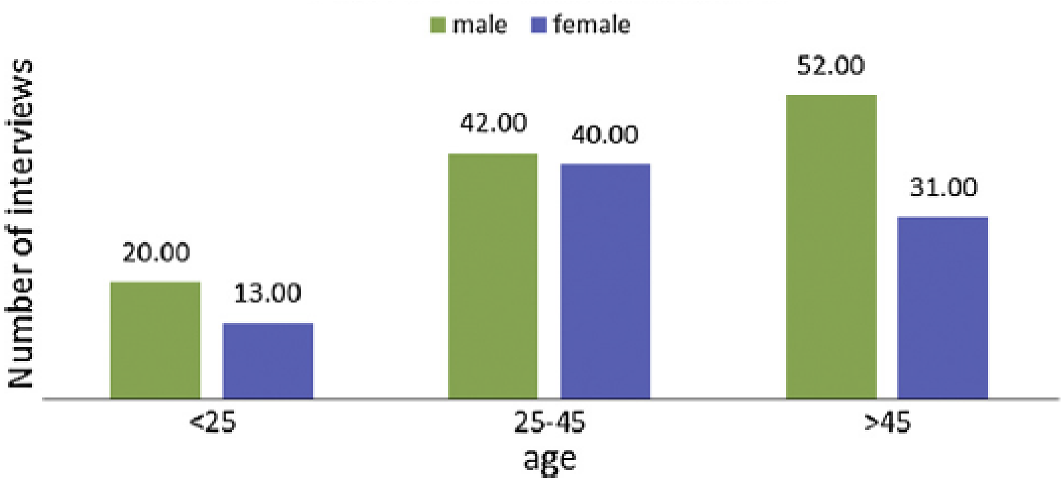


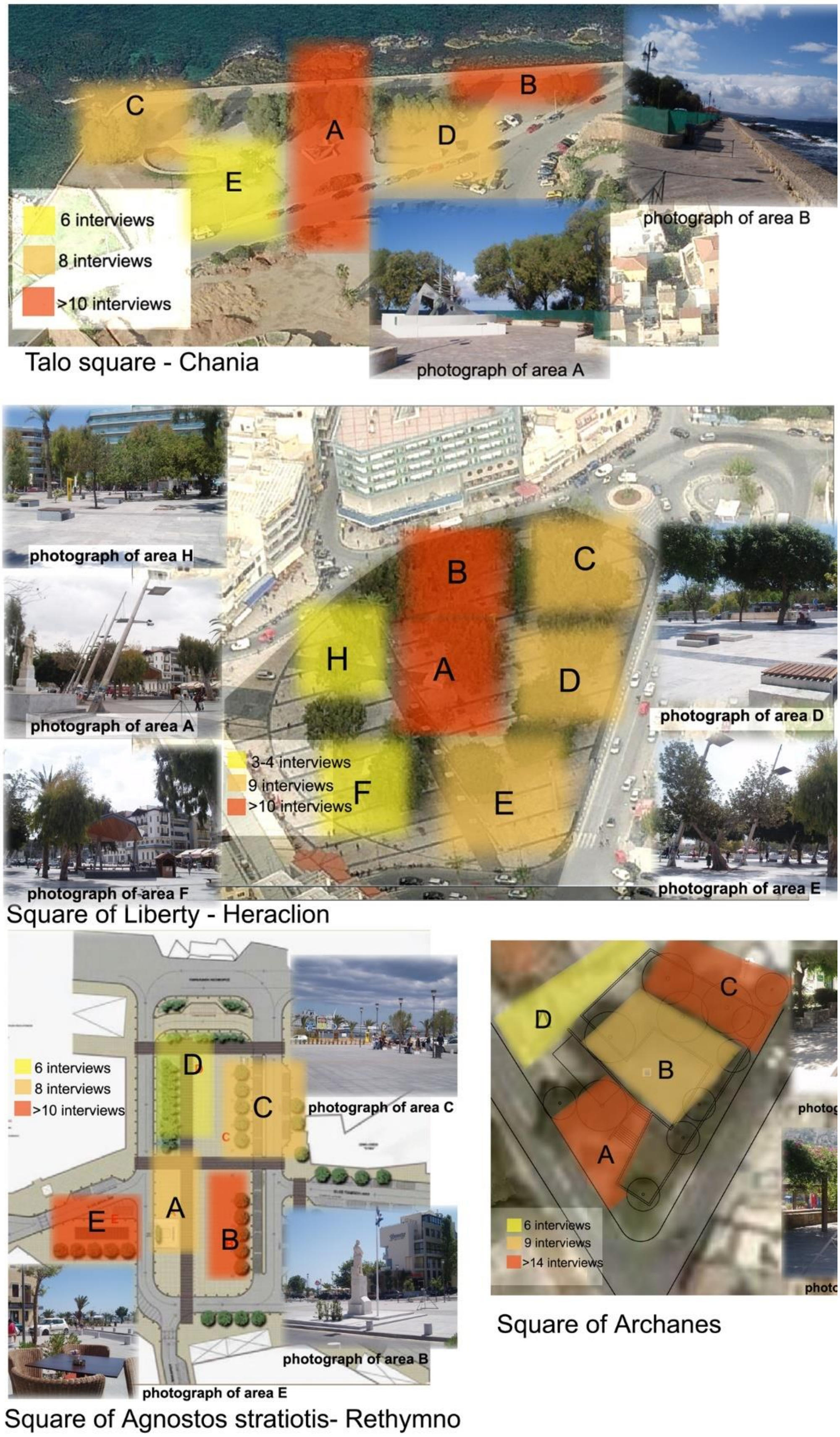

Figure 4: Profile of interviewees based on age classification and gender.

A summary of climatic data for the selected time of interviews, in different cities of Crete, appears in Table 4. The dataset contains measurements of average air temperature, relative humidity, wind speed and direction, solar radiation intensity for every city. The climatic data have been obtained as described from the weather station sensors that were installed in each interview area, as well as from the portable instrument with measurement uncertainty ± 0.01 ($^oC$) for air temperature, ±2.5 ($W/m^2$) for solar radiation and ±0.5 (dB) for sound level in order to record the comfort conditions on the exact spot where the answers were given. The validation of microclimatic data measured by the weather station is carried through their comparison with the corresponding data measured by the closest official weather station of the city. The values have small differences which derive from the urban infrastructure, the different altitude and vegetation. The difference is bigger for the parameter of wind speed which is mainly due to the difference in altitude measurement. The measurements of the on-site weather station were obtained from a level of 2.00 m. from the ground surface of the square, within the level of obstacles or vegetation which certainly affect the observed measurements, while the location of the official weather station of each city was placed in a higher spot, and its place has been carefully studied so as not to exist any barriers. The placement of the weather station exactly in the middle of every square without considering the vegetation or any obstacles may cause different observations. This action was intentionally made for the wider logging of the actual microclimatic parameters that affect the comfort conditions.

Table 4 Mean values of climate data from the on-site weather station

| | | **Temperature ($^oC$)** | **Wind Speed (m/s)** | **RH (%)** | **Dewpoint ($^oC$)** | **Radiation ($W/m^2$)** | **Sound (dB)** |
|---|---|---|---|---|---|---|---|
| **Summer** | **Chania** | 27.44 | 0.93 | 61.51 | 19.38 | 869.56 | 54.21 |
| | **Rethymnon** | 26.21 | 1.78 | 64.55 | 19.03 | 908.94 | 59.79 |
| | **Heraklion** | 31.19 | 1.15 | 46.21 | 18.28 | 976.93 | 57.23 |
| | **Archanes** | 29.21 | 0.72 | 42.87 | 15.30 | 902.37 | 62.01 |
| **Winter** | **Chania** | 15.44 | 2.19 | 49.88 | 5.01 | 720.96 | 50.01 |
| | **Rethymnon** | 15.91 | 1.75 | 46.83 | 4.33 | 455.79 | 55.05 |
| | **Heraklion** | 17.33 | 1.05 | 69.52 | 11.71 | 626.25 | 49.52 |
| | **Archanes** | 13.58 | 0.00 | 87.98 | 11.66 | 91.87 | 65.02 |

The analysis of the users answered the questions is expected to provide certain evidence about the social class of people who use every square and their site-specific characteristics which are crucial for further study. In all the squares about 70% of the people lived or worked nearby and 30% were foreign visitors. The heat map in Picture 8 shows the frequency of use of each square and provides a clear picture of the preference of residents and visitors to the area. The heat map includes the site plan of the square grated in a colour scale from red to yellow according to the number of questionnaires that were conducted at that point. It reveals the basic routes and the most preferred resting areas of the visitors. From the answers to the questions: "how often do you visit the area" and "do you live or work in the neighbourhood" we can assume that in Chania, Rethymnon and Heraklion, the percentage of local residents is larger (70%) than those who visited the site a minimum per week (30%) meaning that some people do not choose the site for daily or weekly use even if they live or work nearby. Unlike in Archanes, the reverse effect is observed; many visitors use very often the square. This result may however not be very representative of the square, bearing in mind the fact that Archanes is a nearby destination from Heraklion and questionnaires were made in Sunday where many people visit the restaurants and cafes that are around the square.




Picture 8: Site of the squares and placement of the questionnaires.

Before any further step, a more descriptive analysis of the replies of the respondents about the comfort conditions is necessary. The questions were related to thermal comfort, annoyance from the sun, wind, humidity, and acoustic comfort. All responses were analysed in five-point scale (thermal comfort, wind tolerance) or three-point scale (sun tolerance, humidity tolerance, traffic sound annoyance) and the possible responses range from tolerable discomfort (±1) to intolerable discomfort (±2). The index Actual Sensation Vote (ASV) is a result of all the responses together with the general question, "*Are you comfortable?*" This provides a clear picture of comfort conditions in each square. For the "research on design", it is important to define which of these parameters is the most crucial for the feeling of comfort according to the interviewees. The answers to the question *"What you consider most important when you chose a place to sit in a square?"* appears in Figure 5. This question can be very helpful when designing because makes it possible to regulate all aspects of comfort, as well as to calibrate the factors affecting comfort and the statistical analysis can conclude to the parameter that mostly affects comfort conditions (temperature, sunshine, acoustic environment). The results from this question are that sunshine has the greatest percentage of answers in all the squares 58.45%, assuming that sun control is an important factor which influences the comfort vote and is decisive for the viability of the square. It should also be noted that the other two factors, namely the acoustic environment 24.86% and temperature 16.69% are also important for the sustainability of the square (Figure 5).

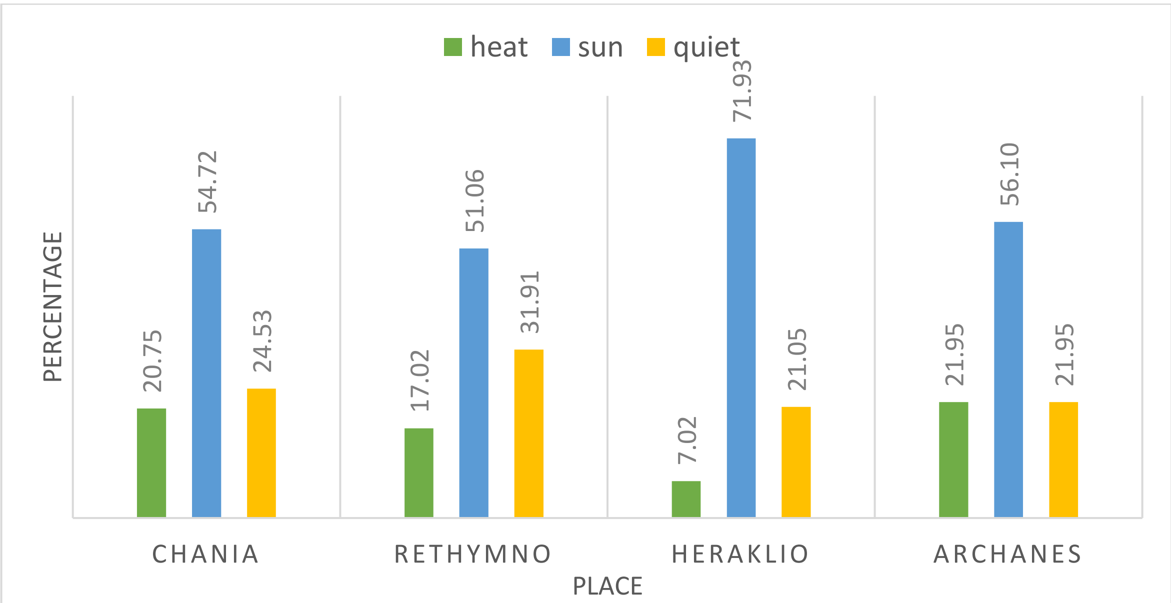



Figure 5: Answers to the question: "What you consider the most important parameter when you choose a place to sit in a square?"

Figure 6 and Figure 7 show the responses to thermal comfort, respectively in summer and winter and Table 5 shows the average temperature prevailing in the squares when the vote of comfort was positive. In Chania, Talos square accumulates the highest percentage of positive thermal comfort both in summer (37%) with average air temperature 27.7°C and in winter (73.1%) with average air temperature 15.4°C. In Rethymnon, the percentages of extreme votes (too little, too much) both in summer and winter appear increased even though the air temperature both in summer (26.1°C) and in winter (16.3 °C) appears between the comfort levels according to the ISO 7730 (International Standard 2008). This phenomenon is mainly due to the usage of high-reflectance materials in the surfaces of the square in combination with the lack of vegetation that could protect the pedestrians from the direct and diffuse solar radiation especially during the summer period. Additionally, during the winter season due to poor design and lack of any protection from low temperatures, resulted in increasing the number of pedestrians that were feeling uncomfortable. The answers about solar radiation tolerance are shown in Figure 8. Generally, in winter the measurements of solar radiation were from 350W/m$^2$ to 550W/m$^2$ whereas in the summer the radiation increased significantly from 850 W/m$^2$ to 950 W/m$^2$. Only in Archanes the results from the measurements of solar radiation are very low because of the presence of dense greenery that shades the square in combination with the small sky view factor that prevented the sun penetration. Despite the very low level of solar radiation, the mean value of the measurements is 25.6W/m$^2$, during the interviews in Archanes (Table 5). While in winter all squares have a sufficient comfort answers rate, in the summer the positive answers about comfort are increased in Chania (44.4%) and Archanes (91.3%). The average solar radiation, as it was measured from the weather station, does not vary so much in relation to the other two squares (Rethymnon and Heraklion) (Table 5). These responses were determined mostly by the ground material as well as the naturalness of the place. Both the squares in Archanes and in Chania have large areas of tall trees and vegetation and as a result, the amount of the received solar radiation measured was limited (not more than 500W/m$^2$ as measured the portable pyranometer) unlike the other two squares where the reflective paving materials multiplied the received solar radiation (about 700-950W/m$^2$ as measured by the portable pyranometer).

As Figure 9 and Figure 10 demonstrate, the wind votes are strongly influenced by wind speed rather than by other factors that influence mostly solar and thermal comfort. In all squares both in summer and winter, there was no measurement of wind speed above the 2m/s, for that reason most of the responses given were favourable to the little wind that existed.

The Relative Humidity (RH) (Figure 11) was measured very high in both winter and summer in all regions, which is normal taking into account the Mediterranean climate of the island. The answers about the humidity were not equivalent to the RH measured, only in Archanes where the percentage of the RH in winter was very large the pedestrians were able to quantify their discomfort due to the high humidity levels.

Finally, Figure 12 presents the responses of annoyance from the noise pollution of the squares. The responses "silence" and "very quiet" cannot be considered negative and on the charts were considered as positive votes. It is obvious, that Chania has the largest percentage of positive responses about the noise pollution levels in both winter and summer, even if the sound level does not vary much from region to region. The significant difference of the Talo square is the sea, which produces enough noise (the decibel meter near the sea measured noise around 60 dB) but also absorbs most of the annoying noise.

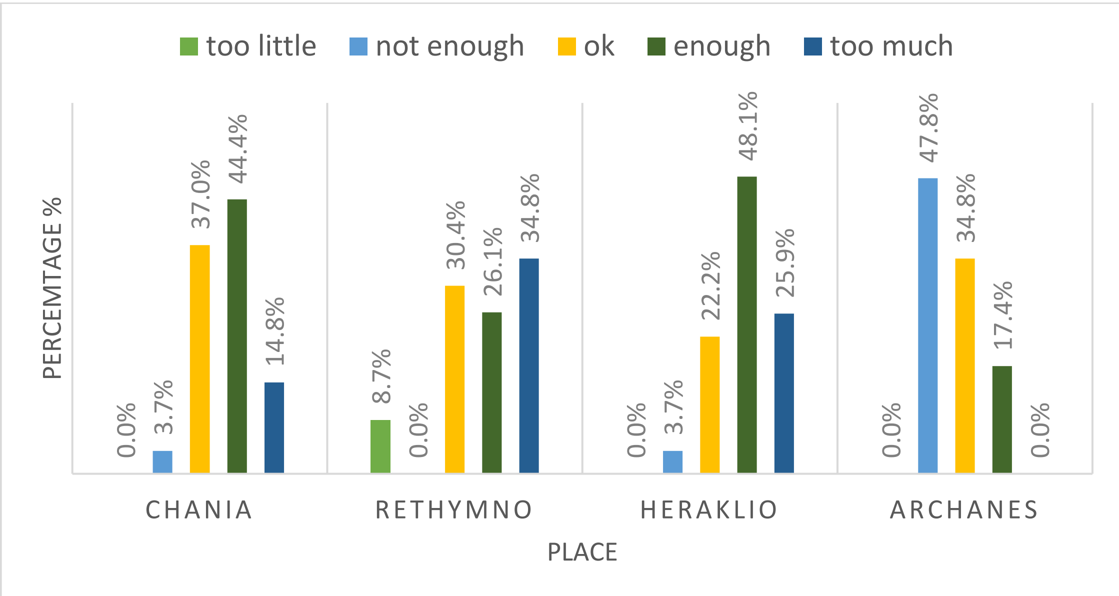



Figure 6: Thermal comfort in summer.

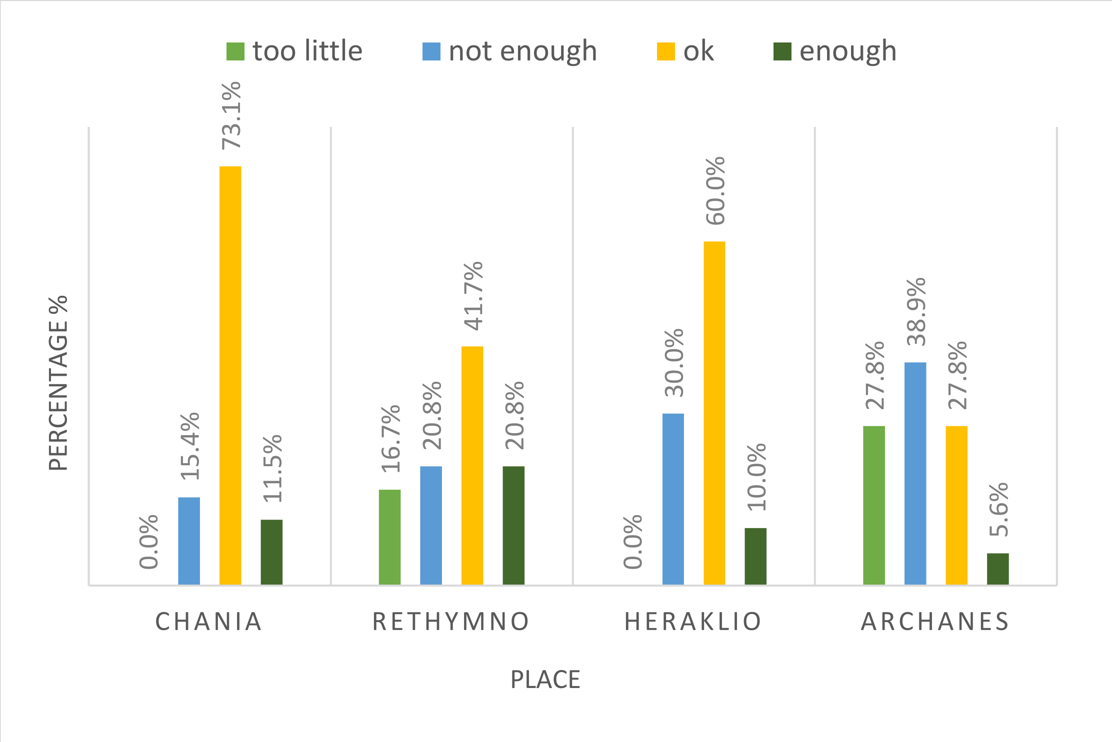



Figure 7: Thermal comfort in winter.

Table 5: Mean values of microclimatic data for the comfort votes (OK) of the questionnaires.

| | | Air Temperature ($^oC$) | Wind Speed (m/s) | RH (%) | Solar Radiation ($W/m^2$) |
|---|---|---|---|---|---|
| **Summer** | **Chania** | 27.7 | 0.9 | 61.5 | 855.4 |
| | **Rethymnon** | 26.1 | 1.8 | 64.4 | 902.1 |
| | **Heraklion** | 31.1 | 1.2 | 46.3 | 968.1 |
| | **Archanes** | 29.1 | 0.7 | 42.9 | 894.3 |
| **Winter** | **Chania** | 15.4 | 3.0 | 50.2 | 749.4 |
| | **Rethymnon** | 16.3 | 1.9 | 47.1 | 511.5 |
| | **Heraklion** | 17.3 | 1.1 | 69.6 | 309.1 |
| | **Archanes** | 13.4 | 1.0 | 86.8 | 25.6 |

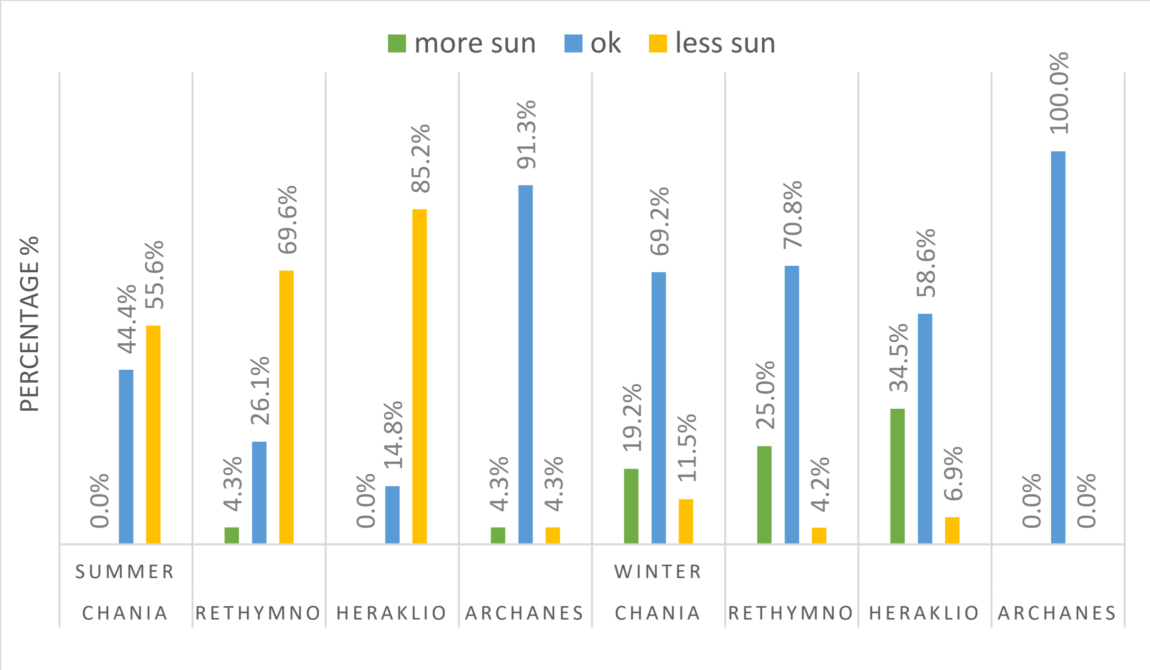



Figure 8: Answers for sun tolerance in solar radiation.

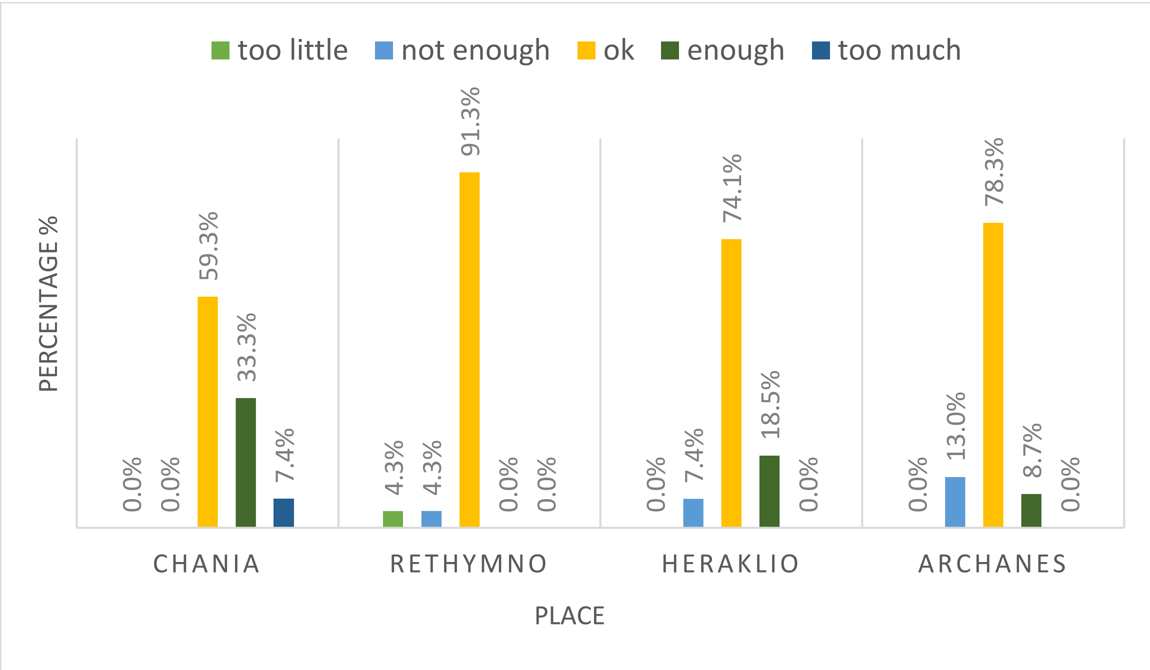



Figure 9: Answers for wind tolerance in summer.

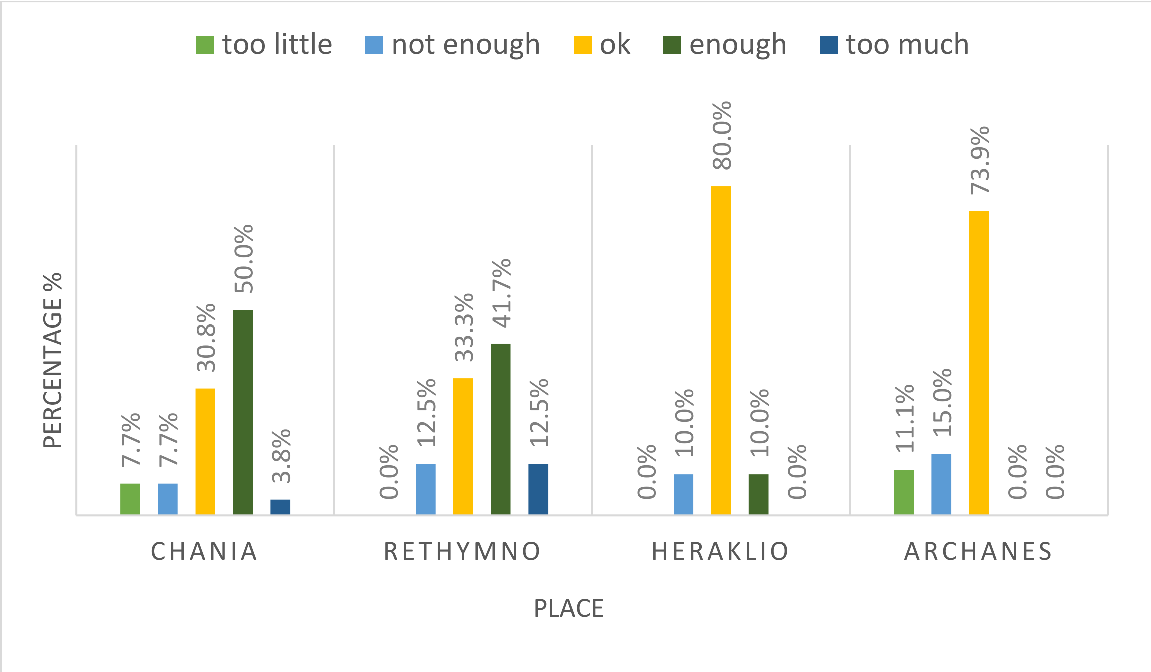



Figure 10: Answers to wind tolerance in winter.

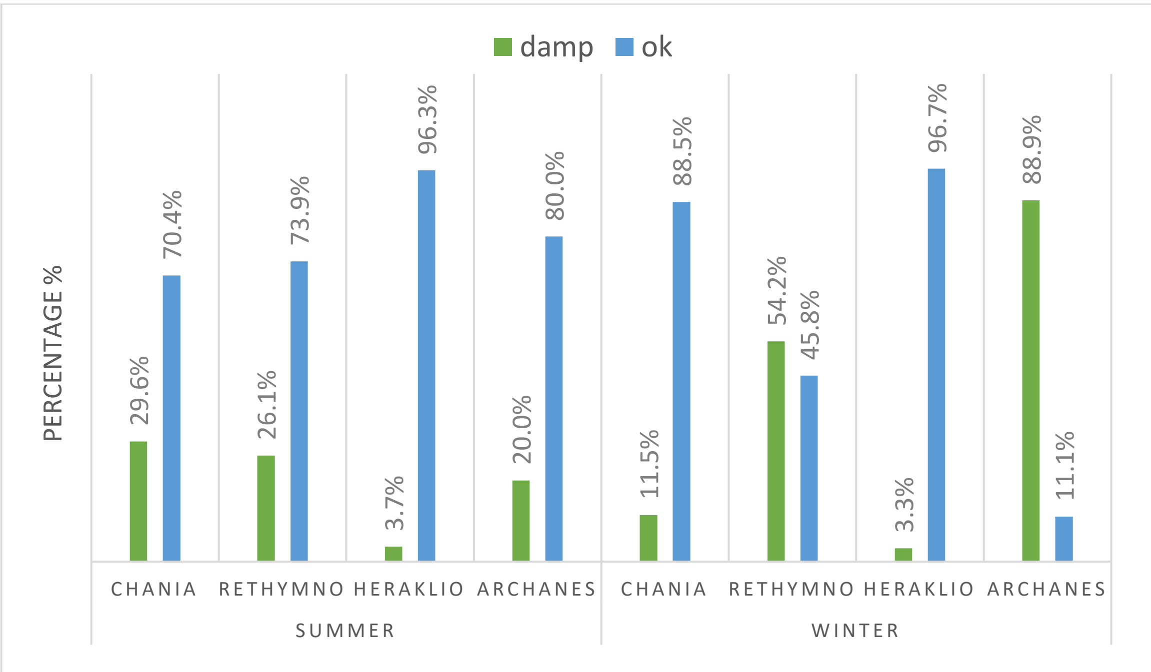



Figure 11: Answers to Humidity tolerance.

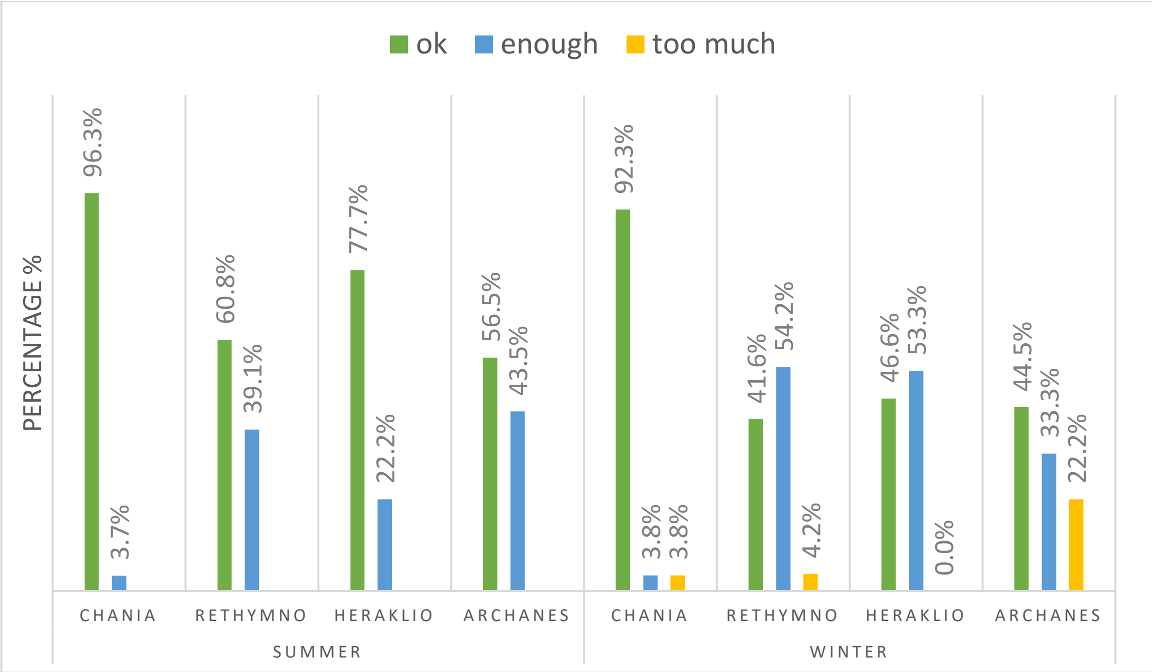



Figure 12: Answers to noise annoyance.

The study identified the climatic factors which affect most of the responses of comfort levels and their interaction while field surveys reveal various issues regarding the adaptation of users to the outdoor environment.

A basic assumption of this study is that the comfort conditions in each square are a result of the interaction of all the microclimatic parameters together. Especially for Crete, the results from the correlation analysis showed that air temperature and solar radiation are the most crucial parameters, with values of $R^2$ 0.87 for air temperature and 0.82 for solar radiation regarding the positive comfort votes taking into account both physical and psychological factors. Furthermore, humidity and wind speed affect the positive comfort votes only when air temperature measurements are on extreme boundaries. The share of people who feel comfortable during the interview in Crete is about 67%, which is lower than the results from RUROS project showing over 75% annually (Nikolopoulou & Lykoudis 2006). This requires the differentiation according to the special characteristics of the area and the construction of a skilled comfort model so that any form of intervention into the open space can have a positive effect on the viability of the city. It is worth noticing that all squares in the study have been regenerated during the last ten years, so can be assumed that the design solutions did not include any research of the perception and comfort conditions prevailing in them. This fact can ameliorate the basic purpose of this study as it is obvious that every attempt of designing open urban space must consider bioclimatic parameters, site specifications, people habits and local weather parameters in order to assure that it will become a sustainable open place of social interaction.

This combination could lead to an optimum design of the urban open space that matches all types of expectations. This suggests another kind of approach to the researcher and gives another palette of tools to the design team.

### 3.3. Thermal comfort

This section deals with issues of human thermal comfort and their impact on climate analysis as a basis for formulating design principles. Thermal comfort can be defined operationally as the range of climatic conditions considered comfortable and acceptable (Givoni 1998). Two major approaches of research on human responses to the thermal comfort environment can be applied. The first focuses on "thermal comfort" defined from subjective responses of humans, while the second focuses on objective physiological responses to climatic factors and physical activity, aiming at evaluating the level of thermal stress. The determination of comfort conditions in outdoor urban environments is of great interest during the last decade (Monteiro & Alucci 2006; Orosa et al. 2014; Tsitoura & Tsoutsos 2017).

The thermal comfort can be described with the use of certain indices. The most common of them are:

1) **Wet Bulb Globe Temperature (WBGT)** index (Yahia & Johansson 2014) takes only climatic data into account such as air temperature, radiant heat, solar radiation and air flow. Its use is quite wide, while it was first developed by the US Military for preventing heat stress injuries during training. The calculation method consisted of the dry bulb temperature, the wet bulb temperature and the black globe temperature.

For the outdoor environment and direct solar radiation, the index is calculated by the following formula:

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_d$$

where:

- $T_w$ is the Natural wet-bulb temperature;

- $T_q$ is the black globe thermometer temperature;
- $T_d$ is the dry-bulb temperature.

2) **Predicted Mean Vote (PMV)** index (ANSI/ASHRAE 2002) has a solid base in the indoor environment but takes into account relevant factors and the affect thermal sensation. The ISO 7730 defines thermal conditions of the outdoor environment in which the probability of a negative vote is minimized. The index "Predicted Mean Vote" (PMV) and the index "Predicted Percentage Dissatisfied" (PPD) are based on ISO 7730 and are considering the climatic parameters in relation with factors affecting the thermal sensation of each respondent (clothing, metabolic rate, eating or drinking). With PMV and PPD we can obtain answers to the questions: "*Is the thermal comfort in a place not perfect?*", "*How far from perfect is it?*" or "*Within what limits should we maintain temperature and humidity to enable reasonable thermal comfort?*" The PMV-index predicts the mean value of the subjective ratings of a group of people in a given environment. The PMV scale is a fifteen -point thermal-sensation scale ranging from -7 (too cold) to +7 (too hot), where 0 represents the thermally neutral sensation. Even when the PMV-index is 0, there will still be some individuals in the thermal discomfort zone, even if they are dressed similarly and have the same intensity of activity. The thermal comfort evaluation differs from person to person. PMV can be calculated by the following formula (ANSI/ASHRAE 2002):

$$PMV = (0.303e^{-0.036M} + 0.028)L$$

where:

- M is the metabolic rate. The rate of transformation of chemical energy into heat and mechanical work by aerobic and anaerobic activities within the body [W/m2];
- L is the thermal load defined as the difference between the internal heat production and the heat loss to the actual environment for a person hypothetically kept at comfort values of skin temperature and evaporative heat loss by sweating at the actual activity level.

$$L = H - E_d - E_{sw} - E_{res} - R - C$$

where:

- H is the internal heat production;
- $E_d$ is the heat loss due to water vapour diffusion through the skin;

- $E_{sw}$ is the heat loss due to sweating;
- $E_{re}$ is the latent heat loss due το respiration;
- R is the heat loss by radiation from the surface of the clothed body;
- C is the heat loss by convection from the surface of the clothed body.

3) **Standard Effective Temperature (SET)** (Gagge et al. 1986) and for outdoor use OUT SET (Pickup & de Dear 2000) takes for granted an environment with 50% RH with a typical person with standardized clothing, skin temperature and skin wettedness.

4) **Physiological Equivalent Temperature PET** (Höppe 1999) is based on a typical heat budget model of the human thermoregulatory system for outdoor environments with metabolic rate 114W and clothing insulation 0.9 clo. PET describes an equivalent temperature of an isothermal reference environment with water vapour pressure 12 hPa, light air 0.1 m/s, RH 50% and air temperature 20$^{o}$C.

5) **Universal Thermal Comfort Index (UTCI)** (Błazejczyk et al. 2010) is a physiologically relevant assessment model of the thermal environment in order to significantly enhance applications related to health and well-being, the core issues of human biometeorology. The model is based on the state-of-the-art in the cause-effect related assessments of the outdoor thermal environment. The model is designed by a Europe funding program the COST Action 730 (Fiala et al. 2012). UTCI was following the concept of an equivalent temperature (Gómez et al. 2013; Blazejczyk et al. 2012). This involved the definition of a reference environment with 50% relative humidity with water vapour pressure not exceeding 20 hPa, with still air and radiant temperature equalling air temperature, to which all other climatic conditions are compared (Kampmann et al. 2012; Pantavou et al. 2013). Equal physiological conditions are based on the equivalence of the dynamic physiological response predicted by the model for the actual and the reference environment. As this dynamic response is multidimensional (body core temperature, sweat rate, skin wettedness etc. at different exposure times), a single dimensional strain index was calculated by principal component analysis. The UTCI equivalent temperature for a given combination of wind, radiation, humidity, and air temperature is then defined as the air temperature of the reference environment which produces the same strain index value. The calculation of the physiological response to the meteorological contribution is based on the “multi-node” model (Fiala et al. 2012), taking into account the clothing that people wear. Several studies (Bröde et al. 2012; Schreier et al. 2013)

suggest that UTCI due to its sensitivity to humidity, radiation, and wind speed can show very good results in both hot and cold conditions. The study introduced the range of validity of each parameter. These boundaries are listed below:

$$-50℃ \leq T_a \leq 50℃$$

$$-30℃ \leq T_r - T_a \leq 70℃$$

$$0.50m/s \leq V_a \leq 30.3m/s$$

$$5\% \leq RH \leq 100\% \; with \; p_v < 50hPa$$

where:

- $T_a$ is the air temperature;
- $T_r$ is the radiant temperature;
- $RH$ is the relative humidity;
- $V_a$ is the wind-speed;
- $p_v$ is the water vapour pressure.

6) **Humidex** is defined as the temperature of relatively dry air (water vapour pressure less than 10hPa), which has the equivalent effect on human comfort as the air with an actual measured or forecasted temperature and humidity (d'Ambrosio Alfano et al. 2011). Humidex (°C) is calculated by the following formula:

$$H = T_a + \frac{5}{9}(z - 10)$$

where:

$T_a$ is the air temperature;

- $z$ can be expressed as:

$$z = 6.112 \cdot 10^{\frac{7.5T_a}{237.7+T_a}} \cdot \frac{RH}{100}$$

where:

- $T_a$ is the air temperature;
- RH is the relative humidity.

This index has been used for human biometeorological studies focused on thermal perception, human health, air pollution, under a wide range of climatic conditions.

Humidex is a temperature-humidity index introduced in 1979 by Masterton & Richardson (1979) for correlating outdoor thermal discomfort of mild Canada's areas to the two main meteorological parameters: the air temperature and the relative humidity. Its formulation is based on two hypotheses on the thermoregulatory system:

- The “neutral point” of the human body, defined as the temperature range in which, for a naked subject exposed to quiet air, the human body heat balance in the absence of the accumulation term is satisfied, is from 27°C to 30°C;The human body is unable to get over the heat accumulation when its temperature exceeds a minimum value of 32°C in the presence of a relative humidity value greater than 75%.

Humidex is thought to be an empirical index formulated under particular hypotheses and under particular climatic conditions (Mild Canada areas) and it is intrinsically unable to take into account the radiative heat flow, the metabolic rate, the air velocity and finally the clothing insulation as well as the heat balance (d’Ambrosio Alfano et al. 2011; Giannopoulou et al. 2014). Concerning moderate environments, Humidex provides a good estimation of thermal comfort only in a narrow range of thermohygrometric conditions (i.e. higher temperature in summer season or lower temperature in winter season) (Charalampopoulos et al. 2013).

By comparing temperature - humidity indexes pointed that humidex is more sensitive to humidity changes indicating the contribution of humidity to heat stress while in the case of intense heat conditions there is a fairly good relationship between the index and the temperature of the human body (Santee & Wallace 2005).

The existing review studies regarding the comfort conditions on outdoor spaces of the last decade reach the main conclusion about the lack of specifications considering both the measurement standards and the subjective human perception (Ng et al. 2012).

Liang Chen and Edward Ng (Chen & Ng 2012) summarize the outdoor thermal comfort research in the past decade 2001 - 2011. Divide the thermal comfort assessment methods into a steady state that use indexes like PMV and PET and pointing out the lack of internationally accepted non- steady state indices. In many studies after the analysis of behavioural aspects of the outdoor thermal comfort, there is a need for tools for predicting the effect of a particular change in a climatic factor on the comfort of persons in the outdoor environment Kantor, Unger and Gulyas (Kántor, Égerházi, et al. 2012; Kántor, Unger, et al. 2012) by using 6 surveys (Hungary, Sweden, Montreal, Portugal, Taiwan, RUROS European cities) analyse the monitoring parameters and tools and compares the basic parameters such as) Preferences vs perceptions, Thermal Sensation Votes (TSV) vs perceptions, TSV vs PET and assessed temperature values vs objective temperatures. The conclusions are:

- The thermal comfort investigations should be standardized to make comparable the data collected in different locations; The calculated parameters like Mean Radiant Temperature (MRT) should be obtained according to the same method.

In the case of questionnaires, the survey of the same subjective parameters is necessary, as well as the application of the same type of measuring scales with the same grading. Would be expedient, the perceptions about the particular meteorological parameters to be investigated using semantic differential scales on which only the two endpoints are denominated.

Lai Dayi et all (Lai et al. 2014) compares the calibration of the results of the indexes PET and UTCI comfort range from a survey in Tianjin northern China with corresponding results from Europe and from Taiwan. This compare showed that both the PET neutral temperatures (11-24$^{o}$C in Tianjin, 18-23$^{o}$C in Europe and 26-30 $^{o}$C in Taiwan), and UTCI neutral values (9-26$^{o}$C in Tianjin, 17.4-24.5 $^{o}$C in Europe and 12-25 $^{o}$C in Taiwan), are different due to different climates and personal characteristics.

Johansson et al. ( 2013) use 26 studies all over the world. The results indicate the methodology of all the studies regarding measured data, sensors and measuring methodology, type of survey, type of sites, time and season of the survey, number of participants, questionnaire design and scales and all the comfort indexes used.

Regarding the review studies of the last five years on the urban open spaces it can be assumed that they are focusing mostly on the methodology, tools and thermal indexes through which microclimate can be changed rather than a sensitivity analysis of the parameters that affect it. According to preliminary research in four urban open spaces in Crete that included on-site measurements, calculation of the main comfort indexes and questionnaires it can be considered that outdoor comfort in all the squares during summer is quite difficult to achieve according to the calculated indexes while during winter period most of the squares had ideal comfort conditions. The comparison between the actual comfort votes measured on the site and the indexes calculated shows that although the indexes indicate conditions of great discomfort during summer the percentage of actual comfort votes in all the squares is quite high (Table 6). This fact identifies the need for a site-specific comfort model considering the characteristics of the Mediterranean climate.

Table 6: Mean values of the selected comfort indexes in each square.

| | | Temperature | WBGT | PET | OUT_SET | PMV |
|---|---|---|---|---|---|---|
| **Summer** | **Chania** | 27.61 | **28.49** | **40.87** | **35.30** | **4,30** |
| | **Rethymnon** | 26.27 | 27.47 | **36.06** | 30.22 | 3,50 |
| | **Heraklion** | 31.19 | **29.85** | **45.69** | **37.34** | **4.78** |
| | **Archanes** | 29.23 | 27.32 | **44.28** | **36.37** | **4.24** |
| **Winter** | **Chania** | 15.44 | 16.12 | 18.82 | 16.96 | -0.68 |
| | **Rethymnon** | 15.90 | 16.24 | 21.24 | 18.41 | -0,80 |
| | **Heraklion** | 17.31 | 19.14 | 22.58 | 19.13 | -0.69 |
| | **Archanes** | 13.57 | 16.99 | 9.28 | 7.31 | **-2.49** |

In order to find the most suitable index for the correlation with the actual votes the value of every index was calculated for the exact time and place of every interview. Figure 13 shows the exact value of each one of those indices in summer and winter for the hours of the interview, for Talo square in Chania. From the comparison of the indices with the actual sensation votes (Figure 13), we can conclude that:

- OUT SET index is directly affected by the solar radiation that is why appears so unstable and it cannot describe the user tolerance of the climatic conditions; WBGT index is quite close to the air temperature but the comfort levels seem not to follow the temperature variations; PET index is affected by the air temperature and the results, especially during the summer season, cannot describe the comfort votes; PMV index, cannot describe the comfort during summer but it can predict the increase or the decrease of the comfort votes quite realistically in all the squares both in winter and summer season. After the linear regression with the use of SPSS software of each one of these indexes with the actual sensation votes from the interviews of all squares, it is proved that the PMV index can sufficiently predict the comfort votes with using the formula:

$$ASV = PMV \cdot 0.16 + 0.22 \; with \; R^2 = 0.72$$

The result of the correlation with $R^2$= 0.72 shows the high correlation between the votes from interviews and the PMV index.

Obviously, in order to conclude to a basic model of comfort which could predict the comfort vote of the users, it is essential to re-orientate the basic thermal indexes and to use a more specialized model that takes into account the special characteristics of the Mediterranean climate. For the effectiveness of this model, further measurements are needed as well as a sensitivity analysis of the representation of the climatic behaviour of each square.

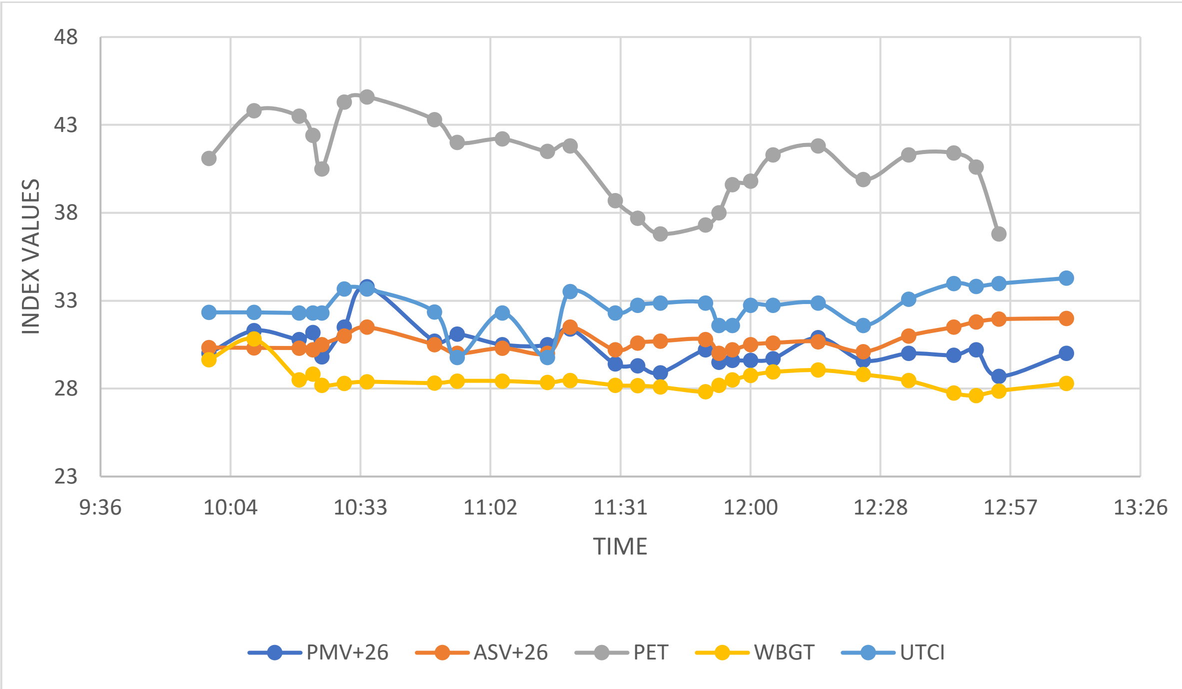



Figure 13: Thermal indexes values for the summer season in Talo square, Chania.

### 3.4. Parameters that affect the sustainability of Mediterranean urban open spaces

The proposed environmental design strategies are mostly applied during summer months because the areas of validation and research are in subtropical climates ($C_{sa}$) where during winter people can adjust by wearing clothing whereas in summer people is harder to adjust the clothing and their metabolism.

The parameters that can be controlled in order to achieve better microclimate conditions are divided into two groups (Tsitoura & Tsoutsos 2017):

- Non-flexible parameters that are difficult to change, which are: Height/ Width ratio of the urban canyon, the orientation, the number of open sides and the general climate conditions of the area; Flexible parameters which are the greenery type and percentage and material properties of the surfaces such as albedo and emissivity.

The necessity of environmental design of the outdoor environment and the control of those parameters as analysed in previous chapters is crucial for the sustainability of the city. Additionally, the city microclimate is responsible both for the quality of life of citizens that use the urban open spaces, and for the energy consumption of the surrounding buildings. Any effort of minimizing the microclimate temperature and achieving thermal comfort in the spaces between the buildings will lead to sustainable urban sites together with indoor comfort and reduced heating and cooling loads.

Good microclimatic conditions within a city have a direct impact on the citizen's health and well-being. Comparing to rural sites, urban environments have larger sickness percentages that are caused by the extreme heating conditions. This situation is worsened by the urban heat island phenomenon that prevents the detonation of the high temperature and strengthens the intensity and the duration of the heat wave. The impact of the urban heat island though is more evident during the night where the night ventilation is reversed. The absence of solar heating leads to the decrease of atmospheric convection and the stabilization of urban boundary layer. This traps urban air near the surface and keeps surface air warm from the still-warm urban surfaces, resulting in warmer night-time air temperatures within the city. In cities with medium or high latitudes, people are not used to high temperatures while in cities of lower latitudes where citizens have learned to deal with extremely hot conditions.

Additionally, the high temperatures within the city environments are responsible for photochemical pollutants, especially in cities with large sunshine periods. This phenomenon also affects both levels of air pollution, especially the smog, which is created by the photochemical reactions of pollutants in the atmosphere. The higher the temperatures the more intense the smog which can cause several health problems.

Despite the obvious consequences that are analysed, the abnormal city temperatures change the local meteorology factors by changing the regional winds, the cloud and fog formation, humidity and precipitation rates.

The focus is directed on the most analysed parameters that are finally the ones that determine comfort conditions and use of urban open spaces. These parameters are:

**a) Height/Width Ratio (H/W)**

The urban canyon geometry is defined mostly by the H/W ratio which affects shading abilities and the radiation hours of the area sides. By increasing the H/W ratio a cooler pedestrian environment is created (Andreou 2014; Andreou & Axarli 2012; Bourbia & Boucheriba 2010; Cohen et al. 2013) because air and surface temperatures are lower, as well as thermal comfort indexes values. The increase of the height causes more shading in every orientation and lowers the air temperature up to 3 $^{o}$C (Cohen et al. 2012; Johansson & Emmanuel 2006).On the other hand, the multiple reflections on the building sides and the low penetration of the wind can have opposite results on the thermal comfort environment during summer. Santamouris (2001) points that although surface temperatures are influenced by canyon geometry there is a weak connection between geometry and air temperature because of the horizontal transport effects. Regarding the cooling load of the adjacent buildings the research of Pearlmutter & Kruger (2008) showed that in case of one storey building the change on the surface materials, adding 10% of vegetation or water for example, can have a dramatic reduction in the cooling demand from about 225kWh to 75kWh while when the height is doubled this reduction is not significant.

**b) Sky View Factor (SVF)**

Shading is considered in a lot of studies to be the most crucial parameter that affects human thermal comfort. In a study conducted in Crete that included questionnaires shading has been voted by 60% to be the first parameter that mostly affects thermal comfort conditions (Marianna Tsitoura et al. 2014; Tsitoura & Tsoutsos 2017). Solar radiation and the level of shading play more important roles than air temperature and wind speed when calculating thermal indices especially during summer periods (Cheng et al. 2012; Krüger et al. 2011; Yahia & Johansson 2014; Yang et al. 2011). SVF of 0.129 has the longest thermal comfort period in the whole year while with mean solar radiation of 300W/m$^2$ neutral temperature is found to be 23.5°C but when mean solar radiation is 136W/m$^2$ the neutral temperature gets 25.7 °C (Müller et al. 2013). However, there is the difference between the different types of shade based on the surface materials and greenery. Hwang et al. (2011) pointed out that with similar SVF values the concrete shading has up to 15% more very hot votes and up to 6% more warm votes that the shading with trees. Also, while in narrower canyons with lower SVF the thermal loads are reduced, this reduction is not reflected in the thermal comfort index (Ignatius et al. 2015). In any case, in Mediterranean climates during summer, the higher the temperature the higher the percentage of people seek shade in an urban environment (Yahia & Johansson 2014). As well as shading affect a lot the surface temperatures of the canyon and contributes to the multiple reflections minimization which leads to lower air temperature values. These facts make shading one of the most crucial factors that affect the outdoor usage in hot environments. On the other hand, low SVF has a negative effect at night and lower wind speeds that can affect thermal comfort, but in any case, the shading during daytime is more important.

**c) Greenery**

A common result of all studies is that the green areas are cooler both under direct exposure to sun and shade. The main reasons for the large differences in temperature and thermal comfort between areas with and without vegetation are the following (Johansson et al. 2013; Müller et al. 2013):

- The ground that consists of open moist soil and a part of the net radiation at its surface is transformed into latent heat;
- The shading effect of leaves and medium-sized greenery;
- The evapotranspiration effect of every kind of vegetation (O'Malley et al. 2015).

Other advantages of the green sites are the environmental and ecological benefit from the aid of green spaces and the considerably low cost of the maintenance and installation (Georgi & Dimitriou 2010). Hamada and Ohta (2010) also measured temperature difference between the urban and green areas about 6.9 °C during the day and 1.9°C during the night in Nagoya, central Japan, while Ignatius (2015) measured a reduction of 1.3°C in maximum temperature and 0.79°C in average air temperature, called the "cool island" phenomenon. This cooling effect exceeded about 300m length. A new park in the city of Athens reduced the temperature of the surrounding areas from 0.5 °C up to 1.2 °C within a distance almost equal to its length (Papangelis et al. 2012). An increase in vegetation about 5% can show a good rate of temperature reduction while the ideal is an increase in vegetation about 15% which can result in 3.5°C during extreme heat conditions and 2.8°C on a typical summer day (Mirzaei et al. 2015).

Comparing the type of vegetation all existing studies agree that the tree coverage is better than grass coverage both for the Mean Radiant Temperature (MRT) and air temperature (Cohen et al. 2012; Yahia & Johansson 2014; Yang et al. 2011). Simulation research showed that vegetation scenarios with trees compared with vegetation scenarios with shrubs does not have many differences in their effect on temperature between seasons, they both have reduction about 0.8 °C in summer and 0.2 °C reduction in spring and autumn (Tsilini et al. 2015). However, measurements showed that larger differences between the grass site and the tree site occur in the hot hours of the day where the lawn temperature pattern is measured similar to the paved squares while the main advantage of the lawn is found during the night in the summer months (Andreou & Axarli 2012; Johansson et al. 2013). In general, vegetation areas reach their maximum reduction potential only with adequate water supply, the differences that were noticed in the study in thermal comfort levels of well irrigated and non-irrigated vegetation areas were quite large especially during daytime (Müller et al. 2013). Georgi & Dimitriou (2010) comparing and measuring the effect on the thermal comfort of a variety of tree species resulted that the species that have the highest amount of evapotranspiration have the best thermal comfort, the species that the study classified in descending order are:

fig →pine→ palm → bitter orange →olive

The temperature reduction is fully dependent on the energy budget system of the area. The oasis effect is fully dependent on the Bowen ratio of the area that is equal to the ratio of the sensible heat to the latent heat. The Bowen ratio is the mathematical method generally used to calculate heat lost (or gained) in a substance, it is the ratio of energy fluxes from one state to another by sensible and latent heating respectively (Bowler et al. 2010). The Bowen ratio is an indicator of the type of surface, on a medium oasis phenomenon and has values between 0.5- 2 while the typical value on city environment is about 5 and it is less than 1 over surfaces with abundant water supplies. Table 7 shows the mean value of the Bowen ratio depending on the environment (Bowler et al. 2010).

Table 7: Typical Bowen ratios values.

| Type of surface | Range of Bowen ratios |
|---|---|
| **Deserts** | >10.0 |
| **Semi-arid landscapes** | 2.0-6.0 |
| **Temperate forests and grasslands** | 0.4-0.8 |
| **Tropical rainforests** | 0.1-0.3 |
| **Tropical oceans** | < 0.1 |

The percentage of the effect of greenery is dependent on the geometry of the tree and its placement. The basic indexes that deal with the effect of the trees on their surrounding environment that describe the heat exchanges of the trees are the index LAI (Leaf Area Index) and the index LAD (Leaf Area Density) (Chen & Ng 2012). The Leaf Area Index is defined as the one sited leaf area of the canopy per unit of horizontal ground area. Practically, the LAI quantifies the thickness of the vegetation cover. Each tree's LAI varies from one season to the other and also changes throughout the tree's growth (Fahmy et al. 2010). LAD is defined as the total leaves area in the unit volume of a tree's horizontal slices along the height of a tree. Practically, LAD describes the vertical leaves distribution (Fahmy et al. 2010). Certain studies suggest that the dispersion of green areas within the city can have a greater effect on the microclimate than the gathering of the greenery on one site only (Santamouris 2001).

**d) Surface Material Properties**

The cover material properties are defining factors of the urban fluxes. The most important material properties according to literature are the albedo value and the emissivity of the material. Albedo is the ratio of irradiance reflected and is measured by albedometers. Within an urban canyon albedo of the cover materials define the percentage of solar radiation that can be reflected.

High albedo materials reduce the urban "heat island" phenomenon because with the increased reflectivity the heat gain of the surfaces through solar radiation is reduced (Deb &

Ramachandraiah 2011; Gaitani et al. 2014; Taleghani, Sailor, et al. 2014; Taleghani, Tenpierik, et al. 2014). Additionally, it has been observed, that high albedo materials also reduce daytime and nocturnal thermal comfort, (Kariminia & Ahmad 2013; Kleerekoper et al. 2012; Taleghani et al. 2015). On the other hand, high albedo in all surfaces can cause glare problems in both the outdoor and the indoor environments. Existing studies (Yang et al. 2011) point that an increase of 0.4 in surface albedo lowers the air temperature at the pedestrian level by 0.2–0.5°C during the day and less than 0.2°C at night, and also the MRT increases by 8.0 to 14.8°C during the day and less than 4.8 °C at night. In order to study the effect of the different material albedo Müller (Müller et al. 2013) measured in detail the microclimate parameters of the white and black pavement. The white pavement surface temperature was measured 3.8°C cooler than its environment while the black pavement was measured 9.8°C warmer, in contrast with the low air temperatures regarding thermal comfort, the global temperature over the white pavement was 2°C higher than black pavement and mean radiant temperature was about 10°C higher in white than black pavement. Similar research studied, surfaces of granite, concrete and asphalt (Benrazavi et al. 2016) and measured that the highest surface temperatures in all the materials occurred in the afternoon with granite to be 15.5°C cooler than asphalt and 9.7°C cooler that concrete while at the same time the difference between surface and air temperatures was 12.8°C in granite, 22.5°C in concrete and 28.3°C in asphalt.

Cool coatings have superior thermal performance in comparison with natural cool materials like white marble mainly because of the differences in their spectral reflectance. Cool materials have developed low reflectivity, about 23% in the visible part of spectrum that can improve the glare problems and high reflectivity, about 85% in the near infrared (Fintikakis et al. 2011; Synnefa et al. 2006) Cool pavements are used for their high albedo values in order to reduce the urban heat island phenomenon in a variety of projects. Santamouris (Santamouris et al. 2015) refer several measurements in sites in the city of Athens that are rehabilitated using cool materials that point 2 °C decrease in the maximum temperature in Messolongiou street, 3.4 °C difference together with the use of greenery in Marousi, 1.9 °C reduction in the peak ambient temperatures in the coastal urban park of Floisvos and also reduction about 7-8 °C in the surface temperatures and about 1 °C in the ambient temperature when using cool materials in the building envelope. Carnielo & Zinzi, (2013) In their study concluded that due to the cool coatings there are sensible reductions of the peak cooling demand of the surrounding buildings that can reach 7.8% reduction for grey cool coating and 14.6% reduction for off-white cool coating in an insulated building.

Simulation research that is conducted on the island of Crete (Tsitoura et al. 2011) showed that the different material properties can have up to 15% effect on the thermal comfort index, meaning that the different surface temperatures can have impact on the thermal adaption of the user.

## 4. Tools for management of microclimate parameters

### 4.1. Bioclimatic design indices

The evaluation and comparison of the bioclimatic design is impossible without a way to quantify the microclimatic data. The different design scenarios need certain indices that combine material properties with microclimatic values in order to be compared and reviewed. Additionally, the outcomes of the bioclimatic design need to be quantified and evaluated. Until today the variety of studies regarding bioclimatic urban design use for comparison thermal indices values (PET, PMV) or microclimatic parameters values (air temperature, Mean Radiant Temperature). This study in order to proceed with the analysis and implement the methodology goals has created indices that combine area materials and their properties with microclimatic values and the comfort index UTCI. These bioclimatic indices are:

- $T_m$ Mean Maximum Air Temperature (℃)
- $T_{ms}$ Mean Maximum Surface Temperature (℃)
- $THA_m$ Mean Maximum UTCI (℃)
- $DH_T$ degree-hours of $T_a > 26$℃ (hours)
- $DH_{UTCI}$ degree-hours of $UTCI > 26$℃ (hours)

The first three indexes are related with the maximum values in certain points while the last two take into account the whole regeneration area. In the following paragraphs is analysed the calculation type for each one of them.

1) **Mean Maximum Air Temperature** $(\mathrm{T_m})$

For the calculation of the $\mathrm{T_m}$ index, the area is divided into different zones according to area's use characteristics. Then each zone is divided into subareas based on the different coating materials. The regional mean maximum air temperature of each subarea is calculated by using the maximum air temperature value at height of 1.6m of the specific coating material, taking into account the simulation results for the hours between 9:00 to 19:00. Afterwards, the $\mathrm{T_m}$ of the total area, is calculated from the geometric mean of all maximum air temperatures of the different zones, according to the following equation:

$$T_m = \left(\prod_{i=0}^{z} T_{mm(i)}\right)^{1/z}$$

( 1 )

where:

- z is the number of different zones;
- $T_{mm}$ is the mean maximum air temperature of each zone, and can be expressed as:

$$T_{mm} = \frac{1}{E}\sum_{i=0}^{n} E_{m(i)}\, T_{mx(i)}$$

where:

- n is the number of surfaces with different coating materials within a zone;
- $E_m$ is the area of a single coating material within a zone;
- $T_{mx}$ is the maximum air temperature of coating material within a zone;
- $E$ is the total area of a zone and can be expressed as:

$$E = \sum_{i=0}^{n} E_{m(i)}$$

2) **Mean Maximum Surface Temperature** ($T_{ms}$)

For the calculation of the $T_{ms}$ index, the total area is divided into different zones according to area's use characteristics. Then each zone is divided into subareas based on the different coating materials. The regional mean maximum surface temperature of each subarea is calculated by using the maximum surface temperature value of the specific coating material, taking into account the simulation results for the hours between 9:00 to 19:00. Afterwards, the $T_{ms}$ of the total area, is calculated from the geometric mean of all maximum surface air temperatures of the different zones, according to the following equation:

$$T_{ms} = \left(\prod_{i=0}^{z} T_{mms(i)}\right)^{1/z}$$

( 2 )

where:

- z is the number of different zones;
- $T_{mms}$ is the mean maximum surface air temperature of each zone, and can be expressed as:

$$T_{mms} = \frac{1}{E}\sum_{i=0}^{n} E_{m(i)}\, T_{mxs(i)}$$

where:

- n is the number of surfaces with different coating materials within a zone;
- $E_m$ is the area of a single coating material within a zone;
- $T_{mxs}$ is the maximum surface air temperature of a coating material within a zone;
- $E$ is the total area of a zone and can be expressed as:

$$E = \sum_{i=0}^{n} E_{m(i)}$$

3) **Mean Maximum UTCI** ($THA$)

For the calculation of the $THA$ index, the total area is divided into different zones according to area's use characteristics. Then each zone was divided into subareas based on the different coating materials. The regional $THA_m$ of each subarea was calculated by using the maximum UTCI value at height of 1.6 m of the specific coating material, taking into account the simulation results for the hours between 9:00 to 19:00. Afterwards, the $THA$ of the total area, is calculated from the geometric mean of all the maximum UTCI values of the different zones, according to the following equation:

$$THA = \left(\prod_{i=0}^{z} THA_{m(i)}\right)^{1/z} \tag{3}$$

where:

- z is the number of different zones;
- $THA_m$ is the mean maximum value of UTCI index of each zone, and can be expressed as:

$$THA_m = \frac{1}{E}\sum_{i=0}^{n} E_{m(i)}\, THA_{mx(i)}$$

where:

- n is the number of surfaces with different coating materials within a zone;
- $E_m$ is the area of a single coating material within a zone;
- $THA_{mx}$ is the maximum value of UTCI index of a coating material within a zone;
- $E$ is the total area of a zone and can be expressed as:

$$E = \sum_{i=0}^{n} E_{m(i)}$$

4) **Degree-hours of $T_a > 26$°C ($DH_T$)**

Because the maximum temperatures cannot fully describe the microclimate conditions since they are also dependent on the time, the study used the index of the degree-hours where $T_a$ exceeded 26°C. This index can describe the duration of extreme heat conditions, to evaluate better the proposed design. For the calculation of the $DH_T$ index, the total area is divided into different zones according to area's use characteristics. Then each zone is divided into subareas based on the different coating materials. The degree-hours of $T_a > 26$°C of each subarea are calculated by using the $T_a$ value of the specific coating material, taking into account the simulation results for the hours between 9:00 to 19:00. Afterwards, the $DH_T$ of the total area is calculated from the geometric mean of all $DH_T > 26$°C values of the different zones, according to the following equation:

$$DH_T = \left(\prod_{i=0}^{z} DH_{Tm(i)}\right)^{1/z} \qquad (4)$$

where:

- z is the number of different zones;
- $DH_{Tm}$ is the degree-hours of $DH_T$ index of each zone, and can be expressed as:

$$DH_{Tm} = \frac{1}{E}\sum_{i=0}^{n} E_{m(i)}\, L_{(i)}$$

where:

- n is the number of surfaces with different coating materials within a zone;
- $E_m$ is the area of a single coating material within a zone;
- $L$ can be expressed as:

$$L = \sum_{i=0}^{10} \left(T_{mm(i)} - 26\right) \ \forall \, T_{mm(i)} - 26 > 0$$

- and, $E$ is the total area of a zone and can be expressed as:

$$E = \sum_{i=0}^{n} E_{m(i)}$$

5) **Degree-hours of $\boldsymbol{UTCI} > \mathbf{26}$°C ($DH_{UTCI}$)**

This index can describe the duration of the user comfort conditions of an area. According to the index comfort scale, UTCI values over 26°C are equal to thermal discomfort since the thermal comfort boundaries of the UTCI are between 22 and 26°C.

For the calculation of the $DH_{UTCI}$ index in each case, the total area was divided into different zones according to area's use characteristics. Then each zone was divided into subareas based on the different coating materials. The degree-hours of $UTCI > 26$°C of each subarea were calculated by using the maximum $UTCI$ value of the specific coating material, taking into account the simulation results for the hours between 9:00 to 19:00. Afterwards, the $DH_{UTCI}$ of the total area was calculated from the geometric mean of all $DH_{UTCI} >$ 26°C values of the different zones, according to the following equation:

$$DH_{UTCI} = \left( \prod_{i=0}^{z} DH_{UTCIm(i)} \right)^{1/z} \qquad (5)$$

where:

- z is the number of different zones;
- $DH_{UTCIm}$ is the degree-hours of $DH_{UTCI}$ index of each zone, and can be expressed as:

$$DH_{UTCIm} = \frac{1}{E}\sum_{i=0}^{n} E_{m(i)}\, L_{(i)}$$

where:

- n is the number of surfaces with different coating materials within a zone;
- $E_m$ is the area of a single coating material within a zone;
- $L$ can be expressed as:

$$L = \sum_{t=0}^{10} (THA_t - 26) \ \forall\, THA_t - 26 > 0$$

- $THA_t$ is the UTCI index of each coating material for each hour;
- and, $E$ is the total area of a zone and can be expressed as:

$$E = \sum_{i=0}^{n} E_{m(i)}$$

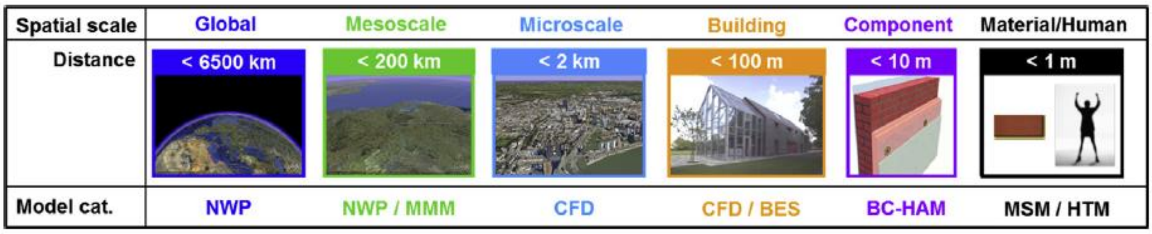
### 4.2. Microclimate models

Previous chapters have pointed out that during the design phase of the urban realm, it is important to implement a certain methodology that takes into account environmental design parameters. The most common way of exploring the urban environment and quantitate the microclimate parameters for minimizing the UHI phenomenon during the design phase is by simulating the proposed design using the microclimatic data of the area. Microclimatic models can give the opportunity, for the urban designer, to explore several design scenarios, to calculate and compare environmental indices, in order to predict the future environmental conditions after the implementation of the proposed design avoiding unforeseen mistakes.

Furthermore, in order for a model to provide the adequate information needed for the calculation of bioclimatic indexes, it should take into account all the energy fluxes that take place within urban canyons. More specifically the model should include information about:

- **Building geometry and placement**: The necessary information must include the city planning design, orientation and building certain architectural elements like shades or special facades.
- **Material properties:** The necessary information includes certain material properties for both ground surfaces and buildings facades. For accurate simulation results, additional information like material properties of the layers below ground surface or indoor temperatures that affect outdoor air temperatures should be added.
- **Weather data:** The primary goal of the simulation process is to track the microclimatic behaviour of real climatic conditions both in winter and summer with high accuracy. The input data of specific local weather parameters is determinant for good results.

All this information varies in the level of detail according to the preferred scale of the simulation models. The simulation scale is the initial selection depending on the requirements of the design project. This decision will define the model's input and output details. Blocken in his research in urban physics computational fluid dynamics, mentions six different scales of urban simulation that is shown in Picture 9 (Blocken 2015). For example, a proposal of a new city planning design should be implemented into meso- or micro- scale simulation analysis and should contain information such as shell geometry of surrounding buildings, material properties of facades and outdoor ground surfaces, and greenery. (Toparlar et al. 2017).




Picture 9: Different scales of urban simulation (Blocken 2015).

For simulating the urban environment, a variety of tools have been designed each one of them can be addressed in different design scales. The urban simulation tools are categorised based on the available computational methods. There are simplified simulation tools in which the results are provided using numerical approximations of the differential equations. On the other hand, there are simulation tools that support computational methods solving thermodynamic differential equations at different heights and points within the urban grid. Picture 10 is shown the most used simulation tools, as were reviewed by Allegrini et al. (2015). Each one of these simulation tools has different requirements regarding the level of detail of the input data. Obviously, as the level of detail increases, the simulation results tend to be more accurate. For example, some of these tools neglect vegetation latent heat flux or building properties.

Regarding the literature research that has been conducted, in order for a simulation tool to accurately predict microclimate parameters, it should include the following calculations:

- Radiation environment for both shortwave and longwave radiation. Usually, it is calculated in relation with geometry divided as direct, diffuse, and longwave radiation;
- Wind speed and convective heat transfer through flow models for adequate calculation results, computational fluid dynamics simulations are needed;
- Building surface temperatures;
- Anthropogenic heat sources like traffic, land-use, noise etc.

| Key | |
|---|---|
| X | Not included |
| L | Link to other program |
| S | Simplified model |
| D | Detailed model |

| | External air flow | SW radiation | LW radiation | Building thermal | User behaviour | Building system | Thermal network | Electrical network | Gas network | District plant | Thermal storage | Wind power | Photovoltaics | Ground source | Spatial | Transportation | Embodied energy | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CitySim | X[1] | D[2] | D | S | D | S | S | X | X | X | S[3] | S[4] | S | S[4] | D | X | X | City energy simulation for groups of buildings / city quarters. | [13] | citysim.epfl.ch |
| EnergyPlus | S | D | S[4] | D | D | D | S | X | X | S | S | S | S | D | S[5] | X | X | Detailed building simulation, limited interactions. | [125] | eere.energy.gov/buildings/energyplus |
| ESP-r | S | D | S | D | D | D | S | D[6] | X | S | D[7] | S | S | S | S | X | X | Detailed building simulation, thermal and elec networks possible. | [127] | esru.strath.ac.uk/Programs/ESP-r.htm |
| IDA ICE | S | D | S | D | D | D | D[8] | X | X | S | S | X | S | D | S | X | X | Detailed building simulation, thermal networks possible. | [129] | equa.se |
| Polysun | X[9] | D | S | S[10] | D | D | D | S | X | S | D | X | D | D | X | X | X | Detailed solar thermal and hydraulic systems. | [130] | velasolaris.com/english/home.html |
| TRNSYS | L | D | D | D | D | D | D | S | X | D | D | D | D | D | X | X | X | Detailed simulation tool for systems and single buildings. | [131] | trnsys.com |
| Envi-met | S | S | S | S | X | X | X | X | X | X | X | X | X | X | S | X | X | Microclimate model. | [132] | envi-met.com |
| KULeuven IDEAS lib | S | D | D | D | D[11] | D | S | D | X | S | S | X | D[12] | D[13] | X | X | X | District-level Modelica library. | [40] | github.com/open-ideas |
| LBNL District lib | S | D | D | D | S | D | S | D | X | S | S | S | D | D[14] | X | X | X | District (and building) Modelica libraries. | [133] | github.com/lbl-srg |
| energyPRO | X | X | X | L | X | D | D | D | X | D | D | D | D | S | S[15] | X | X | Techno-economic simulation of energy systems. | [134] | energypro.org |
| RETScreen | X | X | X | S | X | S | S | X | X | S | S | S | S | S | X | X | X | Energy, life cycle cost, emissions, finance and risk analysis. | [135] | retscreen.net |
| HOMER | X | X | X | L[16] | X | X | X | X[17] | X | S | X | D | D | X | X | X | X | Microgrid design optimisation. | [136] | homerenergy.com |
| Termis | X | X | X | L | X | X | D | X | X | S | S | X | X | X | L | X | X | Operate, simulate & optimise district heating networks. | | schneider-electric.com |
| Neplan | X | X | X | L | X | X | D | D | D | S | X | D | S | X | L[18] | X | X | Simulate & optimise electrical, water, gas and heating networks. | [137] | neplan.ch |
| NetSim | X | X | X | L | X | X | D | X | X | D | X | X | X | X | L[19] | X | X | District heating, cooling and steam simulation environment. | [138] | vitecsoftware.com/en/Energy/ |
| EnerGis | X | X | X | S | X | S | S[20] | X | X | S | X | X | S | S | D | X | X | GIS-based urban energy and district heat network design tool. | [139] | |
| SynCity | X | X | X | S | D | S[21] | S | S | S | S | D | S | S | S | D[22] | D | X | Integrated tool for holistic urban energy systems modelling [23]. | [140] | imperial.ac.uk/urbanenergysystems |
| EPIC-HUB | X | X | X | L | X | S | S | S | S | S | X | L | L | X | S | X | X | Middleware platform for multi-carrier infrastructure systems. | | epichub.eu |
| MEU | X | L | L | L[24] | S | S | S | S | X | S | X | X | S | X | D | X | X | Energy management tool for cities and multi-energy utilities. | [141] | meu.epfl.ch |
| UMI | X | L[25] | L | L | X | X | X | X | X | X | X | X | L | X | D[26] | D[27] | S | Rhino-based link to Radiance and EnergyPlus. | [142] | urbanmodeling.net |
| Radiance | X | D | D | X | X | X | X | X | X | X | X | X | D | X | D | X | X | Powerful ray-tracing program. | [143] | radsite.lbl.gov |
| Solene | L | D[28] | D | S | S | X | X | X | X | X | X | X | X | X | D | X | X | Energy simulation for city quarters. | [144] | cerma.archi.fr |
| Fluent | D | D | D | X | X | X | X | X | X | X | X | X | X | X | X | X | X | CFD software. | | ansys.com |
| OpenFOAM | D | X | D[29] | X | X | X | X | X | X | X | X | X | X | X | X | X | X | Extensible CFD software. | | openfoam.com |

Picture 10: Detailed comparison of simulation tools (Allegrini et al. 2015).

### 4.3. The software ENVI-met

The study in the proposed methodology and in the evaluation of the case-specific scenarios uses the software ENVI-met for microclimate simulations and calculations of the bioclimatic indices (Bruse & Fleer 1998; Ozkeresteci et al. 2003; Bruse 2004; Samaali et al. 2007).

ENVI-met is well documented and widely used tool for simulating urban climatology. It is simple, and it does not need more than the necessary parametrization components to describe the urban microclimate, while at the same time includes a variety of modules for validating and reporting the obtained results. It has been widely used in studies for:

- Pedestrian thermal comfort (Ali-Toudert & Mayer 2006)
- Managing air quality (Vos et al. 2013)
- UHI mitigation (Emmanuel & Johansson 2006; Müller et al. 2013; O'Malley et al. 2015)
- Urban planning (Chen & Wong 2006; Bowler et al. 2010; Vos et al. 2013)

ENVI-met is "a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in an urban environment with a typical resolution down to 0.5m in space and 1-5 sec in time" (Bruse & Fleer 1998). The tool is created and updated by Bruse while the last update is the version 4.3.0 (Huttner & Bruse 2009). The atmospheric solver of ENVI-met includes a full 3D Computational Fluid Dynamics (CFD) numerical analysis which solves the Reynolds-Averaged non-hydrostatic Navier-Stokes (RANS) equations for each point of the grid in 3D space and for each timestep. The used grid for representation is an orthogonal Arakawa C-grid, the calculations for curvy surfaces is approximated by grid points. The turbulence in the air is calculated using the so-called 2-equation Turbulence Kinetic Energy (TKE).

Additionally, ENVI-met contains newly developed analysis modules to model the fluxes of shortwave and longwave radiation inside of complex environments. The scheme takes into account shading by complex geometries, reflections by different surfaces and building materials and the effect of vegetation on all radiative fluxes.

The tool also includes a database with predefined sets of materials and plants. There are ready to use construction elements as layers of materials for the urban ground surfaces and building facades. The tool provides a Graphical User Interface (GUI) for exploring, modifying and creating new materials and construction elements. Similarly, the tool provides a GUI for modifying or creating new greenery elements. The user can modify the layer thickness and the material row and alter any property (Picture 11). Additionally, the Albero addon allows the full representation of the plants, their properties and provides a GUI for modifying the default parameters. (Picture 12).

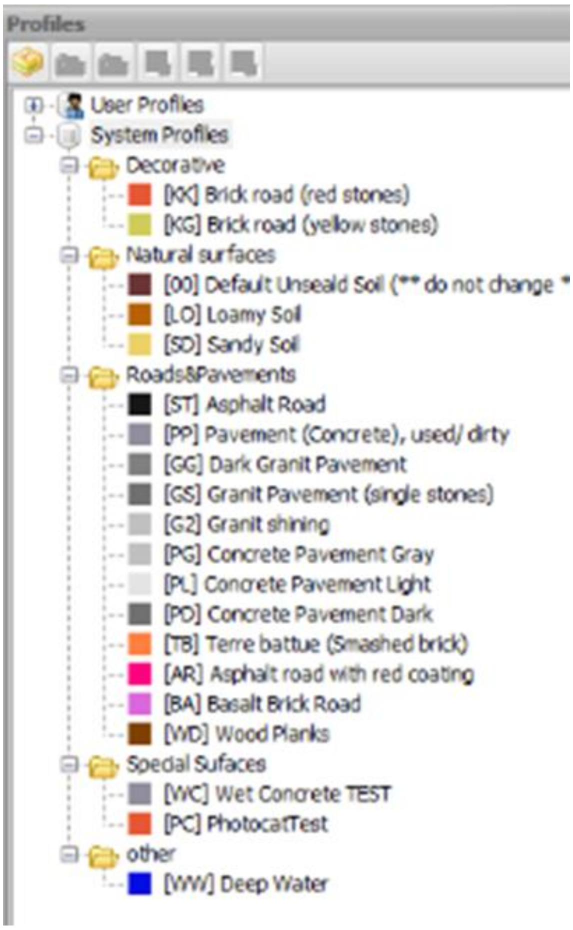



Figure 14: ENVI-met soil profiles.

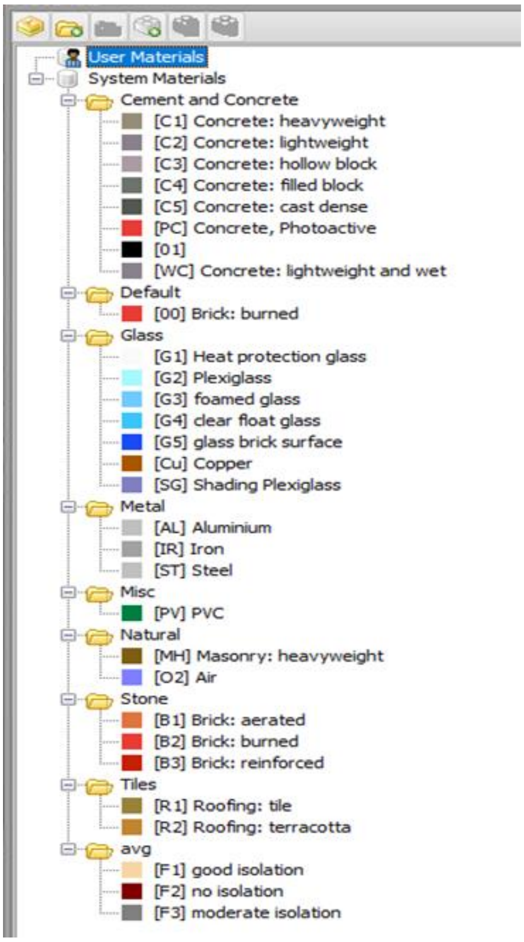
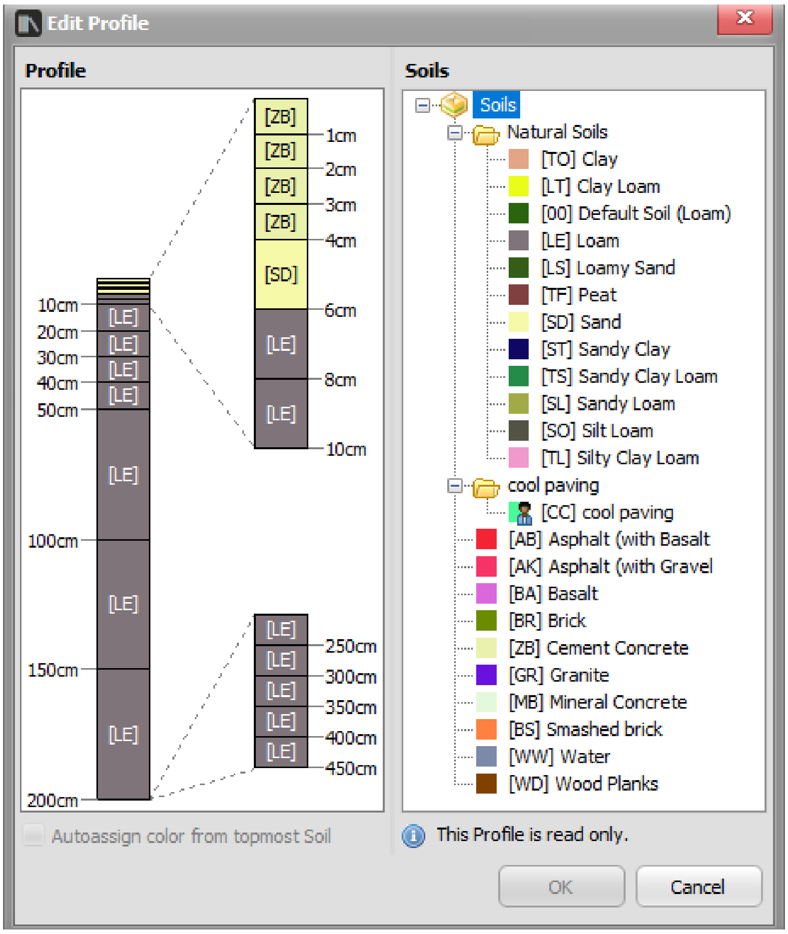
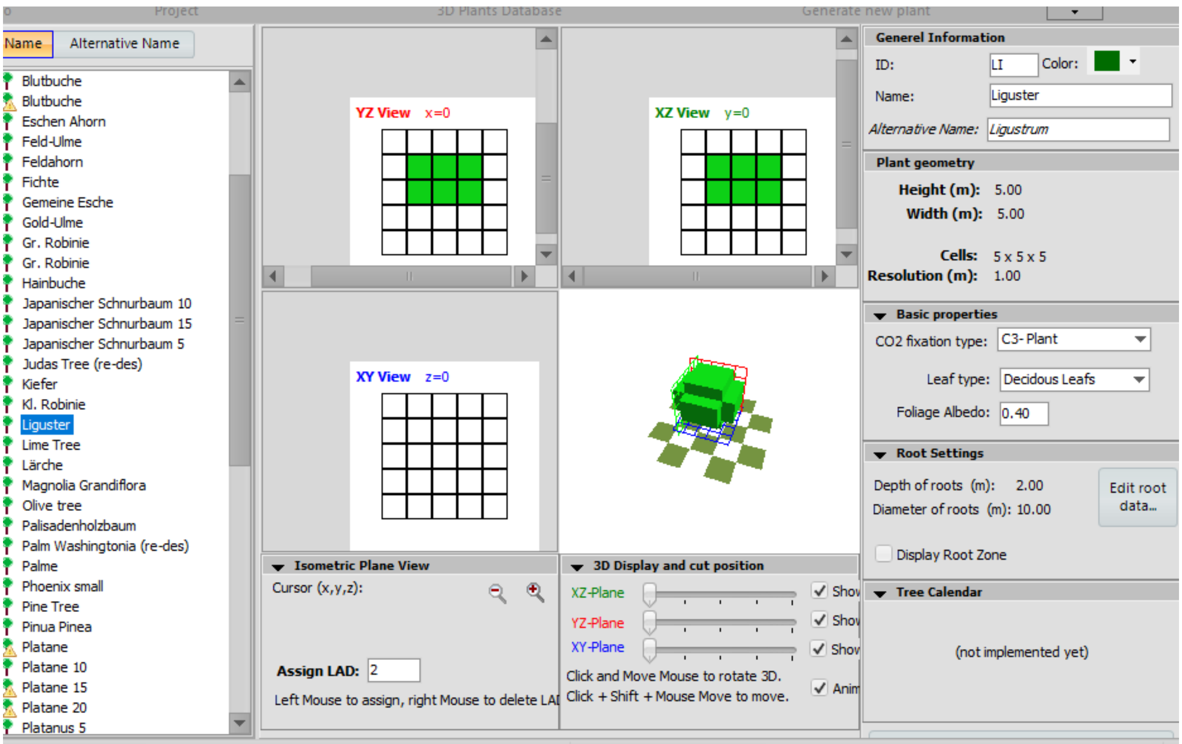



Figure 15: ENVI-met materials.




Picture 11: ENVI-met Soil profile layering.




Picture 12: Albero addon layout.

### 4.4. Validation and sensitivity analysis of the software ENVI-met

The selected software is widely used by such studies and is validated in a variety of different climates (Gusson & Duarte 2016; Jeong et al. n.d.; Elnabawi et al. 2013; Salata et al. 2016).The AIAA defines validation as *"The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model"* (AIAA 1998). In this study, the validation of ENVI-met in the Mediterranean climate is performed using on-site microclimatic measurements in the center of the Rethymnon city, where the location is classified as hot-summer Mediterranean zone ($C_{sa}$).

The microclimatic weather data are measured with the use of three weather stations that were installed at certain points within the selected area, at the height of 3.00m. Table 8 shows the sensors that were installed at every measurement point (Figure 16). The microclimatic simulations were made with the use of the software ENVI-met 4, consisted of an area of 250m x250m with a grid of 0.5m where all the material properties, the urban geometry and the green areas with the exact tree species are added. The software can extract time series data for every microclimatic parameter needed at any point of the area.

Figure 17 shows the measured and simulated temperatures from all measuring points, while Figure 18 shows the mean values of all the measurement points compared with the mean values of the simulation points for three continuous days of observation. The comparison of the simulated and measured values can ensure that the model is sufficiently calibrated, and it can be used for implementing further design scenarios in this area. As shown in Figure 17 and Figure 18 the measured and simulated values have very small differences that are below 1$^{o}$C.

Table 8: Weather station sensors specifications.

| Sensor Type | Accuracy | Range |
|---|---|---|
| **Temperature Sensor** | 0.1 | -20 to 80°C |
| **Humidity Sensor** | 2% | 0 to 100% |
| **Anemometer** | 0.1m/s | 0 - 30m/s |
| **CO2 Sensor** | ± (50ppm + 5% reading) | 0 to 5’000ppm |
| **Pyranometer Sensor** | 5 to 20 µV/W/m² | 0 to 2,000 W/m² |

Figure 16: Weather Stations placed in Rethymnon city.

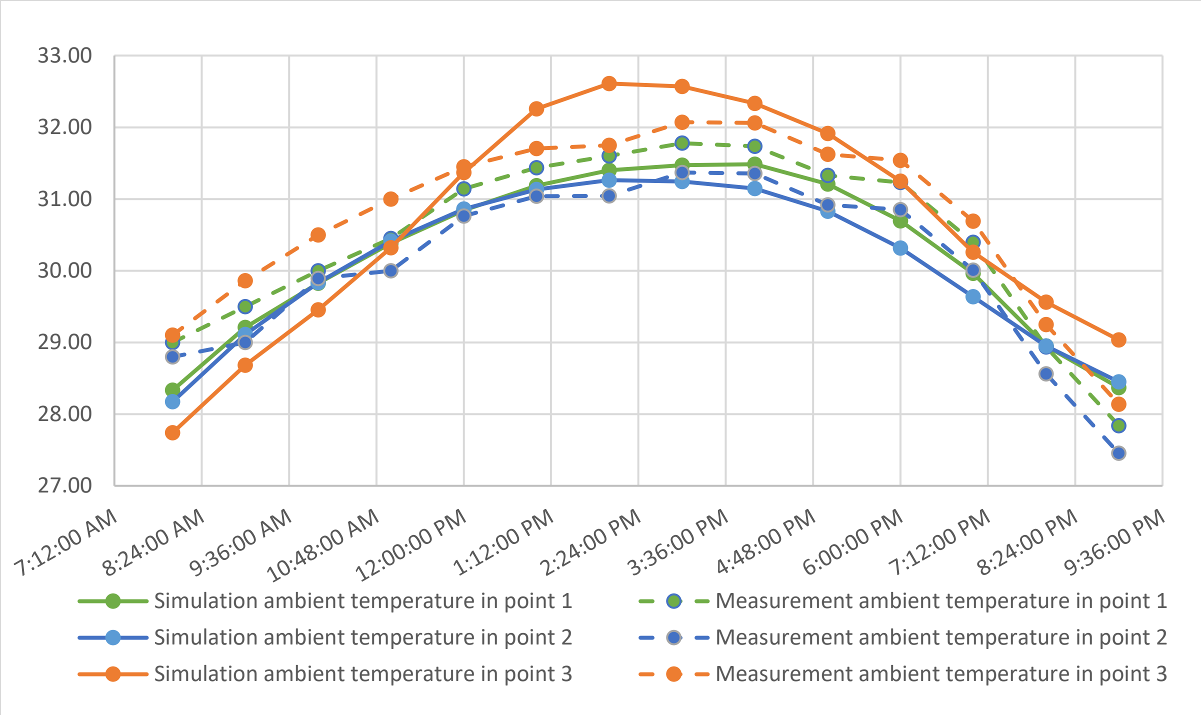



Figure 17: Validation of ambient temperature measured and simulated from 3 measurement points.

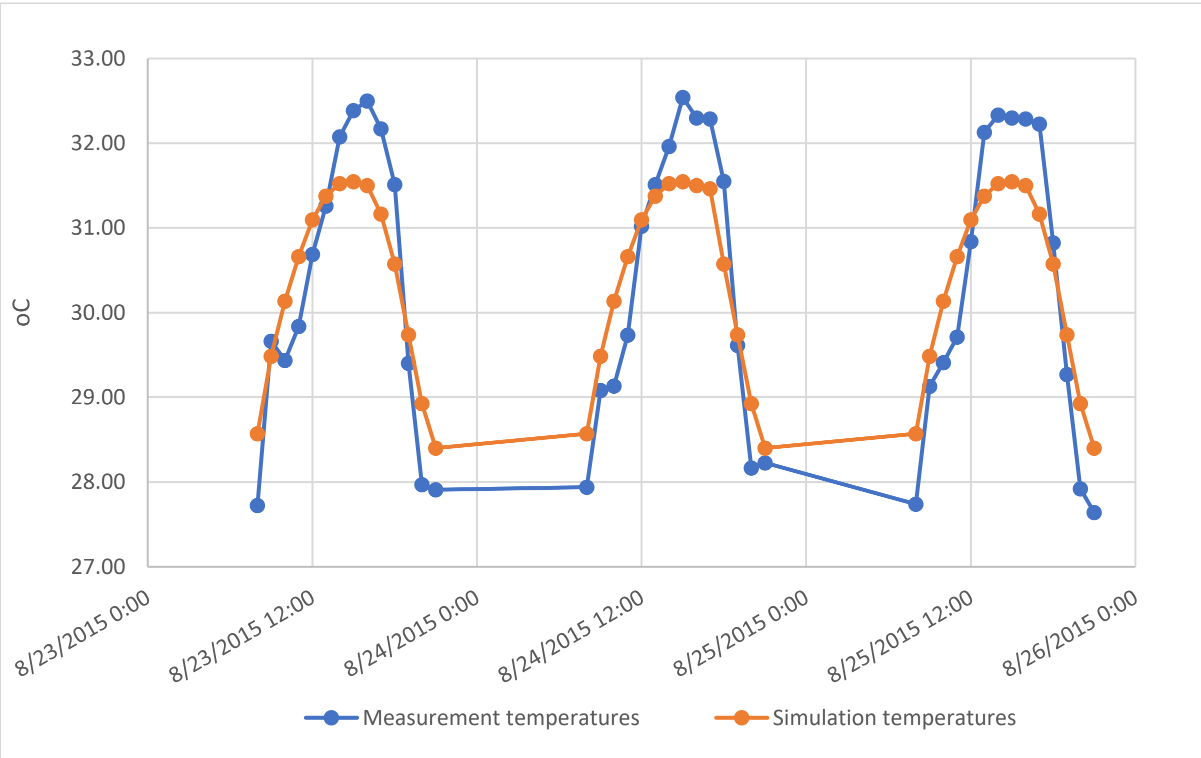



Figure 18: Validation of ambient temperature measured and simulated.

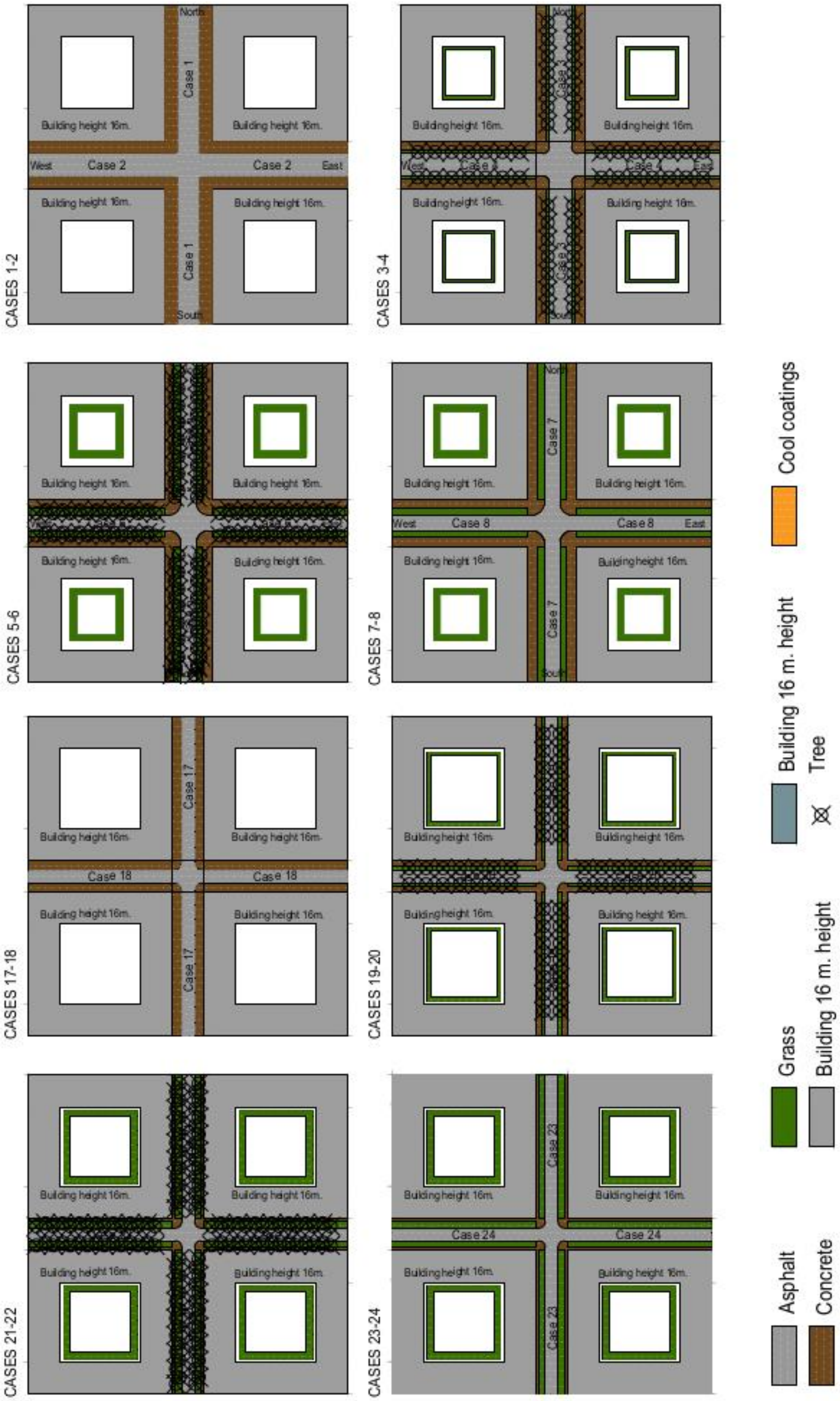
To calibrate the model and to qualify the effect of crucial parameters such as vegetation type and coverage, ground surface materials, building façade materials and user comfort, parametric simulation and sensitivity analysis have been conducted. The analysis includes several simulation scenarios with the software ENVI-met 4 (Table 9). The weather data included in the weather file that is used from the tool, are based on real measurements and represent the weather conditions of a typical summer day of Rethymnon city. Each scenario varied only by one parameter per time regarding vegetation and the material properties in two hypothetical urban configurations that include: a) classic urban canyon with two open sides like roads; and b) other empty areas between the roads representing squares or parks. These hypothetical configurations were defined by an area of 100m x 100m. surface with a grid size of 0.5m. for the simulations. The sensitivity analysis included three different width canyons (10, 15 and 60m) and two different building heights (8 and 16m) and also six different Height to Width ratios in four different orientations (Picture 13-Picture 20). Picture 13-20 show all the cases that are simulated for the sensitivity analysis as described above.

All the different geometries were studied in the case of no greenery at all and for the cases of 25% or 45 % of the simulated space covered by trees, and 25% or 45 % covered by grass. Figure 19 shows the detailed analysis where all the index results for the different greenery percentages and H/W ratios are presented. The best-case scenario is calculated as covered by 70 % with trees because the legislation demands at least 3.5m of the road which covers 30% of the area. Figure 19 shows that for all the indices the results change less than 10% of the increase in the greenery percentage above 45 %. Also, in the study, seven different albedo values that were calculated for the different selected paving material combining asphalt, concrete pavement, cool coatings, earth and grass were used. Table 9 shows all the different cases characteristics. All the cases were simulated with the same grid size and the same meteorological parameters which are shown in Table 9. Wind value is the lowest possible for the program to run the simulation, as the wind parameter is excluded from the analysis because of its benefiting effect both on temperatures and comfort. The results are guidelines for sustainable design and can be used comparingly based on the worst-case scenario. In this way, all cases were compared to the same terms and the output results can indicate the differences between the selected indices in each case for comparison purposes.

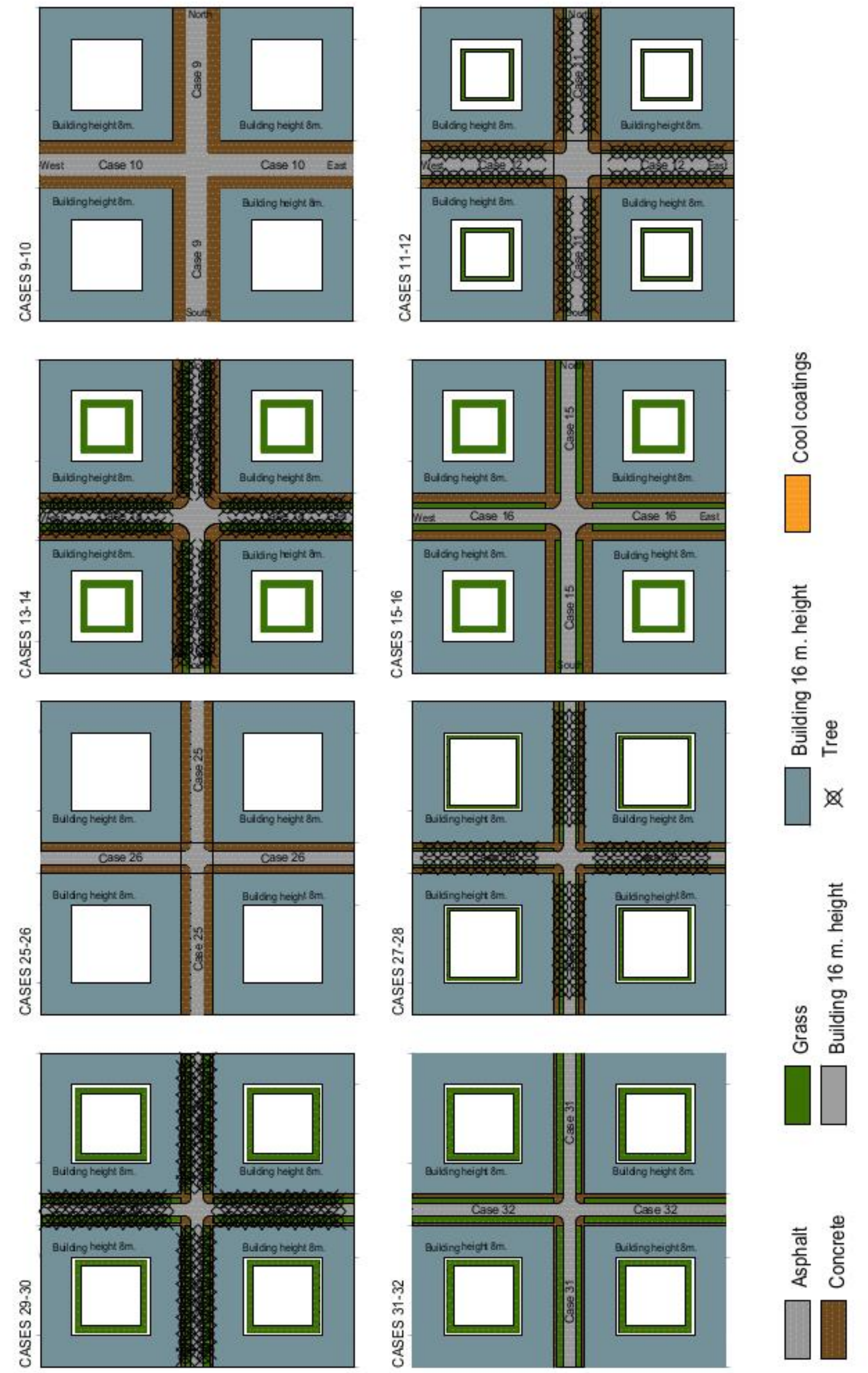
The sensitivity analysis used the simulation results to define each parameter influence and scale for the upcoming parametric analysis. In this way, a series of cases was excluded for not having measurable change on the desired parameter and the list of selected cases that will be included in the designed tool is finalized for further research.

Table 9: Parametric simulation cases.

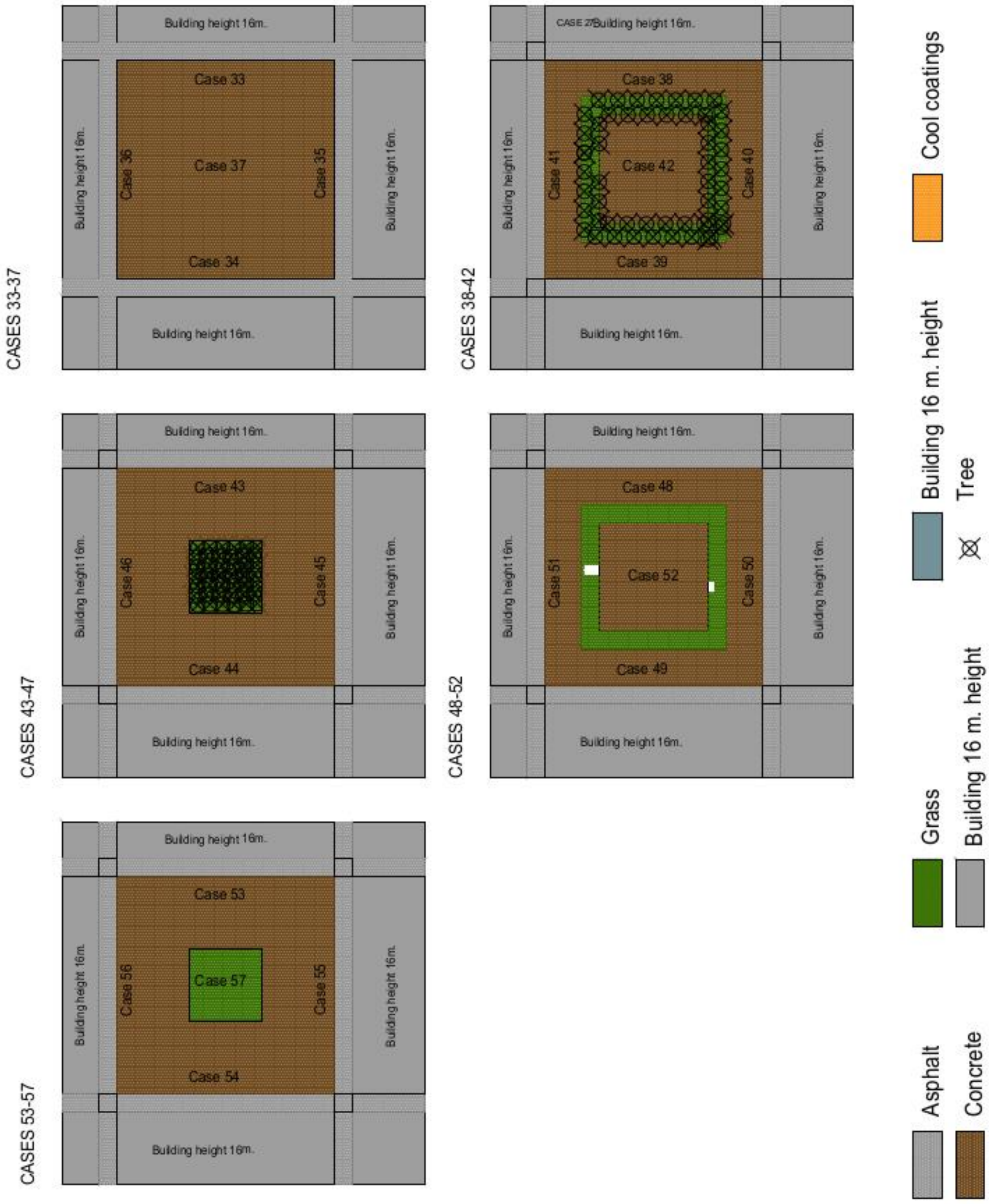
| | |
|---|---|
| **Total number of cases** | **164** |
| **Number of open sides** | 0 2 |
| **Canyon width (m)** | 10 15 60 |
| **Building height(m)** | 8 16 |
| **Height/Width** | 0.27 0.53 1.07 1.60 |
| **Material Mean Albedo** | 0.15 0.16 0.19 0.21 0.23 0.25 |
| **SVF** | 0.00 0.01 0.02 0.03 0.06 0.09 0.10<br>0.13 0.15 0.19 0.27 0.30 0.33 0.35<br>0.40 0.41 0.45 0.57 0.65 0.70 0.83 |
| **Percentage of trees (%)** | 0 25 45 |
| **Percentage of grass (%)** | 0 25 45 |
| **Placement of trees/grass** | center sides |
| **Orientation** | North South East West |



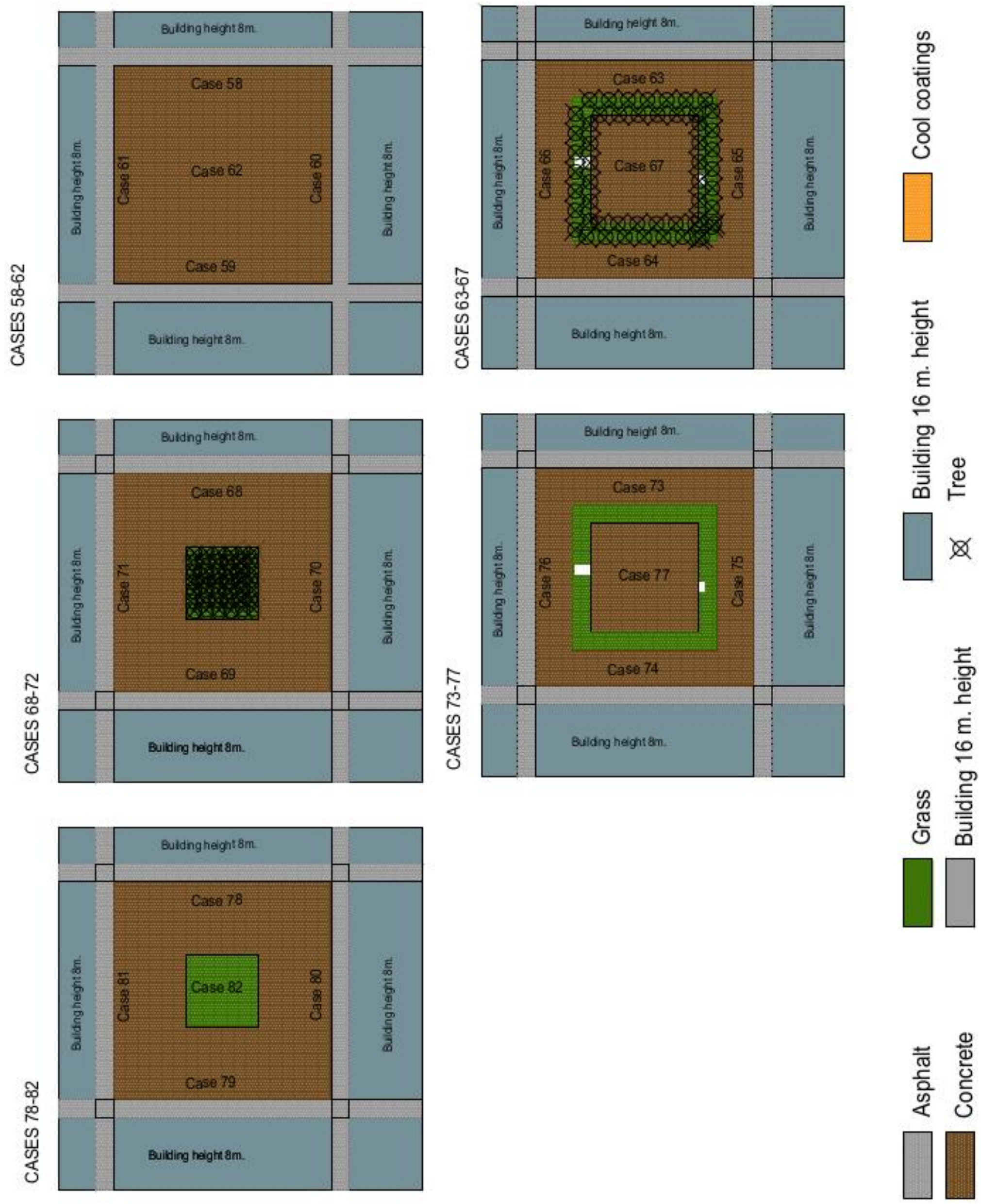

Picture 13: Sensitivity analysis cases 1-8 & 17-24.



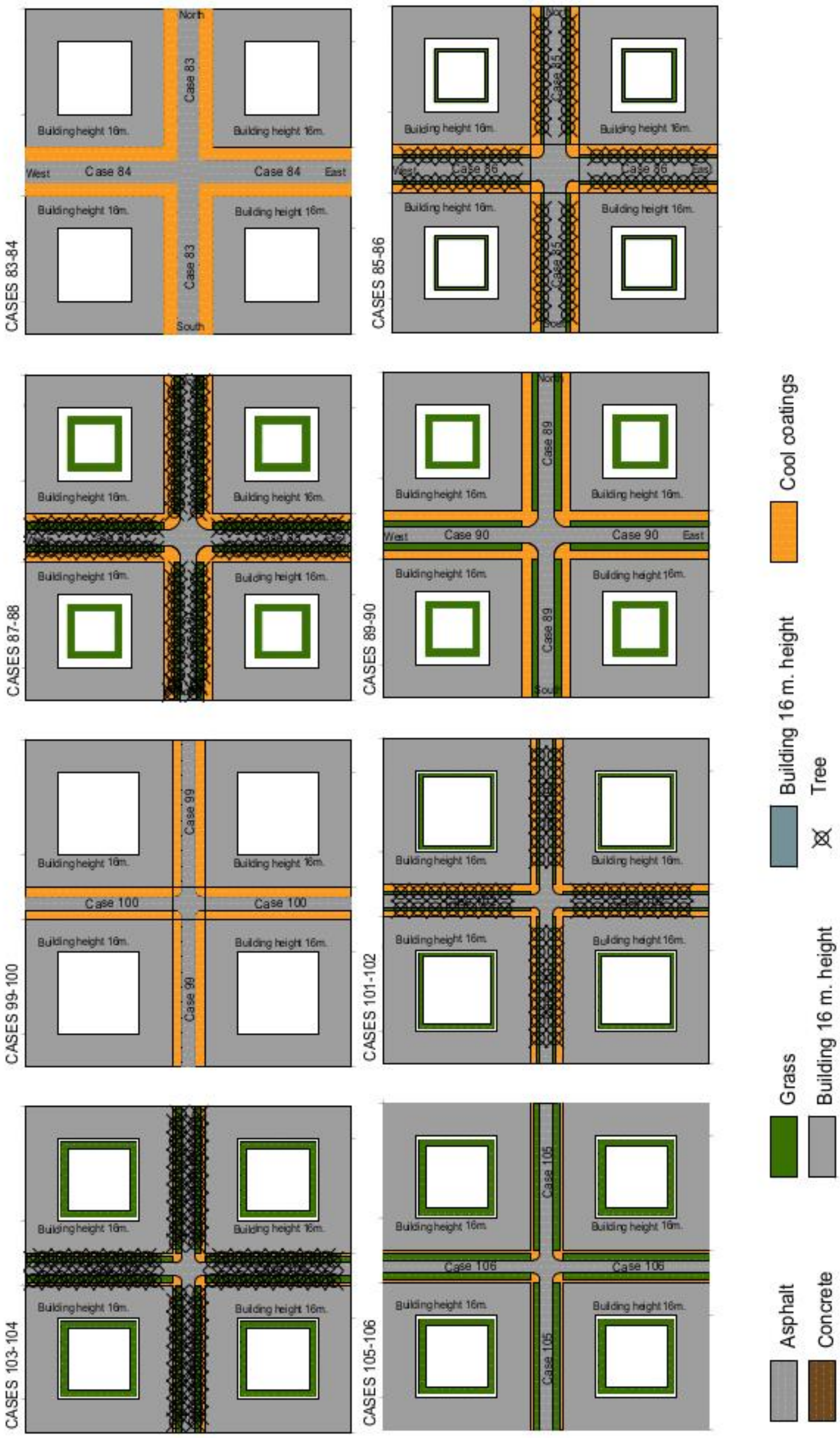

Picture 14: Sensitivity analysis cases 9-16 & 25-32.



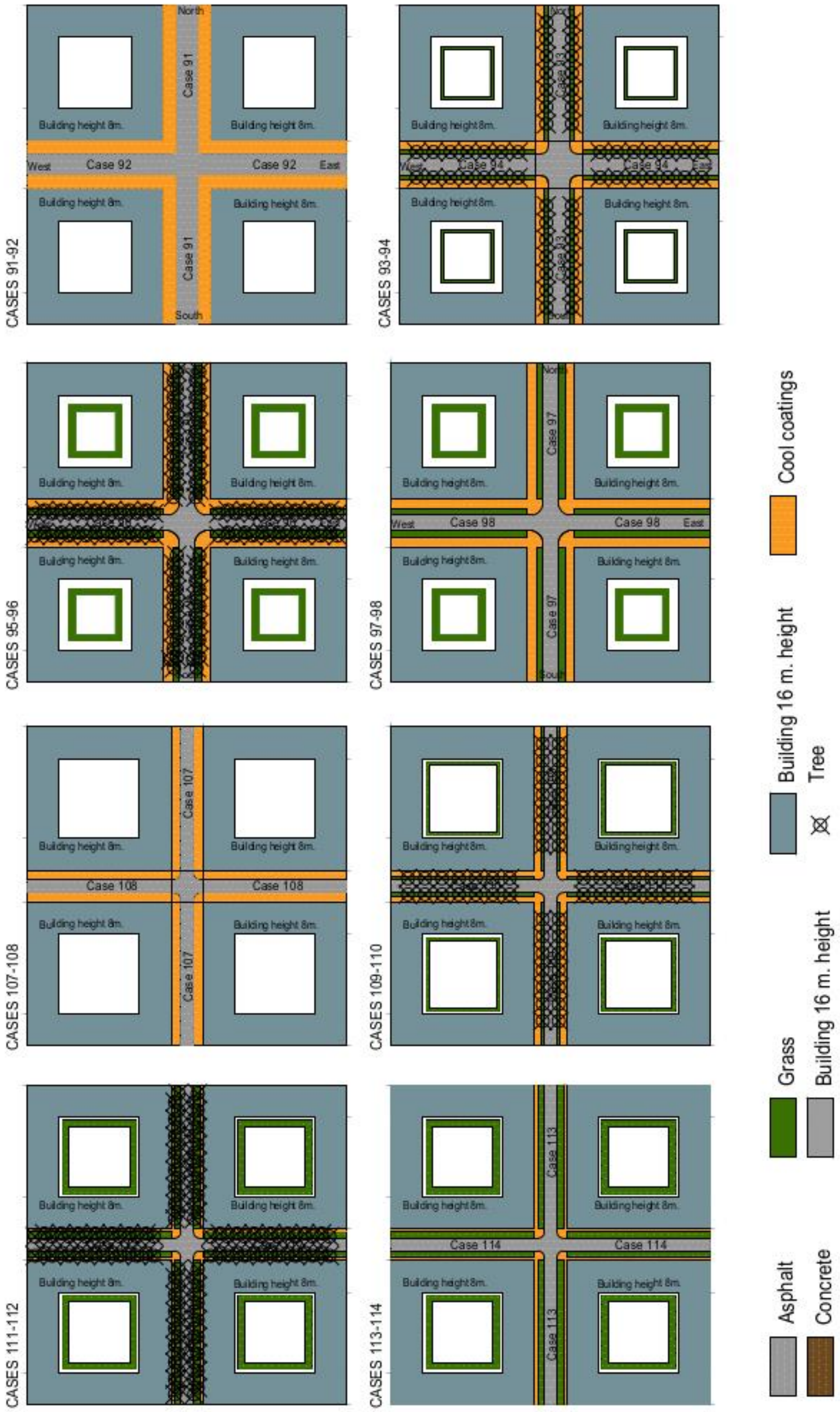

Picture 15: Sensitivity analysis cases 33-37, 38-42, 43-47, 53-57, 48-52.



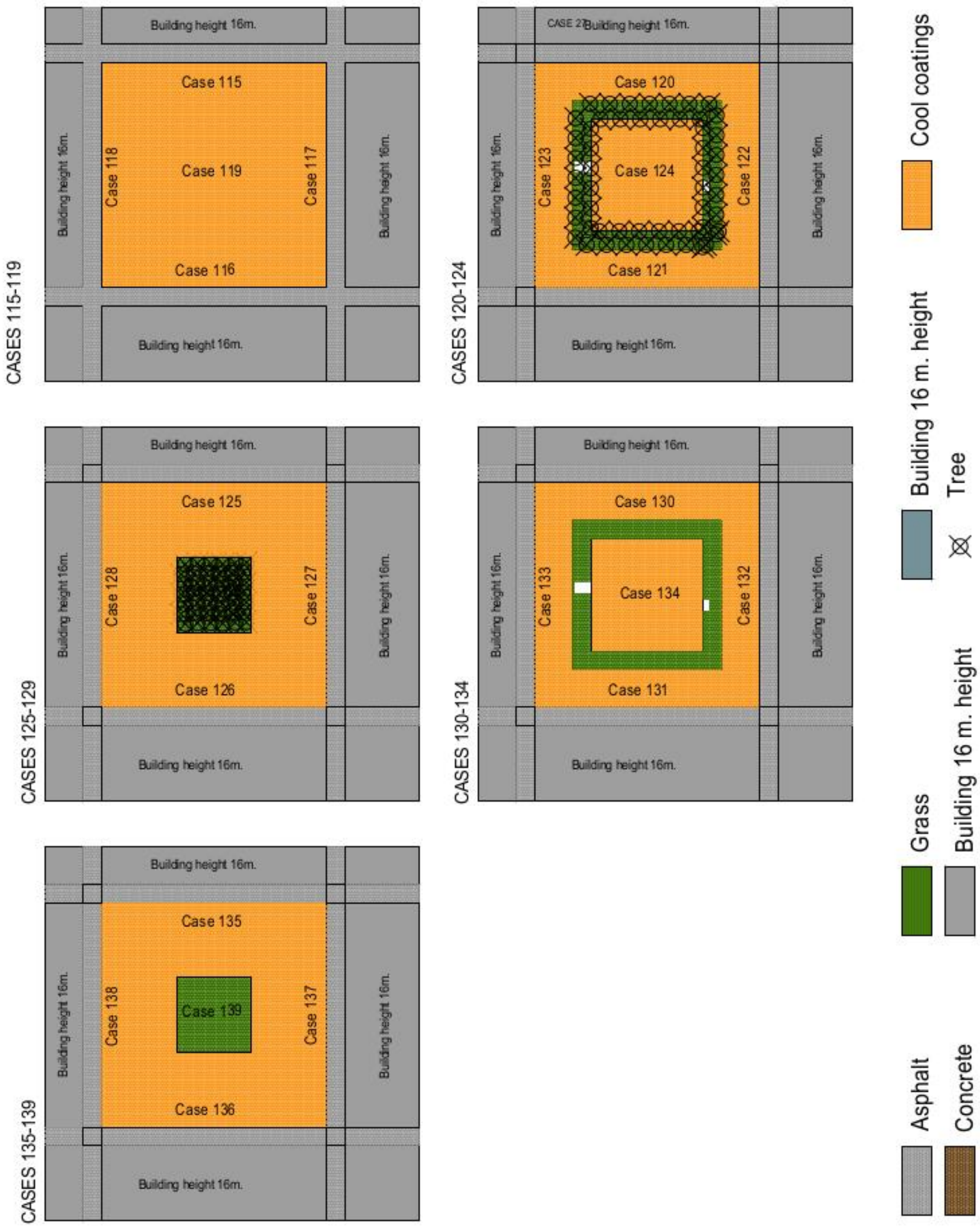

Picture 16: Sensitivity analysis cases 158-62, 63-67, 68-72, 78-82.



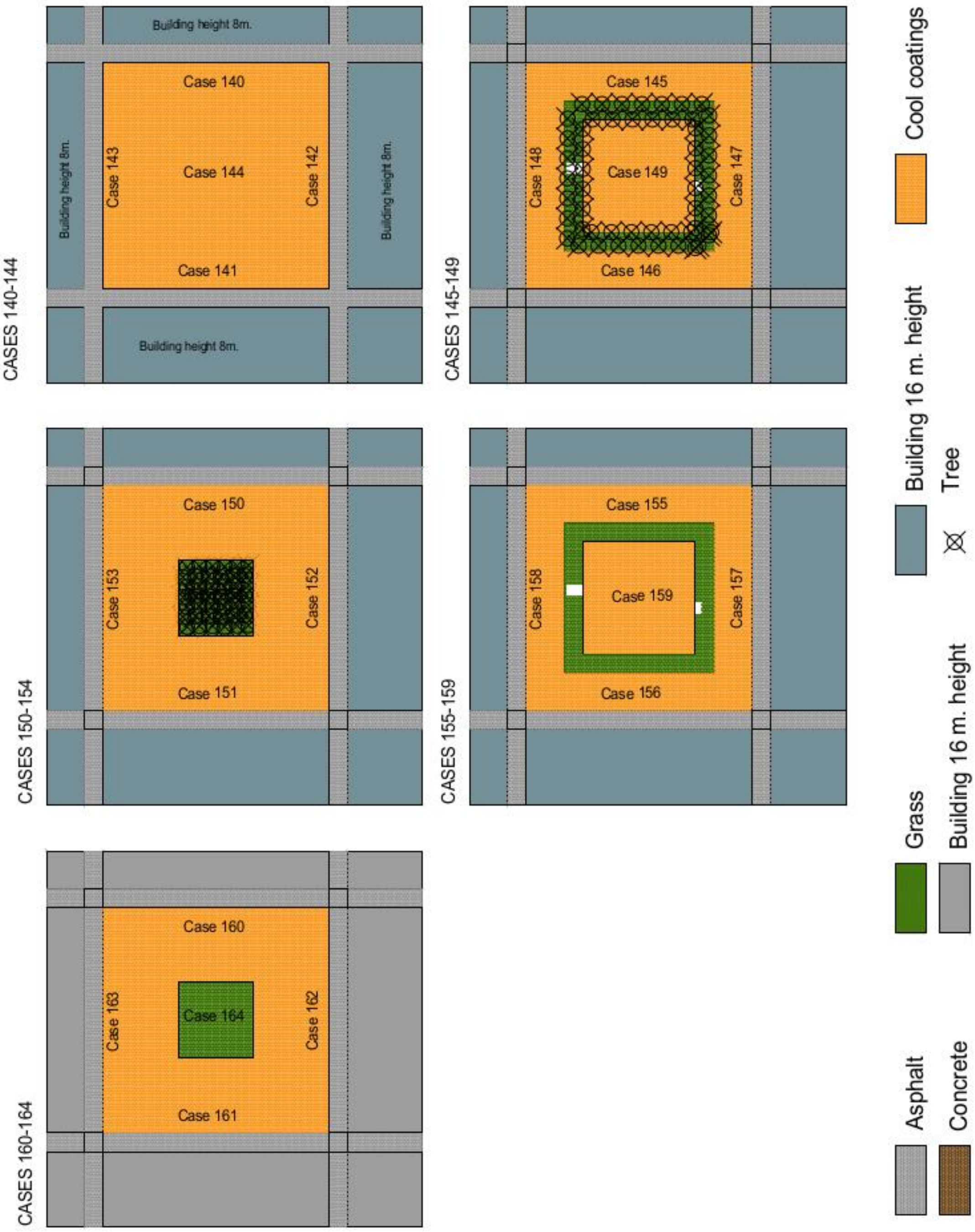

Picture 17: Sensitivity analysis cases 83-90 & 99-106.




Picture 18: Sensitivity analysis cases 91-98 & 107-114.




Picture 19: Sensitivity analysis cases 115-139.




Picture 20: Sensitivity analysis cases 140-164.

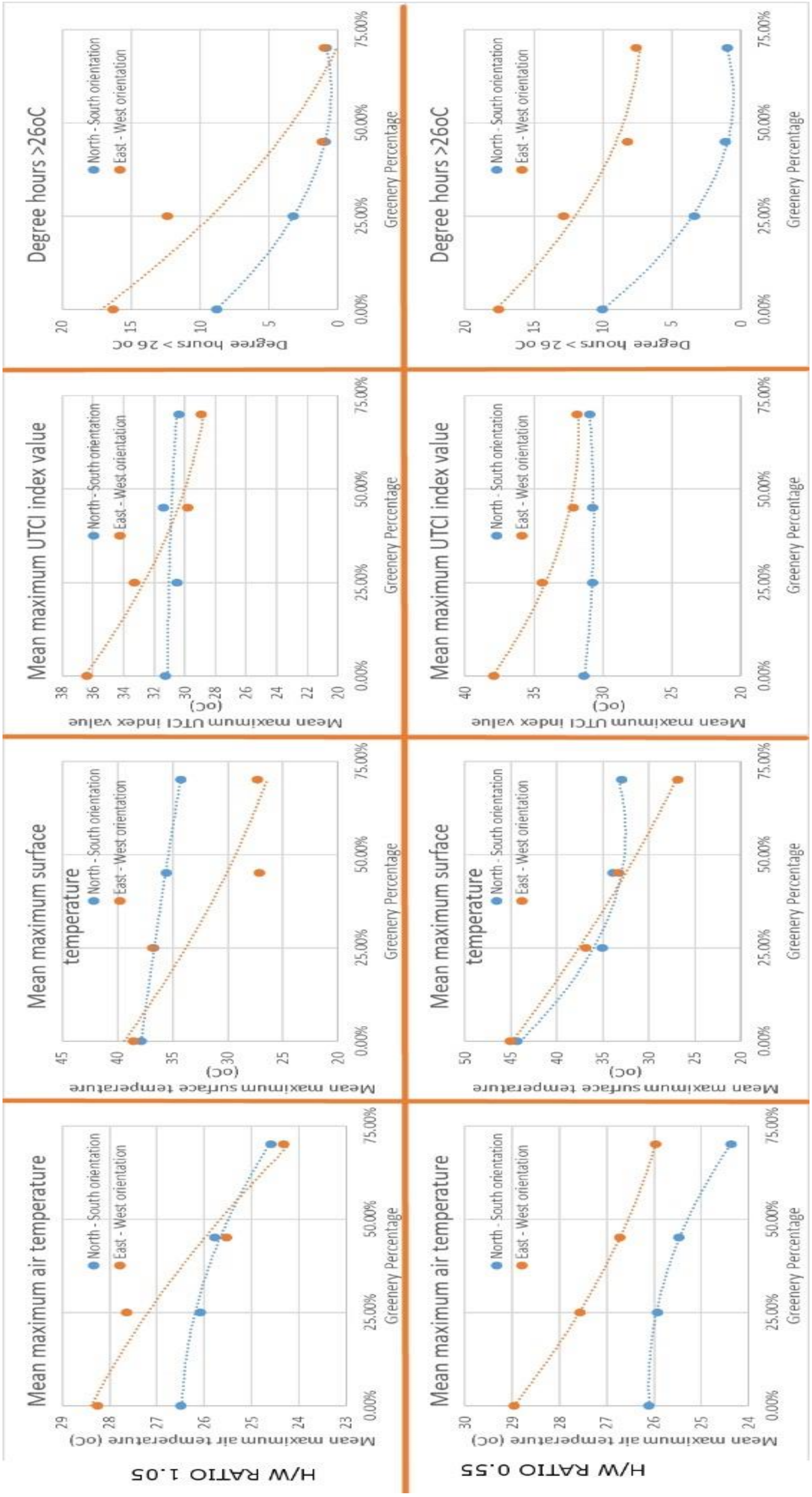



Figure 19: Sensitivity analysis of H/W ratios and greenery percentage.

### 4.5. Parameter classification through simulation analysis

The use and sustainability of outdoor urban places depend on thermal comfort conditions. As mentioned in previous chapter, certain microclimatic parameters can affect thermal comfort. These parameters need to be taken into account during the design process, to provide a comfortable environment with more protected spots within an urban canyon.

This chapter classifies the most important microclimatic parameters that affect user comfort and proposes a simplified methodology that could be implemented during the design phase. The design parameters as analysed previously are:

- **Height/Width ratio**, that mostly affects the shading levels of the adjacent spaces;
- **Sky View Factor** that affects the surface temperatures and defines the exposed area to solar radiation affects mostly the Mean Radiant Temperature and the user comfort. The shading quality in general directly affects the comfort votes during the summer season;
- **Greenery** which has several benefits to the microclimate environment: a) provides good quality of shading and allows wind penetration that has positive effects on comfort; b) through evapotranspiration the ambient air temperature is reduced; c) due to moisty soils the surface temperature is reduced; d) it is a low cost solution for both maintenance and installation; e) The larger the percentage it is used the bigger the ability to minimize the discomfort in extremely hot conditions;
- **Surface material properties** like albedo which have a certain impact on surface temperatures and on the temperature distribution during the afternoon and night hours. The effect of the suitable materials can be multiplied if the design combines the material properties with the shading environment and the orientation of the area.

The chapter analyses each parameter separately, regarding the simulation of a typical urban open space in many parametric scenarios and calculates the effect of one changed parameter each time.

Table 10, describes the results from the parametric simulations for several scenarios. With these values, it is possible to compare the different simulations and to give certain values of the effect of each parameter on the microclimate.

Table 10: Parametric simulation results.

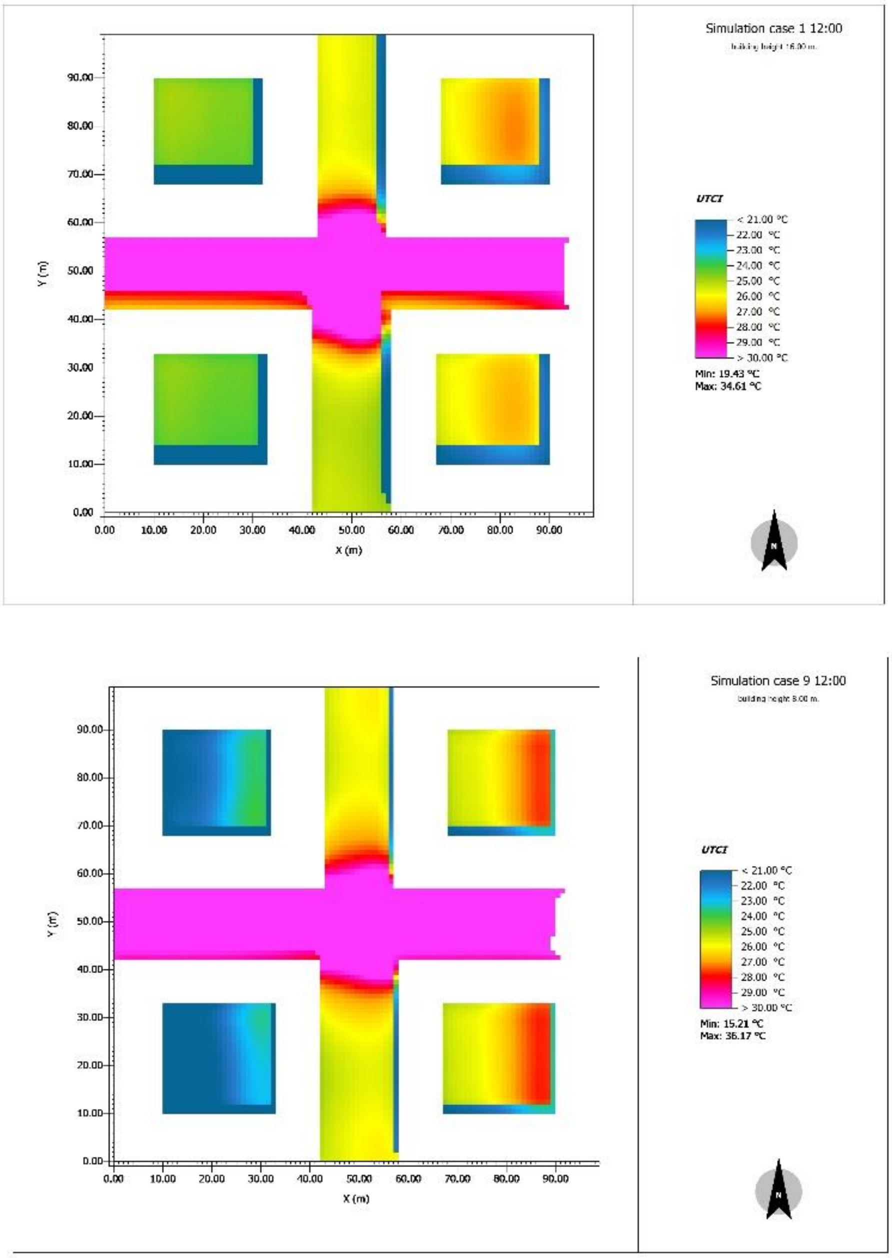
| CASE | H/W | MATERIAL MEAN ALBEDO | SVF | PERCENTAGE OF GREENERY | Orientation | Regional Max Air Temperature | Regional Max Surface Temperature | Regional Max UTCI | $DH_T$ | $DH_{UTCI}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.07 | 0.25 | 0.30 | - | N-S | 25.76 | 37.85 | 27.82 | 8.83 | 9.36 |
| 2 | 1.07 | 0.25 | 0.30 | - | E-W | 28.26 | 38.56 | 36.38 | 16.30 | 55.06 |
| 3 | 1.07 | 0.21 | 0.15 | 25 % trees | N-S | 26.08 | 36.71 | 30.54 | 3.28 | 6.66 |
| 4 | 1.07 | 0.21 | 0.15 | 26 % trees | E-W | 27.65 | 36.79 | 33.32 | 12.40 | 34.91 |
| 5 | 1.07 | 0.19 | 0.10 | 45% trees | N-S | 25.78 | 35.62 | 31.39 | 0.91 | 7.71 |
| 6 | 1.07 | 0.19 | 0.10 | 45% trees | E-W | 25.53 | 27.12 | 29.81 | 1.17 | 16.33 |
| 7 | 1.07 | 0.15 | 0.30 | 45% grass | N-S | 25.74 | 35.45 | 25.73 | 6.86 | 8.90 |
| 8 | 1.07 | 0.15 | 0.30 | 45% grass | E-W | 28.48 | 39.90 | 36.90 | 11.41 | 51.00 |
| 9 | 0.53 | 0.25 | 0.30 | - | N-S | 26.11 | 44.30 | 28.92 | 10.08 | 16.31 |
| 10 | 0.53 | 0.25 | 0.30 | - | E-W | 28.97 | 45.11 | 37.93 | 17.59 | 91.32 |
| 11 | 0.53 | 0.21 | 0.15 | 25 % trees | N-S | 25.94 | 35.03 | 30.74 | 3.36 | 8.32 |
| 12 | 0.53 | 0.21 | 0.15 | 26 % trees | E-W | 27.57 | 36.87 | 34.39 | 12.85 | 46.62 |
| 13 | 0.53 | 0.19 | 0.10 | 45% trees | N-S | 25.48 | 33.96 | 30.73 | 1.12 | 5.51 |
| 14 | 0.53 | 0.19 | 0.10 | 45% trees | E-W | 26.74 | 33.26 | 32.16 | 8.23 | 21.75 |
| 15 | 0.53 | 0.15 | 0.30 | 45% grass | N-S | 25.54 | 35.55 | 28.32 | 8.11 | 12.28 |
| 16 | 0.53 | 0.15 | 0.30 | 45% grass | E-W | 28.70 | 41.79 | 37.74 | 16.50 | 62.23 |

- **Height/ Width ratio**

As shown in Picture 17, by comparing the street simulation cases 1-8 which have H/W factor 1.07 with the simulation cases 9-15 with H/W factor 0.53 can be assumed that:

- Regarding the mean maximum air temperatures (1), the North-South canyons have about the same values whereas the East-West canyons have a difference of 0.5-1°C. Taking the into account the $DH_T$ (4) in all cases the high H/W ratio has fewer $DH_T$;
- Regarding the mean maximum surface temperatures (2), the North-South canyons have about the same values whereas the East-West canyons have larger differences of about 6°C;
- Regarding the mean maximum UTCI values (3) in all cases the higher the buildings the better the thermal comfort. Taking the $DH_{UTCI}$ (5) into account in all cases the high H/W ratio has fewer $DH_{UTCI}$, especially in the East-West orientated canyons, where the difference could reach 12-15 h.

These results show that the H/W ratio mostly affects the East-West orientated canyons where the shading is important because the sunlight penetration is higher while in the North-South canyons is of lower importance since the solar radiation is lower and the reflections in relation to lower wind speeds give the same results regarding the air temperatures (Picture 21).




Picture 21: Comparison of simulation cases 1 and 9.

- **Sky View Factor**

As shown in Table 10 and Figure 21, by comparing the street simulation cases 1,2,7,8,9,10,15,16 which have Sky View Factor (SVF) 0.30 with the simulation cases 5,6,13,14 which have Sky View Factor (SVF) 0.10 can be assumed that:

- Regarding the mean maximum air temperatures (1), the North-South canyons have about the same values whereas the East-West canyons have a difference of 2.0-2.5$^{o}$C. Taking into account the $DH_T$ (4) in all cases the high SVF the $DH_T$ has value of 8 to 9 h in North-South canyons and value of 10 to 15 hours in East-West canyons;
- Regarding the mean maximum surface temperatures (2), the North-South canyons have about 3$^{o}$C difference whereas the East-West canyons have larger differences of about 10-15$^{o}$C;
- Regarding the mean maximum UTCI values (3) in the East-West orientations the lower the SVF the better the thermal comfort of about 5$^{o}$C while in North-South orientations there is the opposite phenomenon. This may occur due to the lack of direct solar radiation on the North-South canyons where the UTCI is mostly defined by the wind penetration. The lower SVF is meaning that there are many obstacles that affect the wind flow and influence the thermal comfort of the area. Taking into account the $DH_{UTCI}$ (5) in all cases the high SVF has more $DH_{UTCI}$, especially in the East-West orientated canyons where the difference could reach 30 to 40 hours.

These results show that SVF mostly affects the surface temperatures because the sunlight penetration is higher (Picture 22). In any case, there is a good correlation of the SVF with both the air and surface temperature while for the thermal comfort in the North-South oriented canyons the simulation showed that with higher SVF values the thermal comfort is lower.

From the above-mentioned analysis, can be assumed that the effect of shading is beneficial on canyons that have direct sunlight exposure while in canyons that don't' have direct sunlight exposure, the higher SVF can affect the wind penetration and can have the opposite results on thermal comfort.

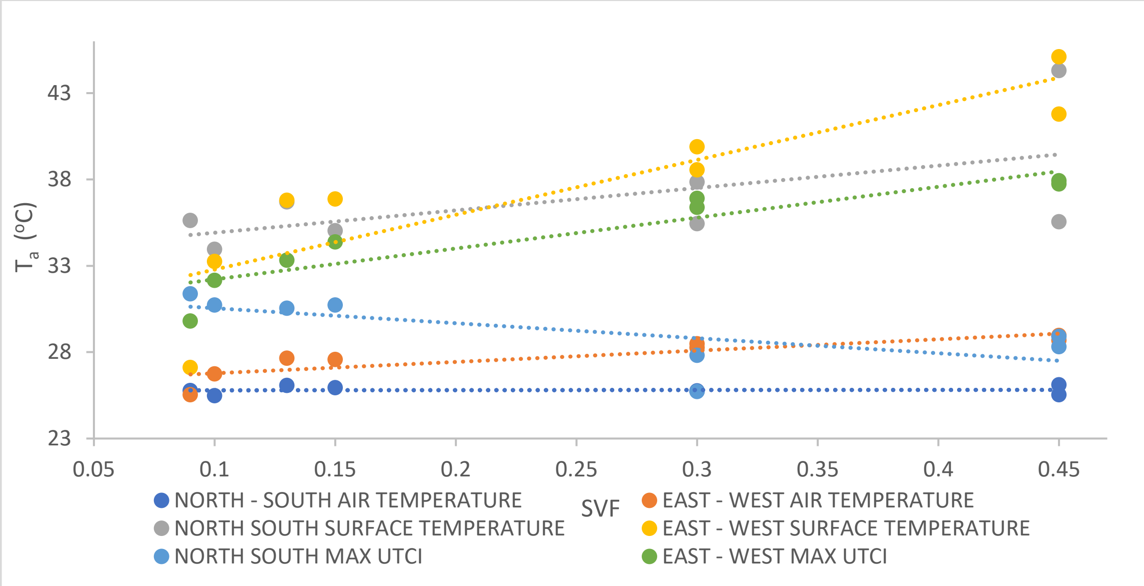



Figure 20: Correlation of SVF with air temperature and UTCI index.

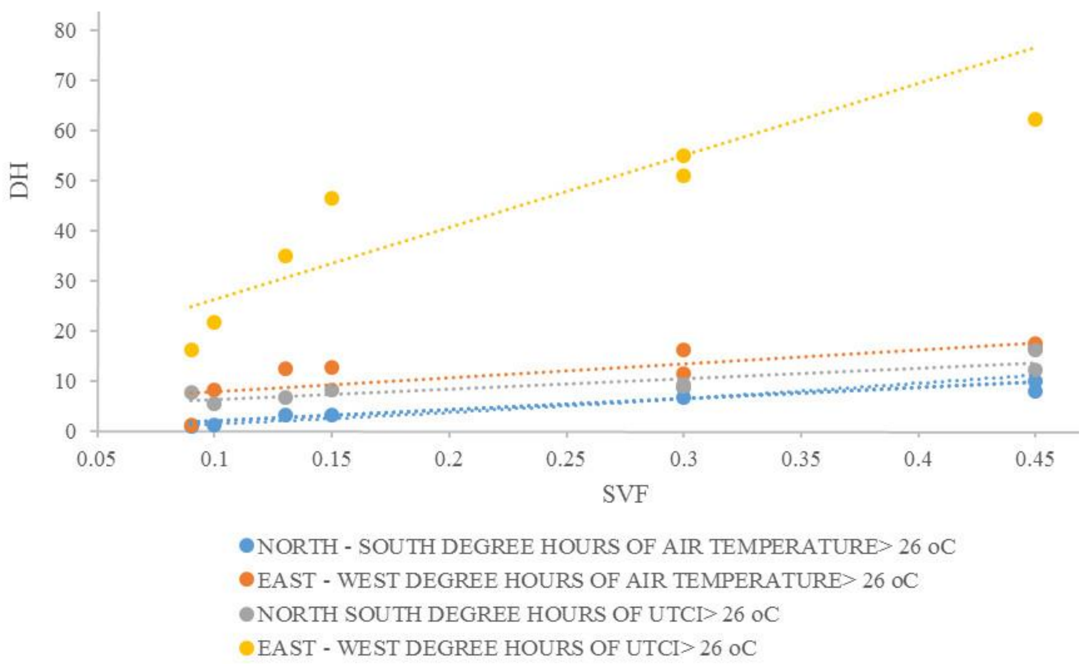
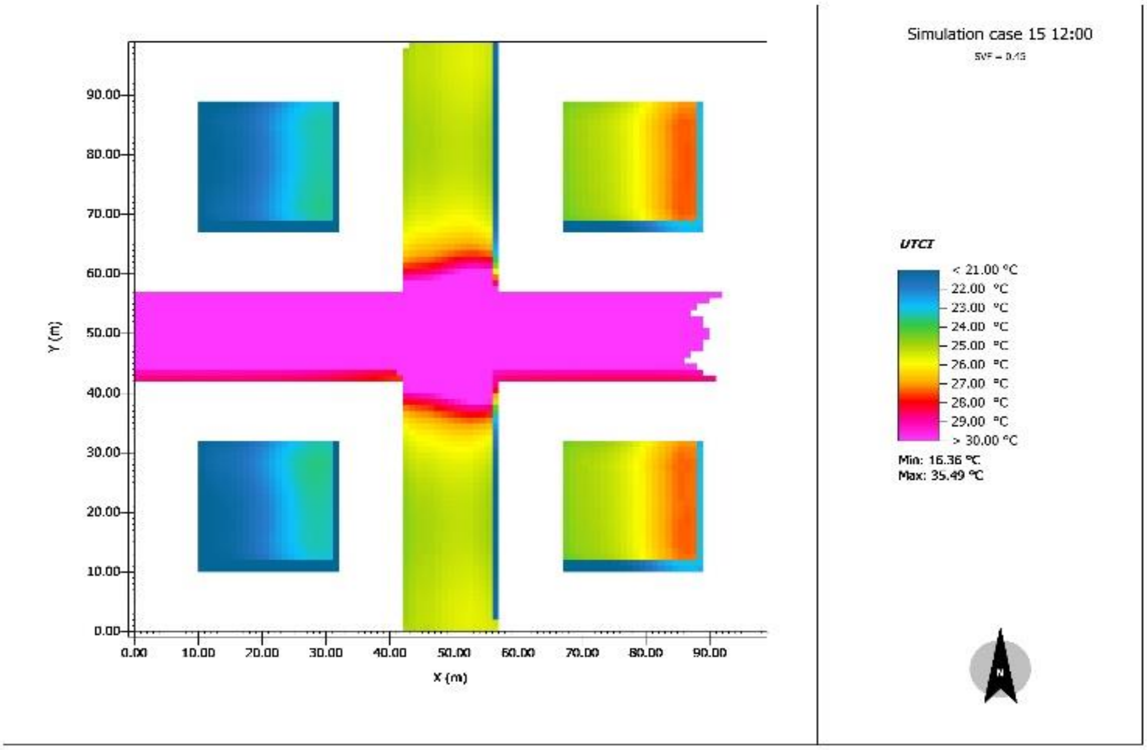
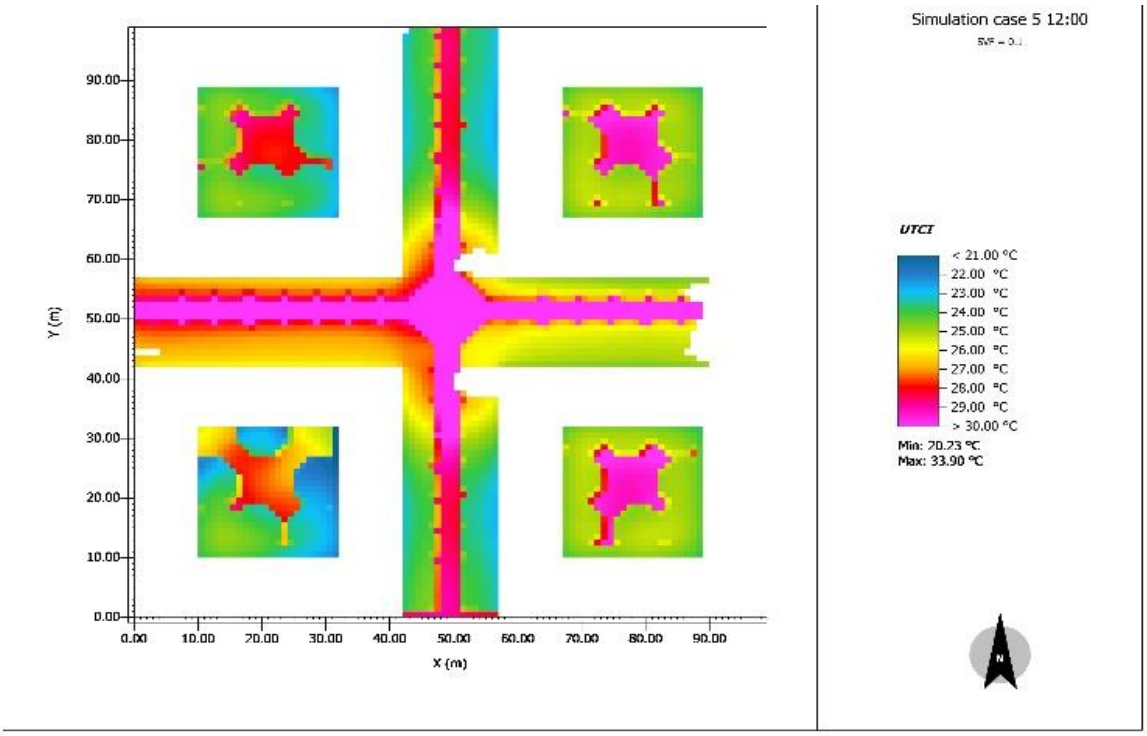



Figure 21: Correlation of SVF with DHT >26 °C and DHUTCI >26 °C.




Picture 22: Comparison of simulation cases 15 and 5.

- **Greenery**

Except for the main results in Table 10, in order to compare more accurately the greenery effects, Table 11 shows the difference between the values as shown also in Figure 22 and Figure 23.

Table 11: Greenery cases comparison

| Greenery Coverage Percentage | Orientation | H/W | Difference of Mean Max Air Temperature | Difference of Mean Max Surface Temperature | Difference of Mean Max UTCI | Difference of $DH_T$ | Difference of $DH_{UTCI}$ |
|---|---|---|---|---|---|---|---|
| trees 0% - trees 25 % | North - South | 1.07 | 0.32 | 1.14 | -2.72 | 5.55 | 2.70 |
| | East - West | 1.07 | 0.61 | 1.77 | 3.06 | 3.90 | 20.15 |
| trees 25% - trees 45% | North - South | 1.07 | 0.30 | 1.09 | -0.85 | 2.37 | -1.05 |
| | East - West | 1.07 | 2.12 | 9.67 | 3.51 | 11.23 | 18.58 |
| grass 0% - grass 45% | North - South | 1.07 | 0.02 | 2.40 | 2.09 | 1.97 | 0.46 |
| | East - West | 1.07 | 0.22 | 1.34 | -0.52 | 4.89 | 4.06 |
| grass 45% - trees 45% | North - South | 1.07 | -0.04 | -0.17 | -5.66 | 5.95 | 1.19 |
| | East - West | 1.07 | 2.95 | 12.78 | 7.09 | 10.24 | 34.67 |
| trees 0% - trees 45 % | North - South | 1.07 | -0.02 | 2.23 | -3.57 | 7.92 | 1.65 |
| | East - West | 1.07 | 2.73 | 11.44 | 6.57 | 15.13 | 38.73 |
| trees 0% - trees 25% | North - South | 0.53 | 0.17 | 9.27 | -1.82 | 6.72 | 7.99 |
| | East - West | 0.53 | 1.40 | 8.24 | 3.54 | 4.74 | 44.70 |
| trees 25% - trees 45% | North - South | 0.53 | 0.46 | 1.07 | 0.01 | 2.24 | 2.81 |
| | East - West | 0.53 | 0.83 | 3.61 | 2.23 | 4.62 | 24.87 |
| grass 0%- grass 45% | North - South | 0.53 | 0.57 | 8.75 | 0.60 | 1.97 | 4.03 |
| | East - West | 0.53 | 0.27 | 3.32 | 0.19 | 1.09 | 29.09 |
| grass 45% - trees 45% | North - South | 0.53 | 0.06 | 1.59 | -2.41 | 6.99 | 6.77 |
| | East - West | 0.53 | 1.96 | 8.53 | 5.58 | 8.27 | 40.48 |
| trees 0% - trees 45 % | North - South | 0.53 | 0.63 | 10.34 | -1.81 | 8.96 | 10.80 |
| | East - West | 0.53 | 2.23 | 11.85 | 5.77 | 9.36 | 69.57 |

By comparing the street simulation cases with variable greenery coverage: a) cases with 0% coverage 1,2,9,10; b) cases 3,4,11,12 with 25% trees coverage, c) cases 5,6,13,14 with 45% trees coverage; and d) cases 7,8,15,16 with 45% lawn coverage can be assumed that:

Regarding the Mean Maximum Air Temperatures (1), the "North-South" canyons have similar values in all the cases, whereas in case of "East-West" canyons the scenarios [trees 0%-trees 45%] give a difference of 2.2-2.7°C, and the scenarios [trees 45%-lawn 45%] give a difference of 2°C. The lawn scenarios do not have any differentiation from concrete regarding the regional max air temperature. Regarding the $DH_T$ value (4), the higher percentage of trees result fewer degree-hours. More analytically, in case of "North-South" canyons, the scenarios [trees 0%-trees 45%] give a difference of $DH_T$ between 8 to 9 degree-hours, and the scenarios [lawn 45%-trees 45%] give a difference of $DH_T$ between 6 to 7 degree-hours. In cases of "East-West" canyons these differences are quite larger, for instance the scenarios [tree 0%-tree 45%] give a difference of $DH_T$ between 10 to15 degree-hours, and the scenarios [45% lawn-45% trees] give a difference of $DH_T$ between 8 to 10 degree-hours.

Regarding the Mean Maximum Surface Temperatures (2), in the case of "North-South" canyons the scenarios [trees 0%-trees 45%] give a difference of about 10°C, and the scenarios [lawn 45%-trees 45%] give a difference of about 8°C. In the cases of "East-West" canyons, the differences are bigger reaching 11.5°C for scenarios [trees 0%-tress 45%], and 9°C for scenarios [lawn 45 %-trees 45%].

Regarding the Mean Maximum UTCI (3), in the cases of the "East-West" orientation larger percentage of trees result improvement of UTCI while in the cases of the "North-South" orientation observed the opposite behaviour. In all the cases of "North-South" orientated canyons, the difference of UTCI values is negative and about 2-5°C meaning that the thermal comfort is better when there is a lower percentage of trees. In addition, was observed that using this orientation the lawn scenarios have more positive results. In the case of "East-West" orientations, the difference of UTCI values is positive and quite bigger. Both scenarios [trees 0%-trees 45%] and [lawn 45%-trees 45%] have similar differences of UTCI values between 6 to 7°C. Taking into account the $DH_{UTCI}$ (5) in all the cases the high greenery percentage has fewer degree-hours. This difference on the "North-South" canyons is about 2 to 4 degree-hours in higher building scenarios and 6 to 10 degree-hours in lower building scenarios. and in the "East-West" orientated canyons this difference could reach 20 degree-hours difference in higher building scenarios and 40 to 60 degree-hours in lower building scenarios.

These results show that greenery percentage is beneficial for all the cases because even if the regional max thermal comfort index appears higher the $DH_{UTCI}$ of thermal comfort show that the larger the percentage of trees the better the total thermal comfort duration (Picture 23). Especially for “East-West” oriented canyons, the differences are more evident. The lawn scenarios show that lawn contributes mostly to the minimization of the surface temperatures and has very small differences in the air temperature and UTCI index. From this can be assumed that the effect of greenery is caused mostly by the shading that is provided and the evapotranspiration plays a smaller role for the calculated differences. This agrees with the research of Shashua-bar & Hoffman (Shashua-Bar & Hoffman 2000), that concludes that shading from trees contributes about 80% of cooling caused by trees in Tel- Aviv, Israel. In any case, greenery is more beneficial on canyons that have direct sunlight exposure because in other case the higher the percentage of trees the lower wind speeds are measured, and this can have the opposite results on thermal comfort. Johansson et al. (Johansson et al. 2013) discovered significant differences in the mean wind speed and the mean radiant temperatures in places with different greening configurations.

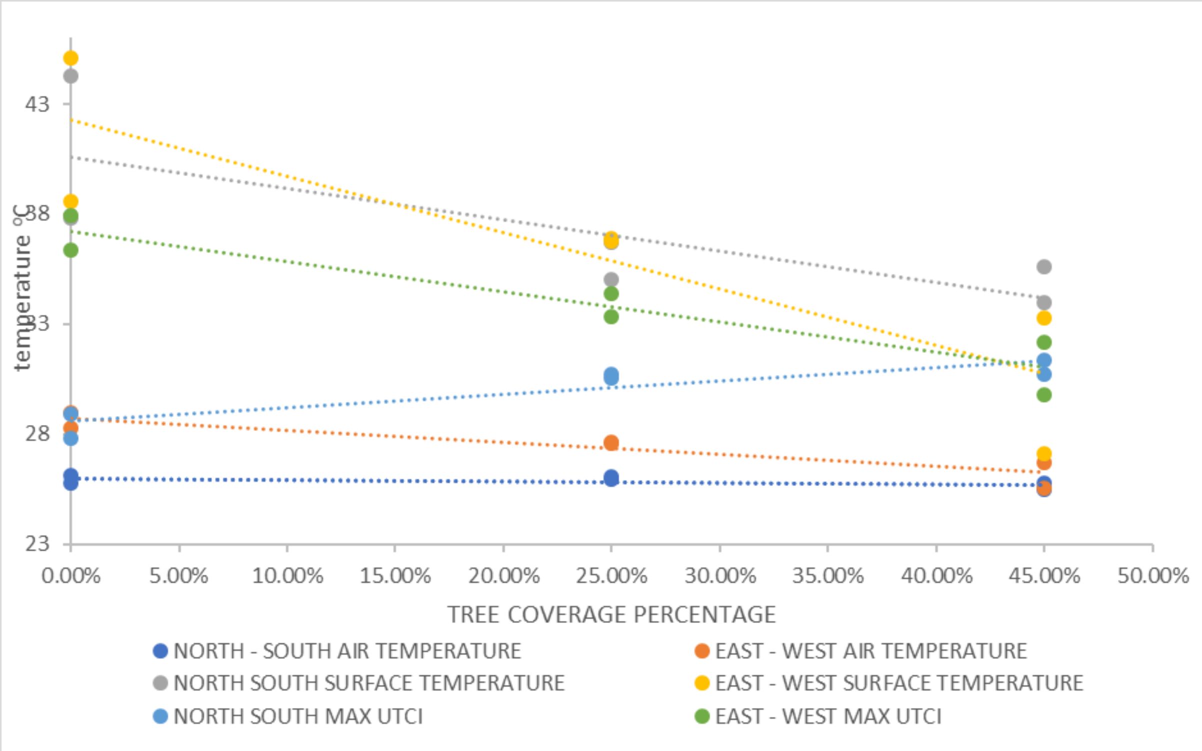



Figure 22: Correlation of tree coverage percentage with air temperatures and UTCI index.

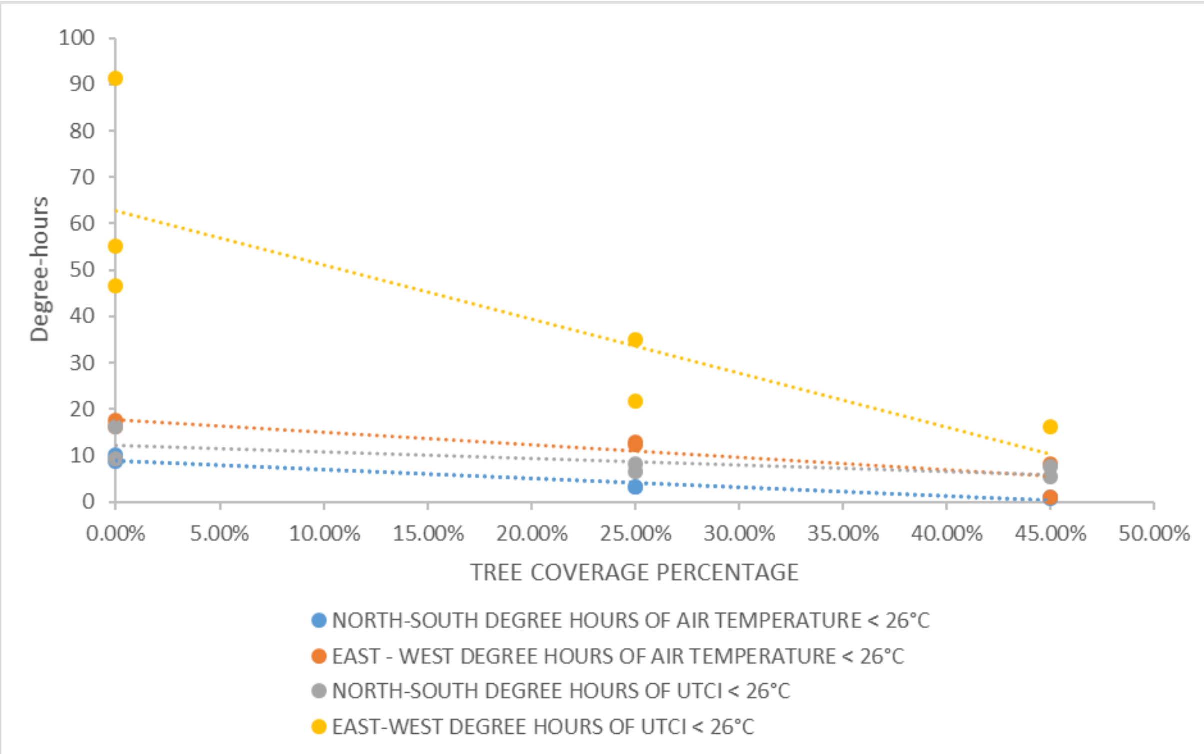
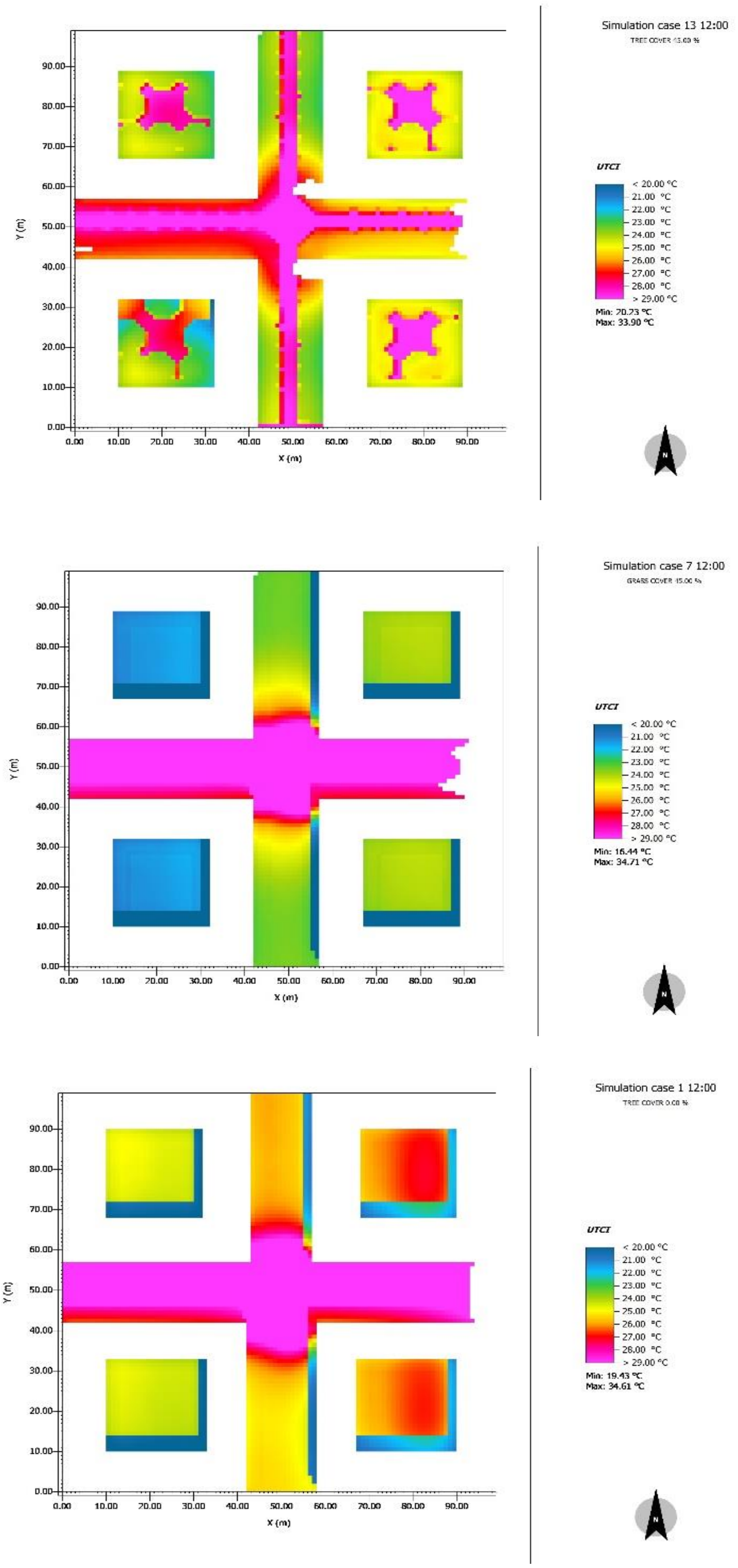



Figure 23: Correlation of tree coverage percentage with $DH_T$>26 °C and $DH_{UTCI}$ >26 °C.




Picture 23: Comparison of simulation cases 13, 7 and 1.

**Pavement material albedo**

In order to compare the different albedo properties of the materials, cases 1,2,9 and 10 are used. These have no vegetation and no moist soils that may mislead the comparison. All the selected cases have concrete pavements of albedo 0.3 and asphalt road with albedo 0.10. The comparison will be done: a) on the areas with the maximum temperatures; b) on the canyon sides; and c) in the center of the schematic (Figure 24). Regarding the air temperatures and the thermal comfort index values there is no significant change between the two materials, however, the surface temperatures seem to have a difference of about 4 to 5°C (Picture 24). Nevertheless, the research for better comparison results of the different albedo materials, needs more simulation cases to be tested where the different materials would be applied in larger areas of the model in order to show differences between air temperatures and thermal comfort values.

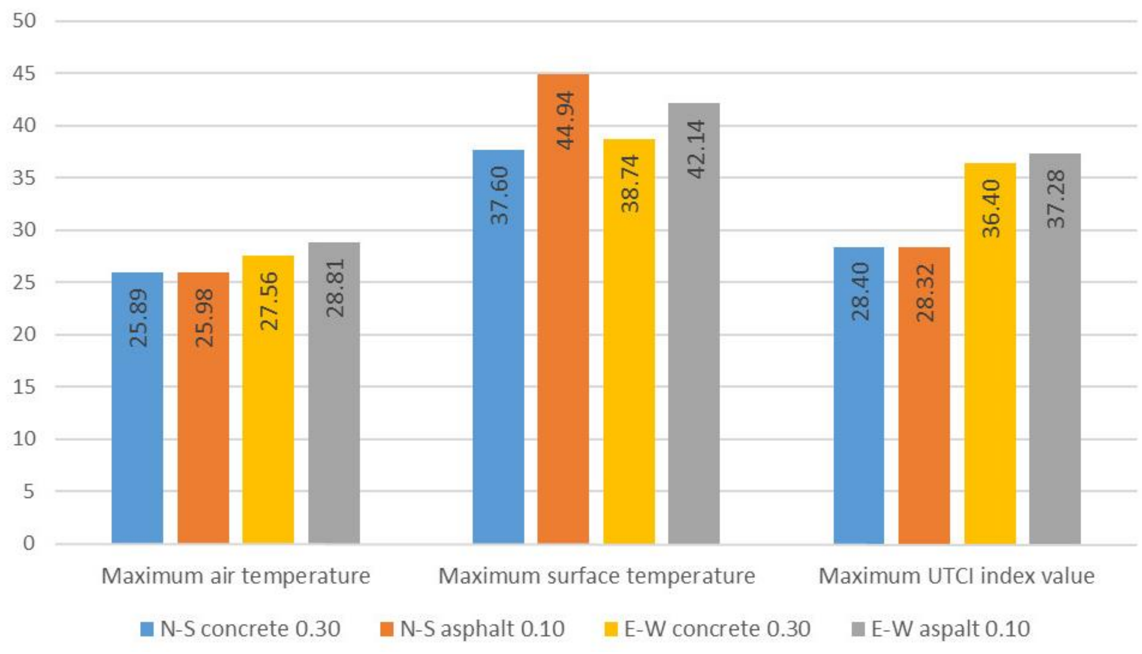
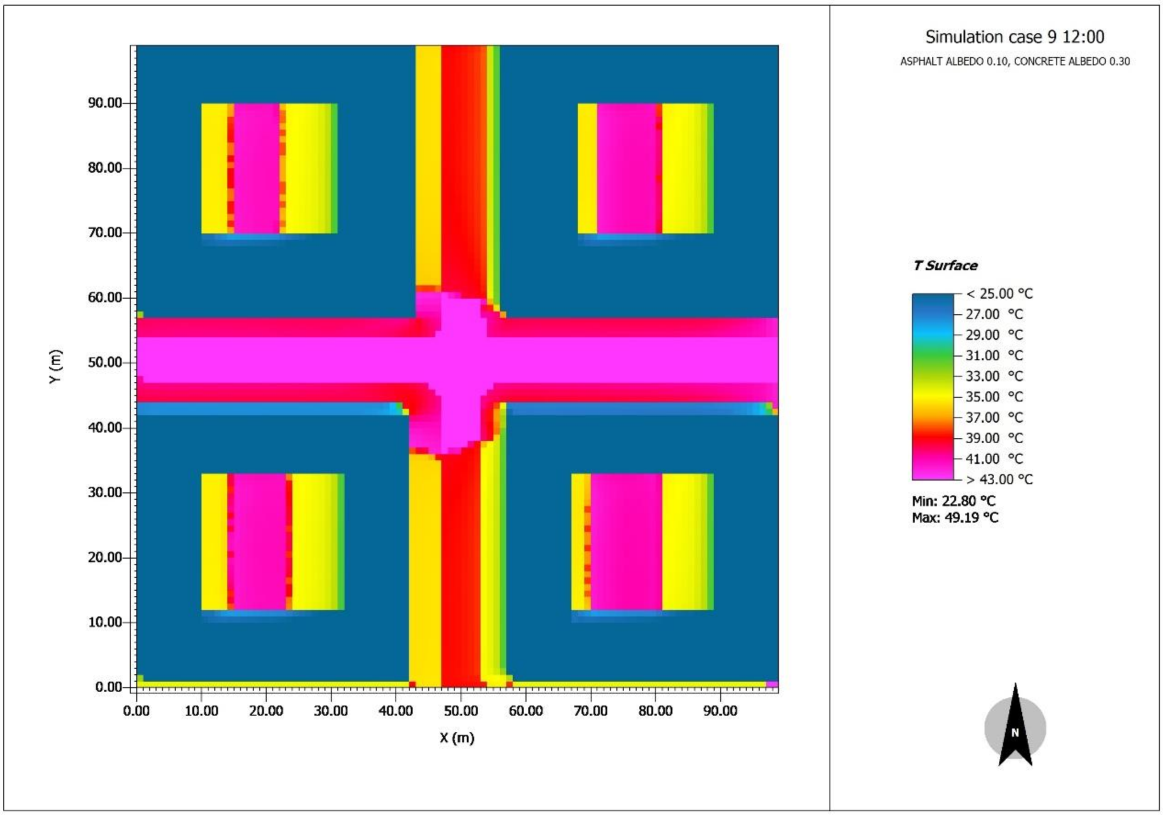



Figure 24: Surface temperature comparison of different albedo materials.




Picture 24: Surface temperature of simulation case 9.

## 5. The outdoor bioclimatic design tool

During the last decades, has been extended interest in the bioclimatic design of buildings and the way that thermal comfort can be achieved in the indoor environment. For this purpose, a variety of tools has been developed that mostly concern energy savings and thermal comfort conditions of indoor spaces (Huang et al. 2015; Allegrini et al. 2015). After the analysis of the indoor environment, in recent decades, the interest has been extended to the outdoor environment and its ability to affect both indoor and outdoor thermal comfort conditions (Rupp et al. 2015). As analysed in previous chapters, the need to design sustainable urban open spaces regarding thermal, acoustic and visual comfort, has become necessary for the use of the urban environments (Djukic et al. 2016; Chatzidimitriou & Yannas 2016; Mazhar et al. 2015). The urban design process needs to be reviewed and new criteria like climate comfort, thermal perception, visual and acoustic comfort (Djukic et al. 2016; Xue & Lau 2016; Lenzholzer et al. 2016; Nasrollahi & Shokri 2016; Meng & Kang 2016) have to be added to the design process while sustainability assessment tools for urban design and development have already been defined (Ameen et al. 2015). The methods of achieving comfort that can be used by the design team are the urban geometry redesign, greenery, urban landscape features and material selection (Galatioto & Beccali 2016; Klemm et al. 2016; Chatzidimitriou & Yannas 2016). The effect of these methods on comfort depends on the location and the use of the space. The benefits of an urban open space that follows certain bioclimatic design rules are a comfortable and healthy environment, in addition to the energy savings of the surrounding buildings (Tsitoura et al. 2016; Tsitoura et al. 2017).

The scope of this chapter is to introduce a bioclimatic decision-making tool that can be used during the design process of urban open spaces, setting a new palette of tools to the stakeholders. The proposed tool allows a simplified and accurate analysis and can be used by the design team to evaluate their subjective decisions during the design phase of the project. The tool takes into consideration the most crucial microclimatic parameters and provides the necessary guidelines to develop sustainable urban open spaces in areas of the Mediterranean zone. The term “sustainable outdoor design” defines the type of urban open space design that promotes thermal, acoustic and visual comfort to the users during the day and night throughout all seasons, taking into account the energy impact of the architectural intervention to the environment. The tool is designed especially for the hot-summer Mediterranean climate ($C_{sa}$) (Zoras 2015) and provides to stakeholders a set of comparable bioclimatic indices that will help them to design and develop sustainable urban open spaces according to proposed guidelines and bioclimatic design rules. (Papamanolis 2015b).

The design team using the microclimatic analysis of the proposed tool, can easily achieve better design, taking into account specific microclimatic constraints. Furthermore, if the design team wants to probe deeper on the analysis, taking as an initial step the use of the proposed tool can apply a more complex methodology that is presented in the following chapters. This methodology can be applied in any location, regardless of the climatic zone characteristics.

### 5.1. Tool architecture

The configuration of the proposed bioclimatic decision-making tool is shown in Figure 25. According to this representation, the input of the tool requires a primary analysis of the area, by providing a set of parameters such as type and characteristics of the canyon, percentages of the coatings, and vegetation properties. The output of the tool consists of certain bioclimatic indices, microclimatic heat-maps and tables for direct comparison of the variety of choices. In this way, the design team using the tool can follow the proposed guidelines during the design phase of a project. The bioclimatic design guidelines include a set of defined dynamic parameters such as coverage percentage of greenery, type of greenery, coverage percentage of paving, and properties of paving materials. Additionally, the tool highlights the problematic spots that demand special processing depending on the orientation and area geometry. The tool uses an embedded database that has been populated with raw data produced by the simulation software ENVI-met 4 and certain microclimate indices that are calculated by post-processing the simulation results.

The aim of the tool is to assist the decision process that the design team follows in order to create a new urban space that prioritizes the user's comfort. The primary analysis is done by setting the static parameters of the area which are the canyon width, building heights and orientation. These static parameters indicate the type of the area and its geometrical characteristics. The output of the tool, according to the selected data gives the evaluation of the proposed design through certain bioclimatic indices:

- $T_m$ Mean Maximum Air Temperature (℃) (1)
- $T_{ms}$ Mean Maximum Surface Temperature (℃) (2)

- $THA_m$ Mean Maximum UTCI (°C) (3)
- $DH_T$ degree-hours of $T_a > 26$°C (hours) (4)
- $DH_{UTCI}$ degree-hours of $UTCI > 26$°C (hours) (5)

Taking into account the preferences of the design team, the desired greenery percentage and the material properties for each orientation the tool recalculates the indices. The output of the tool also provides a comparison methodology of the alternative design scenarios and microclimatic heat-maps of each one. In this way, the design parameters can be adjusted in several alternative forms and finally primary decisions of their design can be selected by incorporating an initial estimation of the dynamics of the microclimate in the area. With this tool, the problem of setting the design principles from scratch is solved since the design is starting to evolve. This first analysis helps the design team to keep up with the priorities that are based on making an urban open space with the longest possible user comfort hours throughout the day according to the indices mentioned.

This tool encourages a simplified way of designing urban open spaces by setting as primary goals: a) improved comfort conditions for the users and b) increased energy efficiency of the surrounding buildings. Even if the design team has no previous expertise in microclimate analysis, using the tool can evaluate the initial concept design and have a quite sustainable solution which focuses on the user thermal comfort.

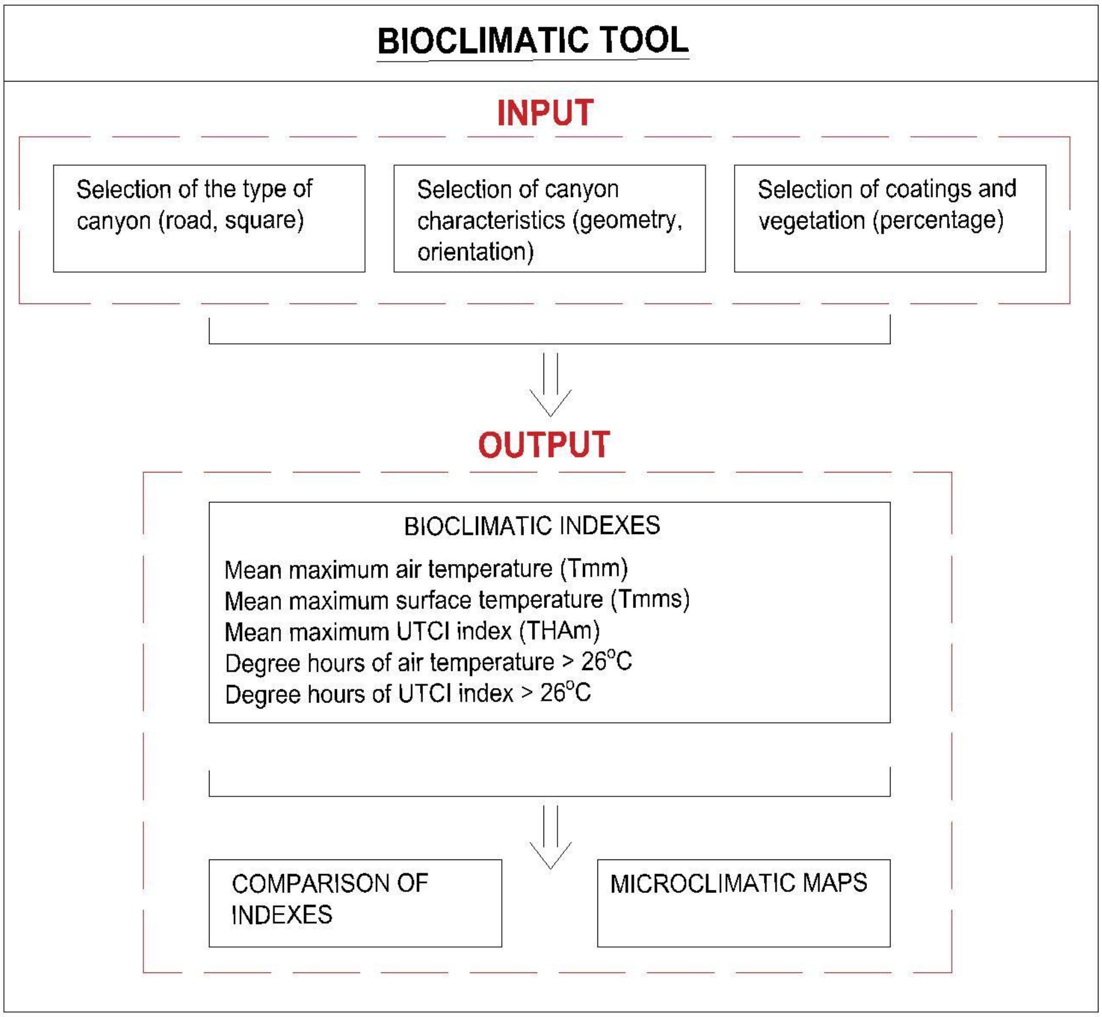



Figure 25: Bioclimatic outdoor design tool configuration.

### 5.2. Tool description - example

The proposed tool includes an interface that shows, depending on the user choices, the saved results from the database with a quick and simple procedure. In order to have this result, the designed interface for completing the input data guides the user to a series of selections depending on each case characteristics and design choices. The core of the tool has saved several simulation results that derived from a sensitivity analysis of the ENVI-met.

After the sensitivity analysis, the data produced by ENVI-met are used by the tool to calculate certain bioclimatic indices. Table 12 shows the calculation of the first 16 cases as described in Table 26 in Appendix for a two-open sided canyon with 15m width.

For each case that is processed through the tool core, output results include microclimatic heat-maps that are produced by the software Leonardo from the ENVI-met simulated period of the hours 12:00 and 16:00 that are also included in the primary analysis and are used from the tool interface for evaluation purposes.

Table 12: Cases results of bioclimatic indexes.

| Case | Mean Max Air Temperature ($T_m$) | Mean Max Surface Temperature ($T_{ms}$) | Mean Max UTCI Index (THA) | $DH_T$ | $DH_{UTCI}$ |
|---|---|---|---|---|---|
| 1 | 25.76 | 37.85 | 27.82 | 8.83 | 9.36 |
| 2 | 28.26 | 38.56 | 36.38 | 16.30 | 55.06 |
| 3 | 26.08 | 36.71 | 30.54 | 3.28 | 6.66 |
| 4 | 27.65 | 36.79 | 33.32 | 12.40 | 34.91 |
| 5 | 25.78 | 35.62 | 31.39 | 0.91 | 7.71 |
| 6 | 25.53 | 27.12 | 29.81 | 1.17 | 16.33 |
| 7 | 25.74 | 35.45 | 25.73 | 6.86 | 8.90 |
| 8 | 28.48 | 39.90 | 36.90 | 11.41 | 51.00 |
| 9 | 26.11 | 44.30 | 28.92 | 10.08 | 16.31 |
| 10 | 28.97 | 45.11 | 37.93 | 17.59 | 91.32 |
| 11 | 25.94 | 35.03 | 30.74 | 3.36 | 8.32 |
| 12 | 27.57 | 36.87 | 34.39 | 12.85 | 46.62 |
| 13 | 25.48 | 33.96 | 30.73 | 1.12 | 5.51 |
| 14 | 26.74 | 33.26 | 32.16 | 8.23 | 21.75 |
| 15 | 25.54 | 35.55 | 28.32 | 8.11 | 12.28 |
| 16 | 28.7 | 41.79 | 37.74 | 16.50 | 62.23 |

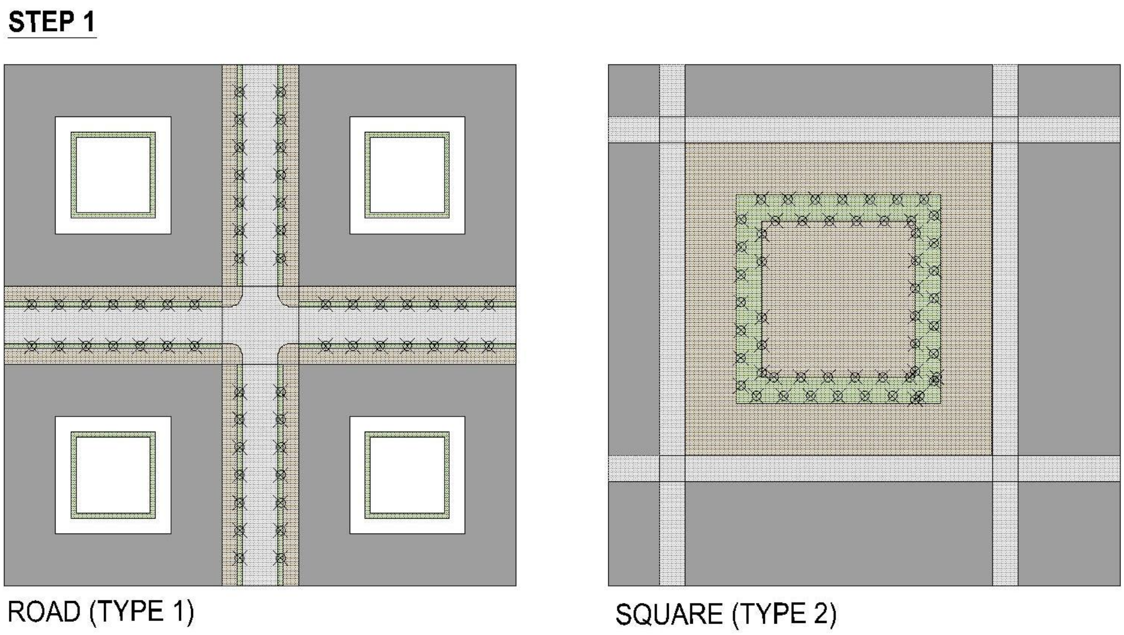
The complete use of the tool's interface is explained through the presentation of a relevant example. Assuming a design team wishes to start a project for a new road configuration 15m wide, surrounded by 8m high buildings in an urban area with an "East-West" orientation.

The initial step is to select the type of area (Picture 25). Then the static parameters must be set. These parameters are the canyon width, building height and orientation (Picture 26). As next step, the tool requires a set of parameters that are the percentage of greenery, the type of greenery and the desired construction materials (Picture 27). The tool will then process the selected data in order to choose a case from the stored simulation data so as to provide an initial assessment of how the design proposal would evolve. Picture 28 shows the results provided for the case example, where the index values of the selected case and additionally two extra analysis possibilities are demonstrated. One is used for comparison with the other design choices (Figure 26) and one for extracting heat- maps of the microclimate parameters (Figure 27). The extra analysis allows more accurate results since the bioclimatic index values are case sensitive and need further input data in order to be usable. These data can only be used as an initial assessment related to the tool results and only further microclimate analysis, including the area of the project and the exact urban characteristics could give correct microclimatic index values. This type of analysis consists part of the methodology used after the finalisation of the design and is described in the next chapters.

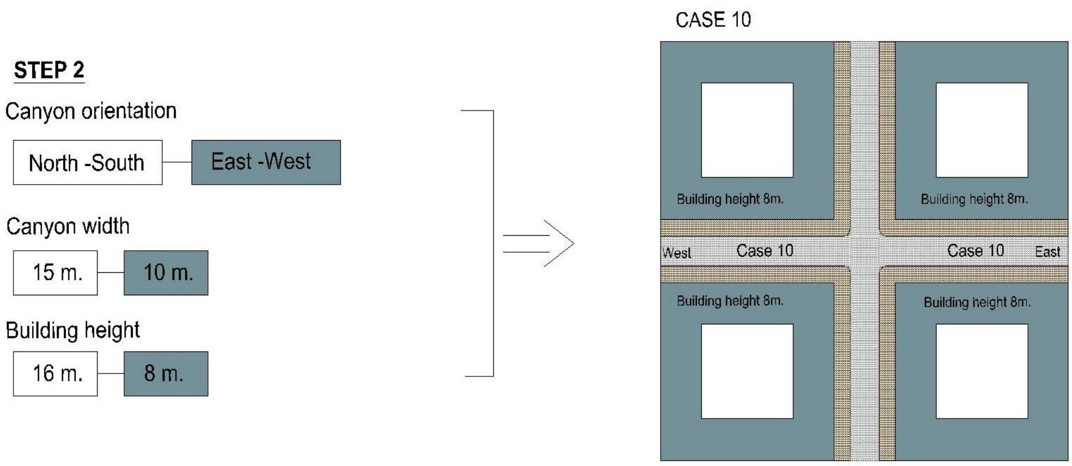
The comparison, as shown in Figure 26, demonstrates the percentage of change in the selected indices by comparing with the case that has been selected. In that way, the designers can explore their possibilities and easily take the final design decisions according to each project needs. For example, as shown in Figure 26, if the designer prefers instead of trees to add smaller plants and grass he can assume that this is going to have a small effect on the air temperature (+4.0% according to Figure 26) but a quite large effect in the $DH_{UTCI}$ of thermal comfort (+33.4% according to Figure 26). All the comparisons are made with the selected decisions that were put in step 3, and if it is decided to be changed, he must return to step 3 and repeat the analysis.

Another possibility of the tool is that it provides to the users heat-maps of the selected case with the basic microclimate parameters (air temperature, surface temperature and UTCI values) (Figure 27). These heat- maps are produced by the software Leonardo with the data from the sensitivity analysis of ENVI-met. The heat-maps provide the image of the microclimate values of the entire area including specific spots that need certain care such as a pavement on the west side. The heat-maps provided for each group of selections on the previous steps show the microclimate of the choices that have been made. In that way, if in step 3 the existing parameters are selected, the heat-maps show the existing distribution, whereas if in step 3 the new design configuration is selected, the hear-maps will show the value distribution of the new design.

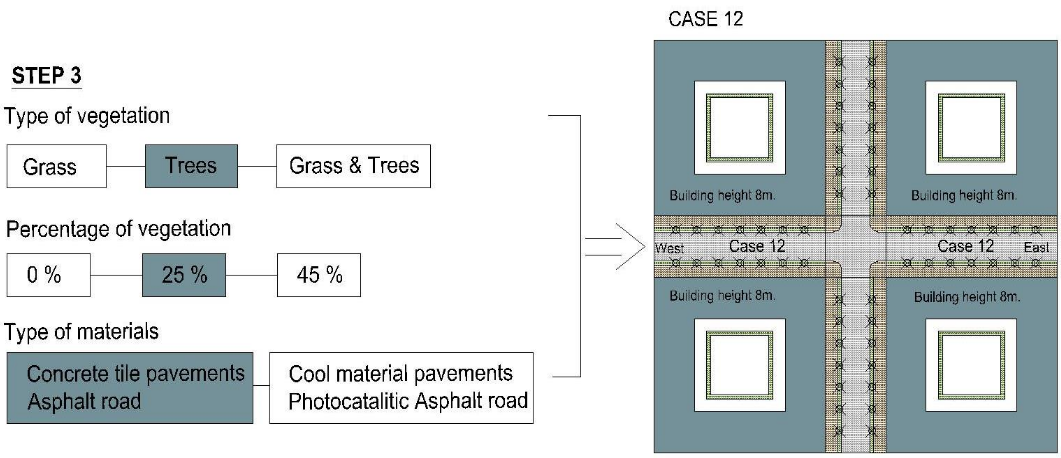
This primary design analysis can offer a good estimation of how the microclimate of the new area will evolve and comparingly take the best decisions regarding thermal perception, but no certain values can be estimated. In order to calculate the microclimate values of the new design, a case-specific analysis must be done.



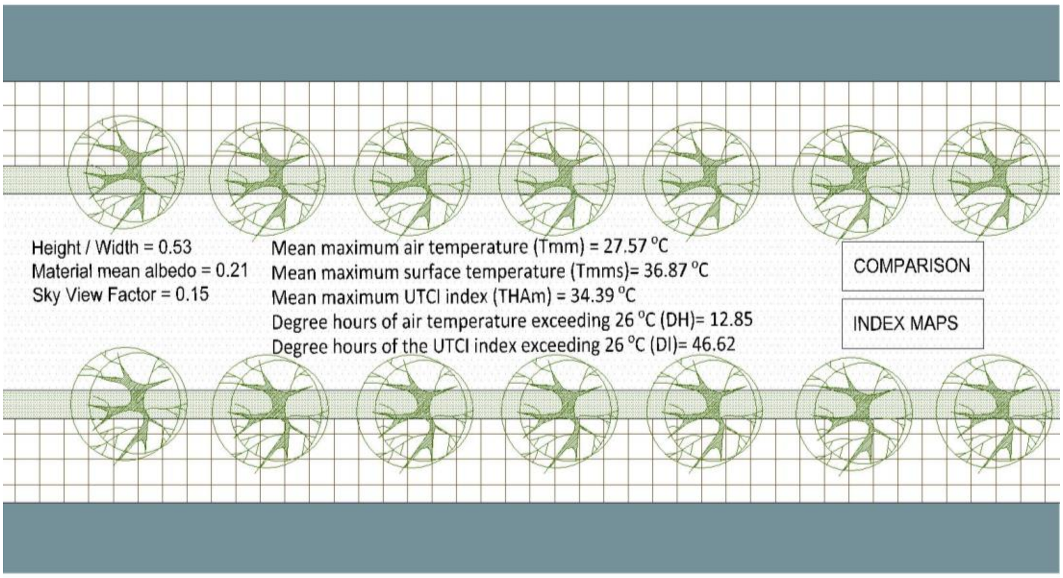

Picture 25: Tool's step 1, selection type of area.




Picture 26: Tool's step 2, selection of orientation, building height and canyon width.




Picture 27: Tool's step 3, selection of type of vegetation and materials.




Picture 28: Tool's step 4, bioclimatic index results.

| Type of vegetation | Grass | Trees | Grass & Trees |
|---|---|---|---|
| $T_m$ | +4.0% | - | -4.9% |
| $T_{ms}$ | +13.3% | - | -1.9% |
| THA | +9.7% | - | -2.0% |
| $DH_T$ | +28.4% | - | -1.87% |
| $DH_{UTCI}$ | +33.4% | - | -14.6% |

| Percentage of vegetation | 0% | 25% | 50% |
|---|---|---|---|
| $T_m$ | +5.0% | - | -7.4% |
| $T_{ms}$ | +22.3% | - | -26.4% |
| THA | +10.2% | - | -13.3% |
| $DH_T$ | +36.6% | - | -90.8% |
| $DH_{UTCI}$ | +95.8% | - | -64.9% |

| Type of materials | Concrete tile pavements Asphalt road | Cool material pavements Photocatalytic Asphalt road |
|---|---|---|
| $T_m$ | - | -1.0% |
| $T_{ms}$ | - | -52.6% |
| THA | - | -21.5% |
| $DH_T$ | - | -57.4% |
| $DH_{UTCI}$ | - | -43.6% |

Figure 26: Comparison of the selected cases.

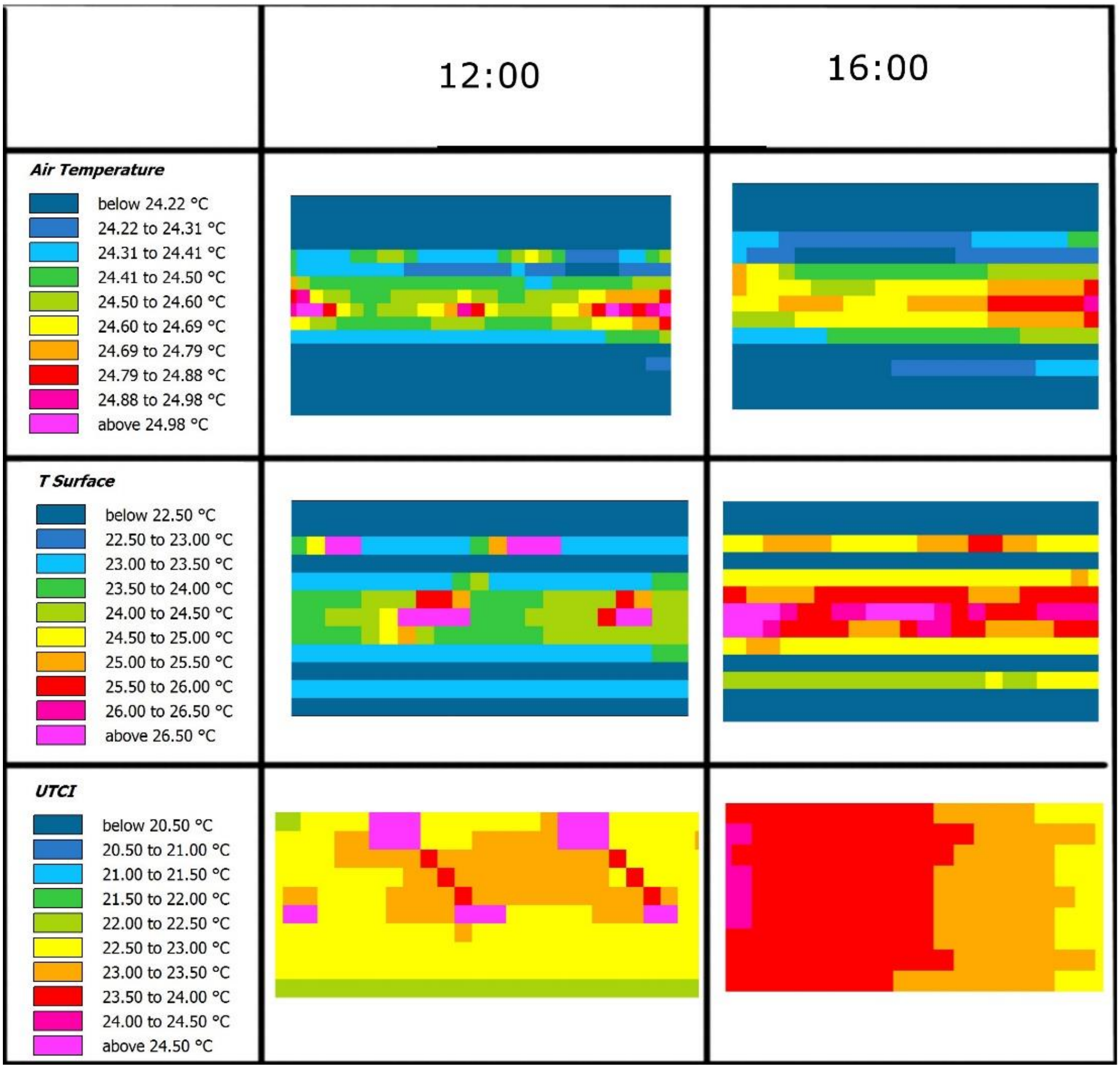



Figure 27: Microclimatic indices heat-maps.

# 6. Proposed methodology of bioclimatic open space design

As mentioned in previous chapters there is a need for detailed bioclimatic methodology to design sustainable urban open spaces. Until now quite a lot of studies have been conducted to implement a more detailed analysis of bioclimatic urban open space design. Each one of them follows a different methodology and uses different bioclimatic indices (Rupp et al. 2015; Tsitoura et al. 2014; Chen & Ng 2012). The proposed methodology includes a detailed and case-specific analysis that will provide accurate results and information about the microclimate conditions of the area. This analysis can be applied to both summer and winter seasons and includes estimations of the energy savings from the surrounding buildings due to changes in the outdoor environment.

This methodology, as shown in Figure 28, derives as a result of extended literature research, field measurements, implemented examples and continuous validation of the produced results. The primary step of this approach includes the use of the bioclimatic decision-making tool as described in previous chapters. The methodology has several steps, each one of them can be analysed furthermore, depending on the required level of detail. This methodology encourages a simplified way of designing sustainable open spaces by setting as primary goals the comfort conditions for the users and energy savings for the surrounding buildings. Even if the design team has no previous experience in microclimate analysis, can go through the first steps of the methodology that include the use of the proposed tool, while for detailed and case-specific design scenarios the analysis includes complex measurements, simulation models and calculations.

The proposed methodology as shown in Figure 28 includes all the typical procedure the design has to proceed, so as to be completed and ready for construction. The methodology, in general, is based on microclimatic measurements of the existing state of the area that are inserted into the input weather file. Moreover, a microclimatic model of both the current area and the new design proposal is produced and the measurements are used for the validation of the model and the verification of the expected results. In this way, the design team can predict the after regeneration microclimatic conditions throughout a day and calculate the comfort indices in order to finalize the design proposal.

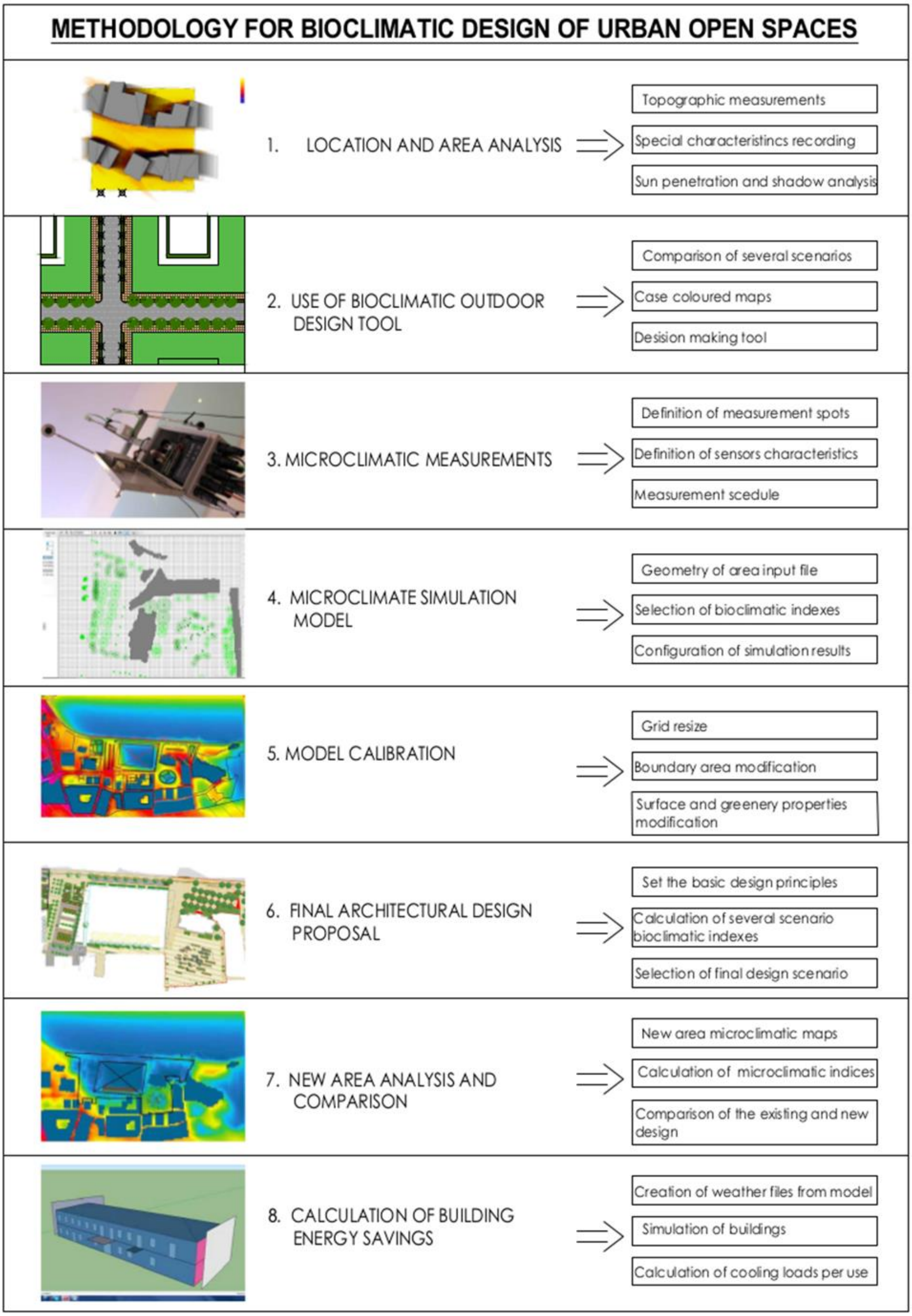



Figure 28: Methodology for bioclimatic design of urban open spaces.

Moreover, with the use of outdoor environment simulation, weather files can be produced that can be useful for a building simulation tool in order to evaluate the energy savings of the old and new design.

All the procedure of this case-specific bioclimatic open space methodology as described in Figure 28, has the following steps:

1. **Location and area analysis**

For the location and area analysis, the necessary data consider the special characteristics of the site such as orientation, geometry and all the parameters that define the environment, like dimensions, building heights, traffic, existing greenery and cover materials of the ground and buildings. In the beginning, the sun movement, penetration and shadows are analysed.

2. **Use of the bioclimatic outdoor decision-making tool**

The use of the tool is necessary during the predesign phase in order to set the initial design principles and form the different design scenarios. The tool can help the decision-making process and allow scenarios comparison through bioclimatic indices and thermal heat-maps. In this way, the design team can detect spots that need special design and lead to advanced thermal comfort conditions.

3. **Microclimate measurement data**

The microclimatic measurements are necessary for the validation of the thermal model and for the construction of the weather file of the simulation tool. The microclimatic data must be obtained by portable weather stations inside the area on height that does not exceed 5m above the ground, and to be calibrated according to the ISO 7726/1998. One typical sensor selection for microclimatic measurements includes:

- Pt1000 temperature sensors for temperature measurements on the surface, and the air in heights +0.60m, +1.60m;
- Relative humidity sensor;
- Pressure sensor;
- Wind speed and direction meter;
- Pyranometer;
- Albedometer;
- Wet bulb temperature sensor;

- Dry bulb temperature sensor.

The data logger is programmed to log measurements each minute and store data every 15 minutes using the moving average for all parameters.

4. **Microclimate simulation model**

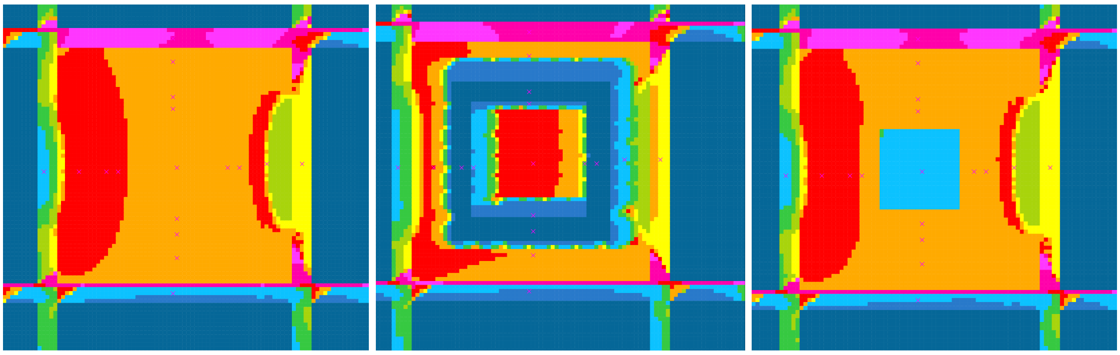
The microclimatic simulation model of the existing area must describe the existing conditions at a certain level of detail. The necessary data that are collected from previous steps, are used as input to the microclimate simulation program ENVI-met 4. The model in combination with the measurements will allow a realistic analysis of the microclimatic parameters and can help to identify the spots that need special attention. With the visualization of the microclimate values with the use of the software Leonardo the area can be reviewed as a whole for all the hours of the day. In this way, the areas that need certain interventions will be obvious.

5. **Model calibration**

The simulation model must describe adequately the existing measurement to proceed with the scenario analysis. Usually, differences over 1$^{o}$C are not allowed between the measured and simulated data. For this purpose, the calibration of the simulation model is necessary. The calibration can be achieved by: a) changing the resolution of the analysis grid, b) modifying of the boundary areas and conditions and, c) configuring in detail the surface materials and soil boundaries in relation with greenery analysis. After the model has been calibrated it is assumed that the results of the new design scenarios will be valid.

6. **Final architectural design**

After the primary goals have been set with the use of the decision-making tool, the existing area analysis has allowed the creation of different design scenarios. These scenarios are modelled, simulated and the produced microclimatic heat-maps in relation with the bioclimatic indices can lead to the finalization of the architectural design proposal that can proceed with further analysis. The heat-maps and the comparison of the bioclimatic indices can evaluate the effect of the different scenario features and can lead to a combined solution that can satisfy the design team prerequisites (Picture 29).



Picture 29: Heat-maps of the different scenarios (Empty area, trees 15m. of the road and grass in the middle).

### 7. New area microclimatic analysis

The finalization of the architectural design allows the creation of the detailed simulation model of the proposed design. In this analysis, all the materials, greenery, geometry, shading and the design elements are considered. From this model heat-maps of the microclimatic parameters after the regeneration are produced, analysed and compared with the existing design. The comparison of the two simulations before and after regeneration is conducted in order to calculate the improvement of the area's microclimate and also to ensure that all the hot-spots and areas that need certain design are going to have acceptable thermal comfort conditions. Leonardo software allows a direct comparison of the results from the two simulations and shows the exact points where the microclimate improvement is going to be stronger and the spots that will not be affected. The new area results include analysis for all the microclimatic parameters (air temperature, wind speed, surface temperature, relative humidity and thermal comfort index UTCI). This analysis is made with:

- Heat-maps of the air temperature, wind speed, surface temperature, relative humidity and thermal comfort index UTCI. With the heat-maps can be tested whether the design can reach certain design goals.
- Comparison figures of parameters before and after the regeneration in certain places of the regeneration areas (Figure 29). This comparison usually includes areas with special interest or difficult to achieve comfort areas (hot-spots) and shows each parameter distribution throughout a day. Figure 29 is an example of such distribution for the air temperatures that is made for the regenerated area in Souda, Chania. With dashed line appears the temperatures of the existing area in certain spots and with this same color continuous line the air temperatures of the regenerated spot.

- Percentage distribution figures of all the designed area for before and after regeneration (Figure 30). These figures show the percentage of each parameter as appears in the whole regeneration area in a selected time. Usually, the time that is selected for the analysis is the hours that the maximum temperatures are observed. Figure 30 shows the distribution percentage diagrams for the index UTCI for Souda square, Chania. With such diagrams, the benefit of the new design proposal in comfort is obvious.

**8. Calculation of energy savings for the surrounding buildings**

As a final step, the energy savings from the cooling demands of the buildings in the area are calculated. The simulation results from ENVI-met can be used for the creation of weather files used by any building simulation tool.

Another way to calculate the energy savings is through the ENVI-met Pro software analysis that is the same with ENVI-met 4 only has a commercial license that allows the estimation of the building energy savings.

With these steps, the analysis of the microclimate is complete and the improvement of comfort conditions and energy demand due to the new design is calculated.

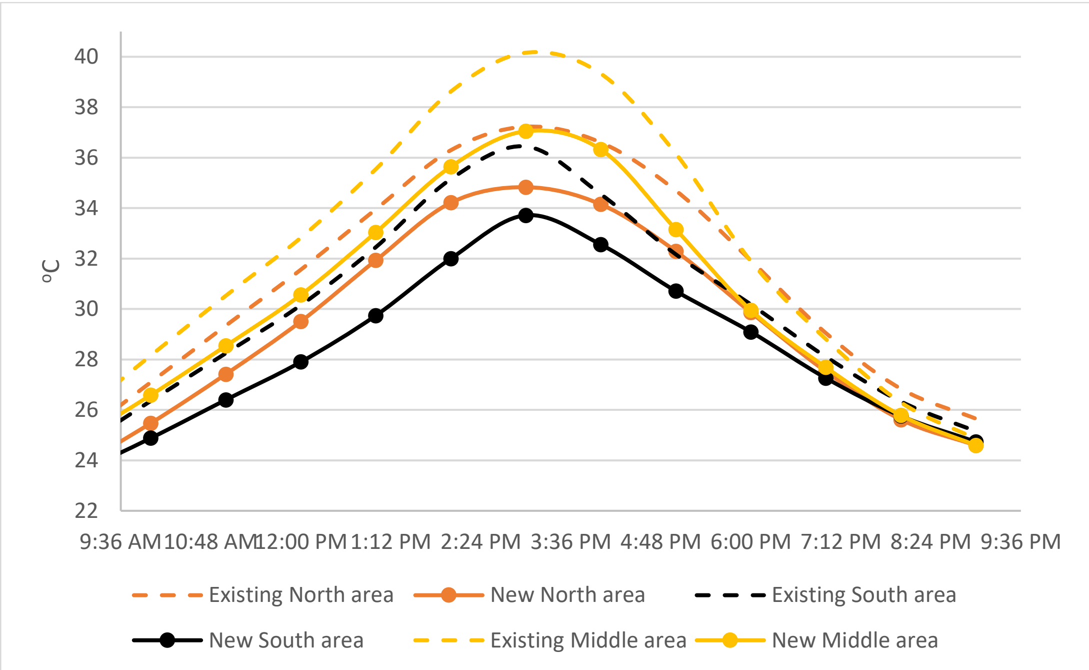



Figure 29: Temperature distribution for the area before and after regeneration.

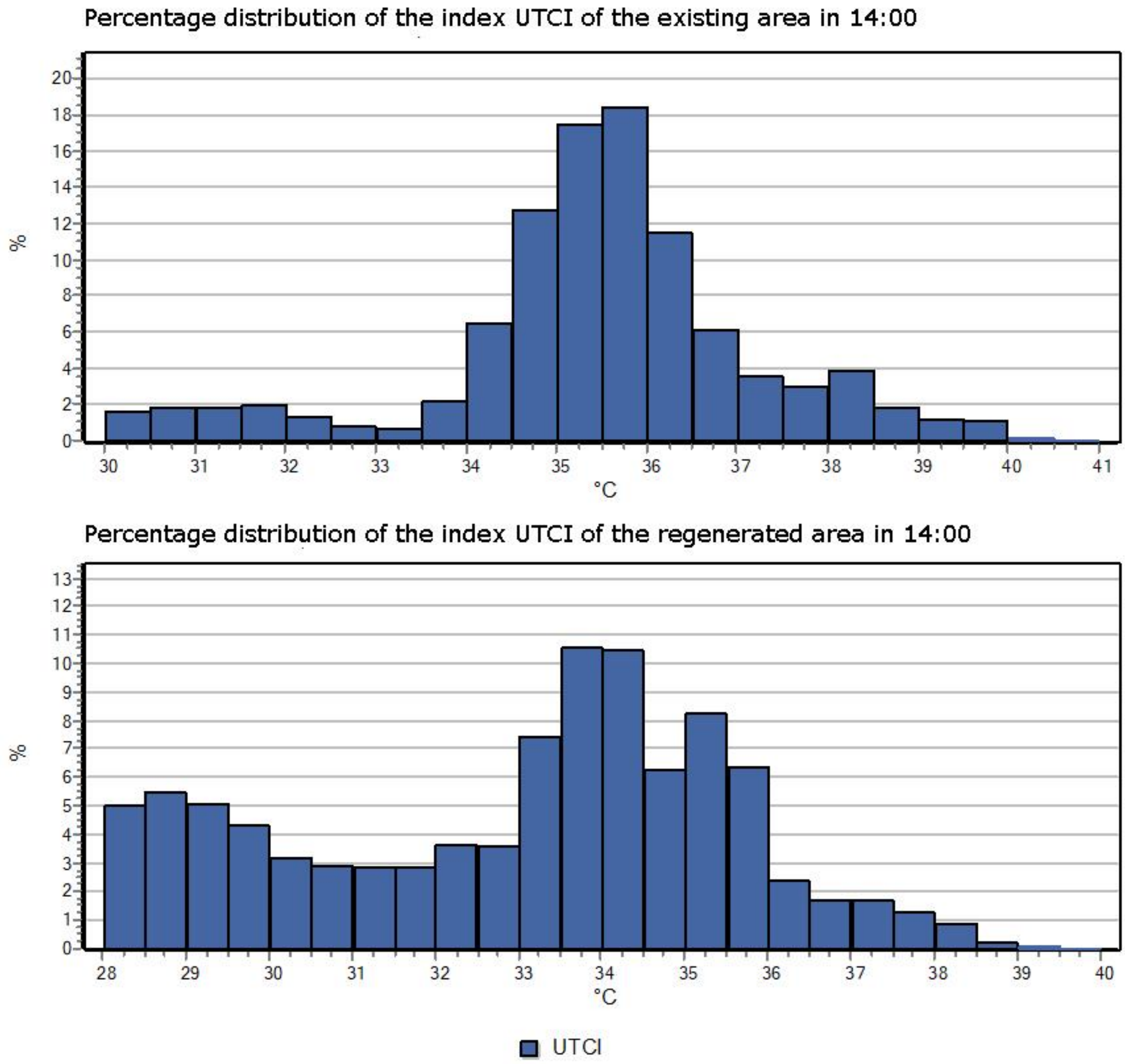



Figure 30: Percentage distribution of the index UTCI of the area before and after regeneration.

# 7. Implementation of the methodology in urban areas in Crete

The described methodology and the bioclimatic decision-making tool intend to guide the design team to follow a bioclimatic approach regarding the design of urban open spaces. This approach provides a new dimension on the initial design decisions and introduces a new palette of possible solutions.

The study introduces a new bioclimatic decision-making tool that is simple and assists in prioritising of possible alternative design scenarios of an urban open space. This tool can be used without demanding any specialized knowledge and the results can be used only for comparison between the tool's different cases. This makes the tool useful mainly in order to determine which parameters of a new design can provide better comfort conditions without the ability to calculate the case-specific comfort boundaries.

Apart from the tool explained above, the study proposes a detailed methodology and case-specific analysis that includes calculation of the bioclimatic outdoor indexes, comparison diagrams and percentage distributions of the microclimate parameters. Additionally, with the described methodology, energy savings of the surrounding buildings can be calculated. The proposed methodology is referred to specialized knowledge and complex measurements and calculations and does not follow the simplicity of the bioclimatic design tool but is necessary for calculating correct bioclimatic index values and comparing the different design scenarios.

## 7.1. Western coastal zone in Rethymnon City

One example of the methodology application is in a newly regenerated area in Rethymnon City, Crete, Greece (35 $^{o}$22 N, 24$^{o}$28E). The selected area of interest is a 25,000m$^2$ area in the center of Rethymnon where the climate is categorized as hot-summer Mediterranean (Csa). The area has both coastal characteristics since a part of it, is nearby the sea and urban characteristics because the eastern part is within the city area. The area is recently regenerated and fully funded by European funds for construction, in order to have better microclimatic conditions. Weather-stations are placed in lower boundaries to measure the microclimate differentiations and development throughout the time. The construction was completed in December of 2015 and the microclimatic parameters have been continuously logged since March of 2014. The previous state of the area (Picture 30) includes two parking areas, one roundabout square and two roads (one near the sea and one behind the playground). The whole area is fully regenerated as shown in Picture 30 with additional trees in front of each parking space, along the sea road, the court fence, while the parking area with the roundabout has been removed. The proposed design included parking areas with trees and compressed soil, cool paving materials, removal of parking spots in a big area and newly proposed greenery areas. The design has been concluded by the design team as appears in Table 13 and after the funding programme, the design has been updated according to the bioclimatic methodology suggestions. In general, the area materials and greenery were changed in favour of bioclimatic design.

Table 13: Design team of the project "Bioclimatic regeneration of western coastal zone of Rethymnon".

| | |
|---|---|
| **Architectural design** | T. PAPAGIANNIS & PARTNERS AEM |
| | G. ANDREADIS & PARTNERS OE |
| **Electrical - Mechanical design** | M. THEODOSIOU |
| **Greenery design** | L. STAMATOPOULOS |
| **Topographic - Transportation study** | N. KOUVAS |
| **Consultants** | O. KLOUTSINIOTI specialist in urban regeneration projects |
| | M. KADARTZIS specialist in urban design |
| | P. KOUGIANOU specialist in urban design |
| | G. FATSEAS specialist in architectural lighting |
| **Bioclimatic study and validation** | M. TSITOURA specialist in bioclimatic urban design |

The microclimatic weather data are continuously measured with the use of three weather stations that were installed in certain spots within the area, at the height of 3.00m and cover the different microclimatic conditions in all the area (Picture 31). Table 14 shows the sensors that were installed at every measurement point. The data are saved on an SD card and are transferred wirelessly to the main server that is accessible through the internet. The measurement system is logging data every 10 minutes from May of 2014 till now after some periods of stopping for constructions and weather-station repairs.

Table 14: Weather stations sensors.

| Sensor Type | Accuracy | Range |
|---|---|---|
| Temperature Sensor (°C) | 0.1 | -20 to 80 |
| Humidity Sensor (%) | 2 | 0 to 100 |
| Anemometer (m/s) | 0.1 | 0 - 30 |
| $CO_2$ Sensor (ppm) | ± (50 + 5% reading) | 0 to 5,000 |
| Pyranometer class B (W/m²) | 5 to 20 μV/W/m² | 0 to 2,000 |

The microclimatic simulations were made with the use of the software ENVI-met 3.1 for both the old and new design of the area. The weather data for the simulations were exported from a local weather station in order to calculate the typical summer day of the city of Rethymnon. The applied model consisted of an area of 250m x 250m with a grid of 0.5m where all the material properties, the urban geometry and the green areas with the exact tree species are added. The simulation was conducted for 3 days and for the validation of the data of the last day were used. The parameters that were compared for the validation of the model are ambient temperature and humidity since the thermal comfort is mainly affected by them. The wind velocity was excluded from this study due to its high calculation complexity since it is considered a factor that benefits comfort in summer. Additionally, the solar radiation was excluded from the validation, considering that the effect in the comfort conditions is included in the ambient temperature and humidity. Picture 32 shows a heat-map from the simulation results of ambient temperature in 12:00, produced by the software Leonardo of the whole area for the new design proposal. The software can extract time series data for every microclimatic parameter needed at any point of the area.

Figure 31 shows the measured and simulated temperatures from all the measuring points. The comparison of the simulated and measured values can prove that the model is sufficiently calibrated, and it can be used for implementing further design scenarios in this area. As shown in Figure 31 the measured and simulated values have very small differences that are below 1°C.

The Root Mean Square Deviation (RMSD) for the simulated and measured air temperatures and the RMSD for the simulated and measured relative humidity of the four measurement points are listed in Table 15.

Table 15 RMSD for simulated and measured points

| Points | Root Mean Square Deviation (RMSD) of $T_a$ | Root Mean Square Deviation (RMSD) of RH |
|---|---|---|
| **Point 1** | 1.36 | 6.5 |
| **Point 2** | 0.63 | 8.7 |
| **Point 3** | 0.34 | 2.3 |
| **Point 4** | 0.71 | 5.1 |

The comparison of the simulated and measured values proved that the model is sufficiently calibrated, and it can be used for implementing further design scenarios in this area. Since these results showed quite a good approximation with the measured parameters, analysis on similar areas in the city of Rethymnon or even on the island of Crete can be considered valid.

The results of the new design according to the methodology and as measured during the summer of 2016 showed that the new design affects:

- Reduction of the mean maximum air temperature by 1.69°C (1);
- Reduction of the areas $DH_T$ by about 45.9% (4);
- Reduction of the mean maximum surface temperature by 8.45°C (2);
- Improvement of the user thermal comfort by about 46.00% of the index UTCI (3).

Picture 30: Case study area old and new design.

Picture 31: Different weather stations that were installed within the area.

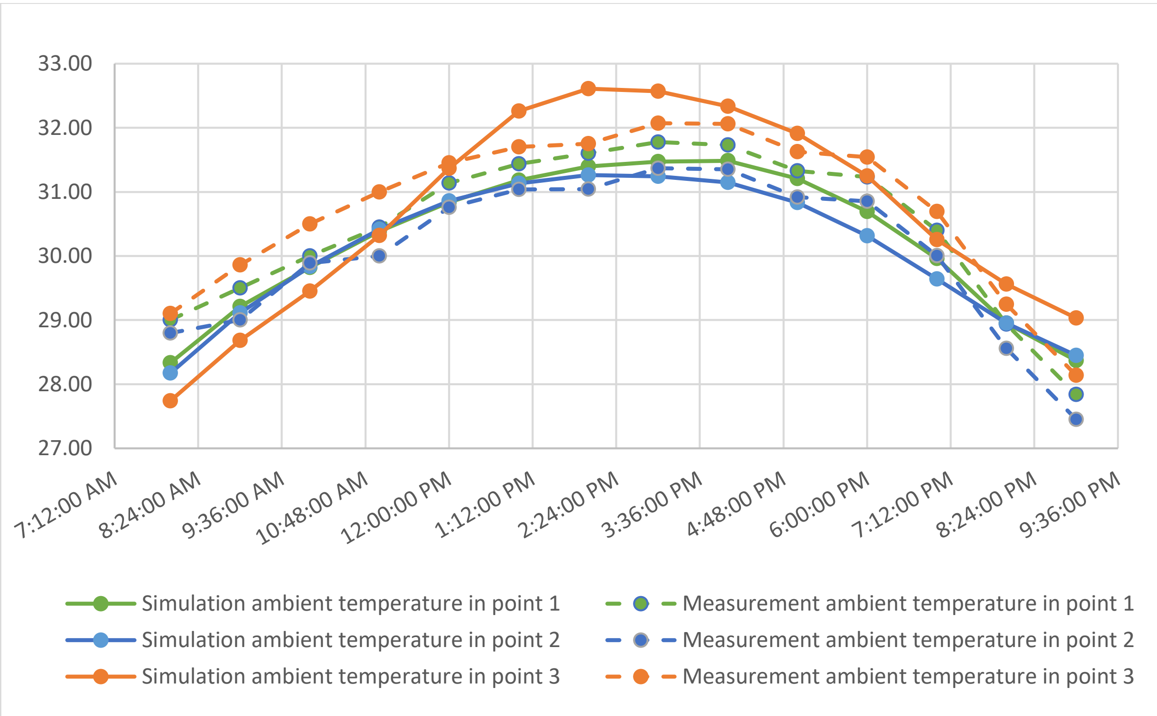
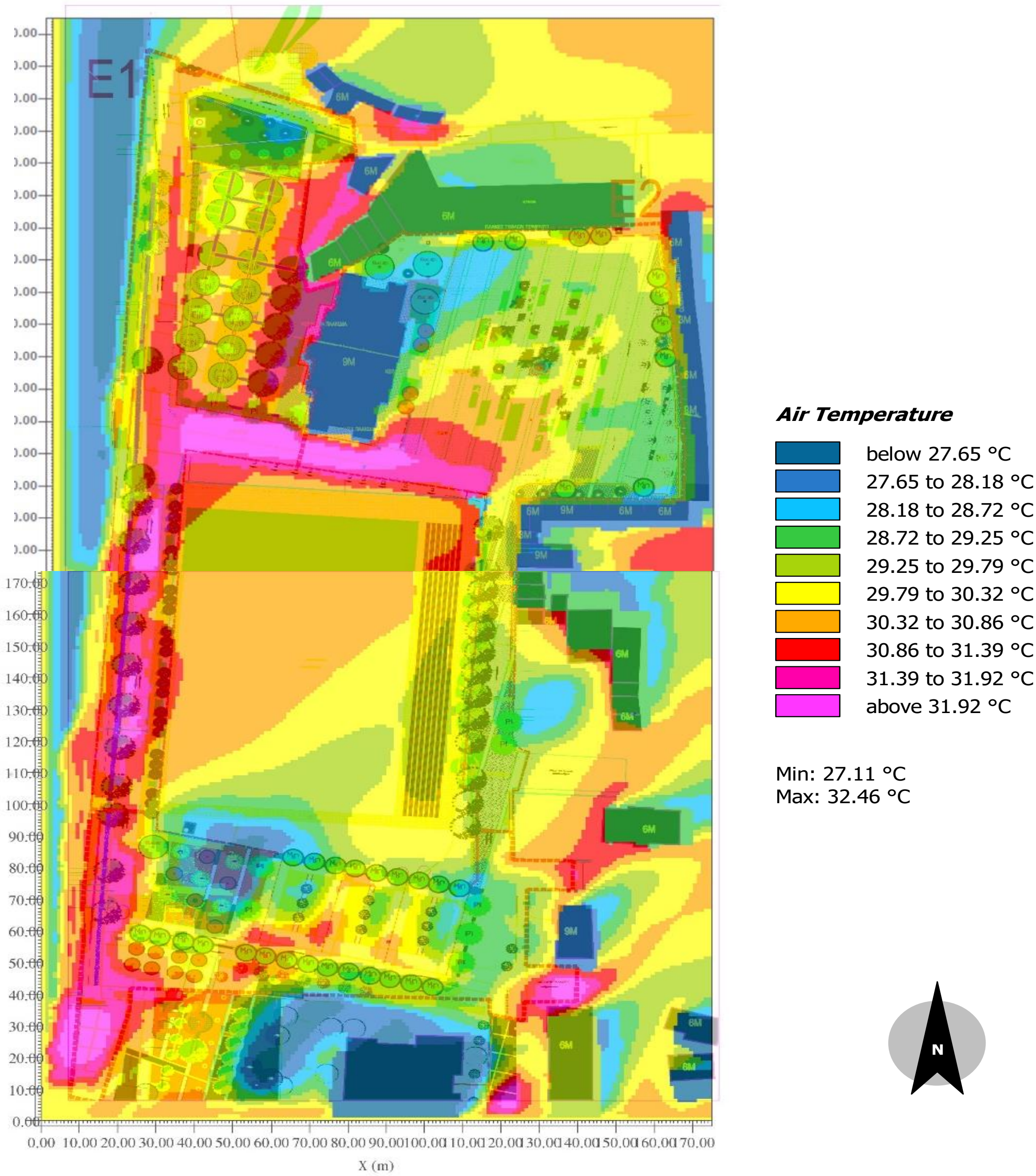



Figure 31: Comparison of the ambient temperature measurements and simulations in the points of the weather stations 1,2,3.




Picture 32: Thermal map of the design area after the regeneration.

## 7.2. Agelou Sikelianou Street Rethymnon City

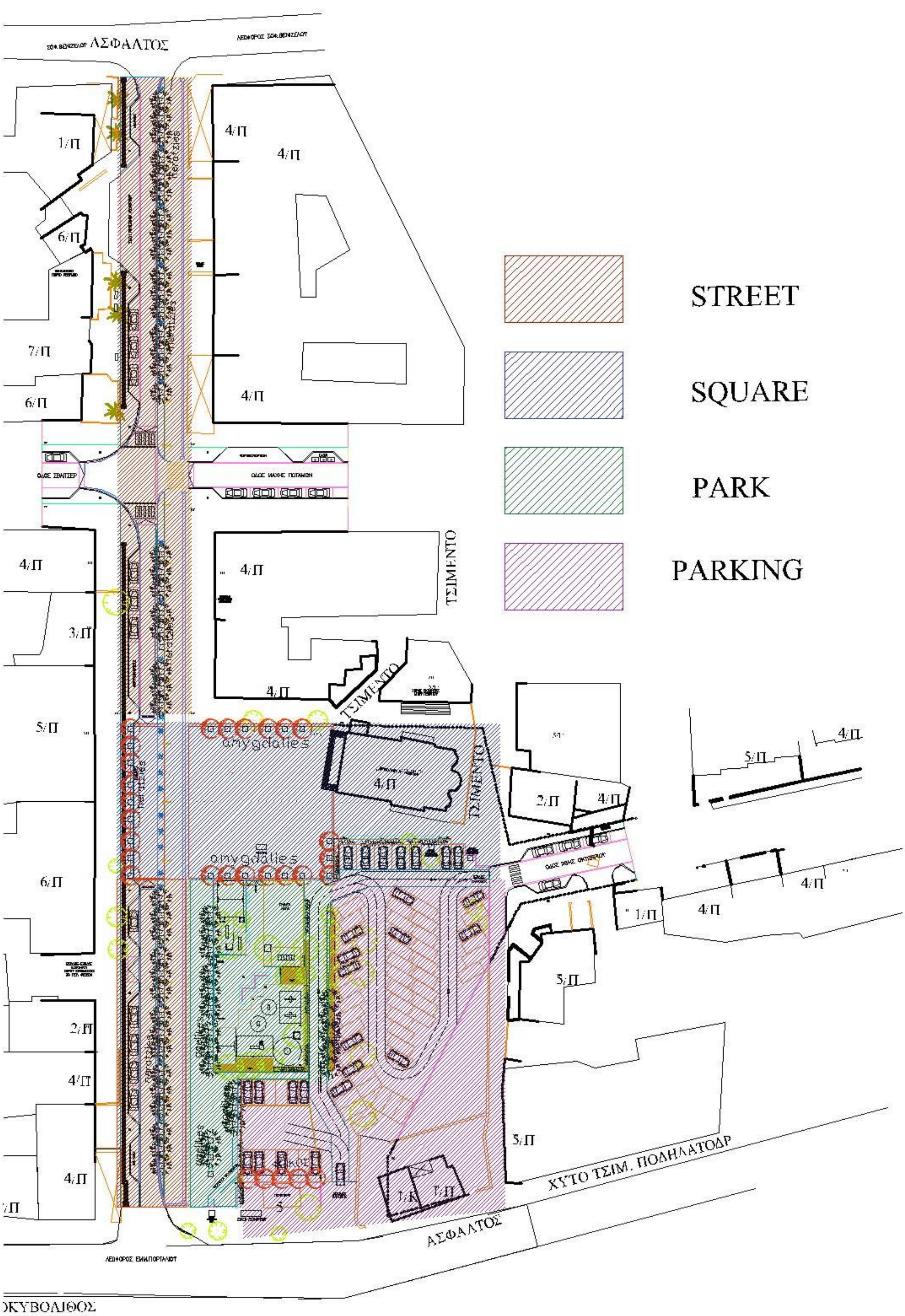
Agelou Sikelianou street is a connection road between the two main roads of the city of Rethymnon, Crete. Its northern part is the coastal road and the beach of Rethymnon. It has a small green park and the church of Saint George but in our days the whole area is used as parking area. Due to unorganized space management, the cars are left by the citizens at anyplace, causing a chaotic result (Picture 33).


Picture 33: Intervention areas as it is today

The proposed design (Picture 34) widens the pavements and creates a continuous zone of greenery, with trees and grass, between the road and the pavement, park and square of Saint George area. In front of the church, a new square is created with trees, open areas, and benches. The park is just redesigned, and all its trees are maintained while new trees are added. In the area behind the park a large organised parking place is created with marked spots that are equal to the initial number of parked cars. In this parking, spots for electric car chargers are included. The whole study is fully funded and is currently under construction. The materials that are used are photocatalytic asphalt in the road, natural surfaces of grass, compressed soil and sand in the parking and playground and cool coatings for the square and pavements. All the design team as appears in Table 16 consists of persons working for the technical services department in the municipality of Rethymnon and the final architectural design depicts our suggestions according to the implementation of the methodology and the use of the bioclimatic design tool. The bioclimatic aspects of the final design and the microclimatic amelioration of all the parameters are adequately analysed in the bioclimatic study.

Table 16: Design team of the project “Regeneration of Agelou Sikelianou str and Saint George Square in Rethymnon.

| | |
|---|---|
| **Architectural design** | **TECHNICAL SERVICES DEPARTMENT OF MUNICIPALITY OF RETHYMNON** |
| **Electrical - Mechanical design** | TECHNICAL SERVICES DEPARTMENT OF MUNICIPALITY OF RETHYMNON |
| **Greenery design** | TECHNICAL SERVICES DEPARTMENT OF MUNICIPALITY OF RETHYMNON |
| **Topographic - Transportation study** | TECHNICAL SERVICES DEPARTMENT OF MUNICIPALITY OF RETHYMNON |
| **Bioclimatic and innovation study** | M. TSITOURA specialist in bioclimatic urban design |



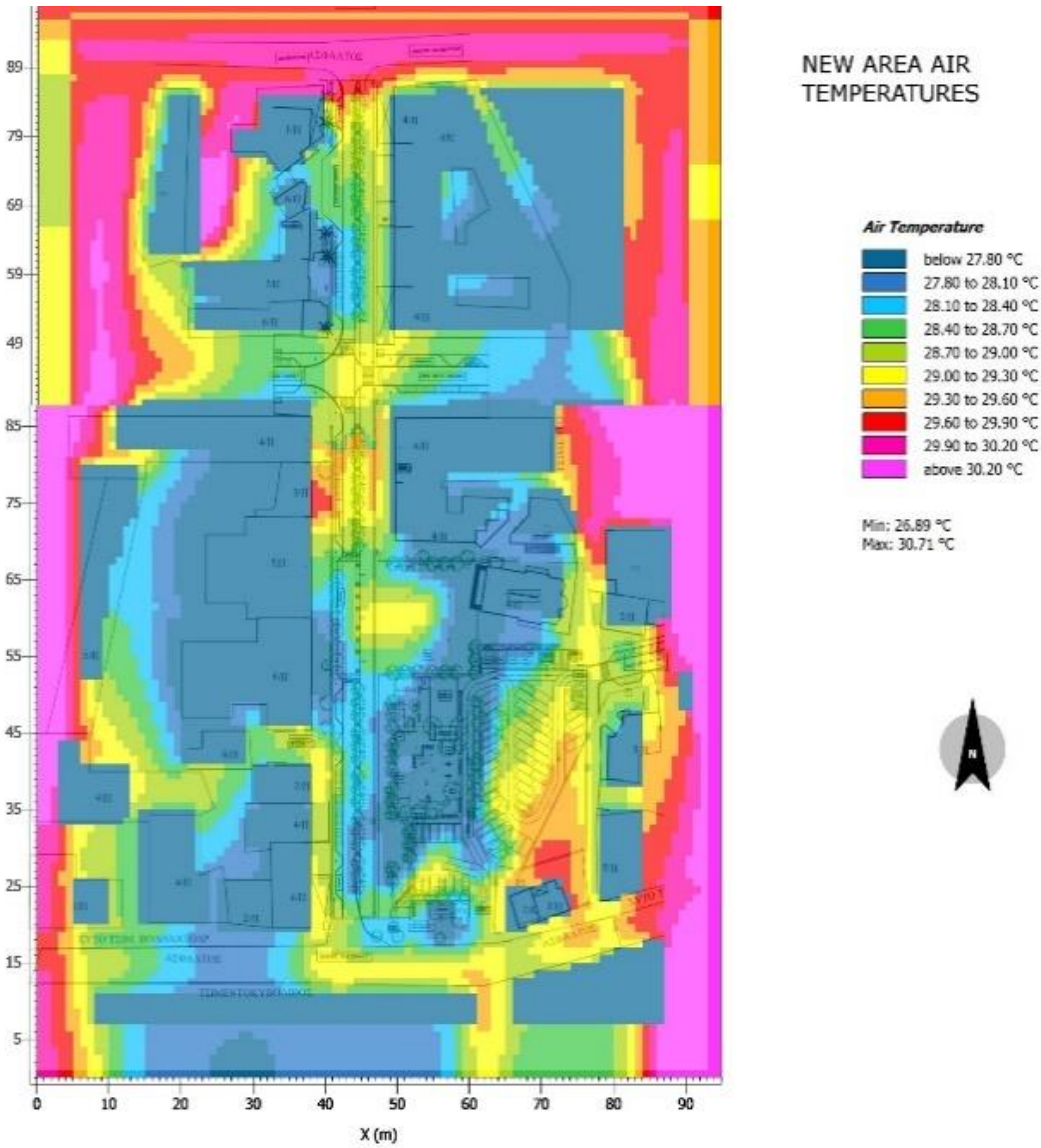

Picture 34: New design proposal.

The proposed methodology for "research on design" as implemented in this street is expected to have a lot of benefits in the urban realm of Rethymnon. The whole area will be fully regenerated, and hopefully, people will use it more, not only as a parking place. The microclimatic analysis by simulation showed that with the new design proposal the thermal comfort and radiation environment will be considerably improved especially on the pavement area. Picture 35 and Picture 36 show the heat-maps that come from simulation results, of the temperature distribution during summer in 14:00 while Table 17 shows the bioclimatic indices values as calculated on different spots before and after regeneration. As shown in Table 17, the maximum air temperature difference will be 2.0$^{o}$C on the pavement area and the thermal comfort is expected to be improved about 14.0%. The new design will also affect a lot the $DH_{UTHI}$ where the bioclimatic index UTCI will be in acceptable comfort boundaries (<26$^{o}$C). According to the simulation results, the pavement area is expected to have more degree-hours of thermal comfort conditions.

Table 17: Bioclimatic indexes values before and after regeneration of Ag. Sikelianou street.

| | **Ambient Temperature** | | **$DH_T$** | | **Surface temperature** | | **UTCI index** | | **Degree-hours of UTCI >26$^{o}$C** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **$^{o}$C** | **%** | **DH** | **%** | **$^{o}$C** | **%** | **$^{o}$C** | **%** | **DH** | **%** |
| **Road** | 0.60 | 1.77 | 7.18 | 14.13 | 6.93 | 15.63 | 4.61 | 11.73 | 12.62 | 63.07 |
| **Pavement** | 2.00 | 5.90 | 13.70 | 26.45 | 11.50 | 25.83 | 5.38 | 13.18 | 18.52 | 61.07 |
| **Square** | 0.66 | 1.91 | 10.44 | 19.09 | 11.36 | 24.00 | 4.96 | 11.55 | 25.82 | 61.74 |
| **Park** | 1.01 | 3.12 | 8.32 | 21.63 | 0.38 | 1.00 | 0.01 | 0.30 | 0.25 | 2.97 |
| **Parking** | 0.14 | 0.42 | 1.66 | 3.63 | 10.36 | 22.33 | 1.00 | 0.24 | 2.27 | 9.60 |


Picture 35: Heat-map of the temperature distribution with the new design proposal.




Picture 36: Heat-map of the temperature distribution at 14:00 in the existing areas.

### 7.3. Souda Square, Chania City

The area has a surface of 5,000$m^2$ and is located on the entrance of Chania port (35$^o$29' N, 24$^o$04' E). Because of its privileged location, the square constitutes the first urban open space that visitors are using when disembarking from the ships. In its nowadays form, it consists of three small planted islands between wide roads and is mainly used as a free parking place (Picture 37). The area during the arrivals and departures of boats is overcrowded with people seeking directions, heavy trucks, buses, and cars. The drawings in Picture 38 and Picture 40 show the existing area site plan and the proposed design. The new area configuration that has been designed, has secured funding and construction will soon begin (Table 18). The existing streets are narrowed, parking places are removed and two large pavements on the eastern and western areas are created. Especially the western pavement is fully planted and shaded in order to receive organized resting areas. The northern part of the area has a commercial use and is located 1.3m. higher from the southern part because of the natural soil inclination. The northern part is covered by trees and benches while the south part is more natural, with large grass areas, trees and two water fountains that are connected with water routes as shown in Picture 39. There is an extended use of cool coatings materials and natural soils, to minimize surface temperatures.

Table 18: Design team of the project "Regeneration of Souda square, Chania".

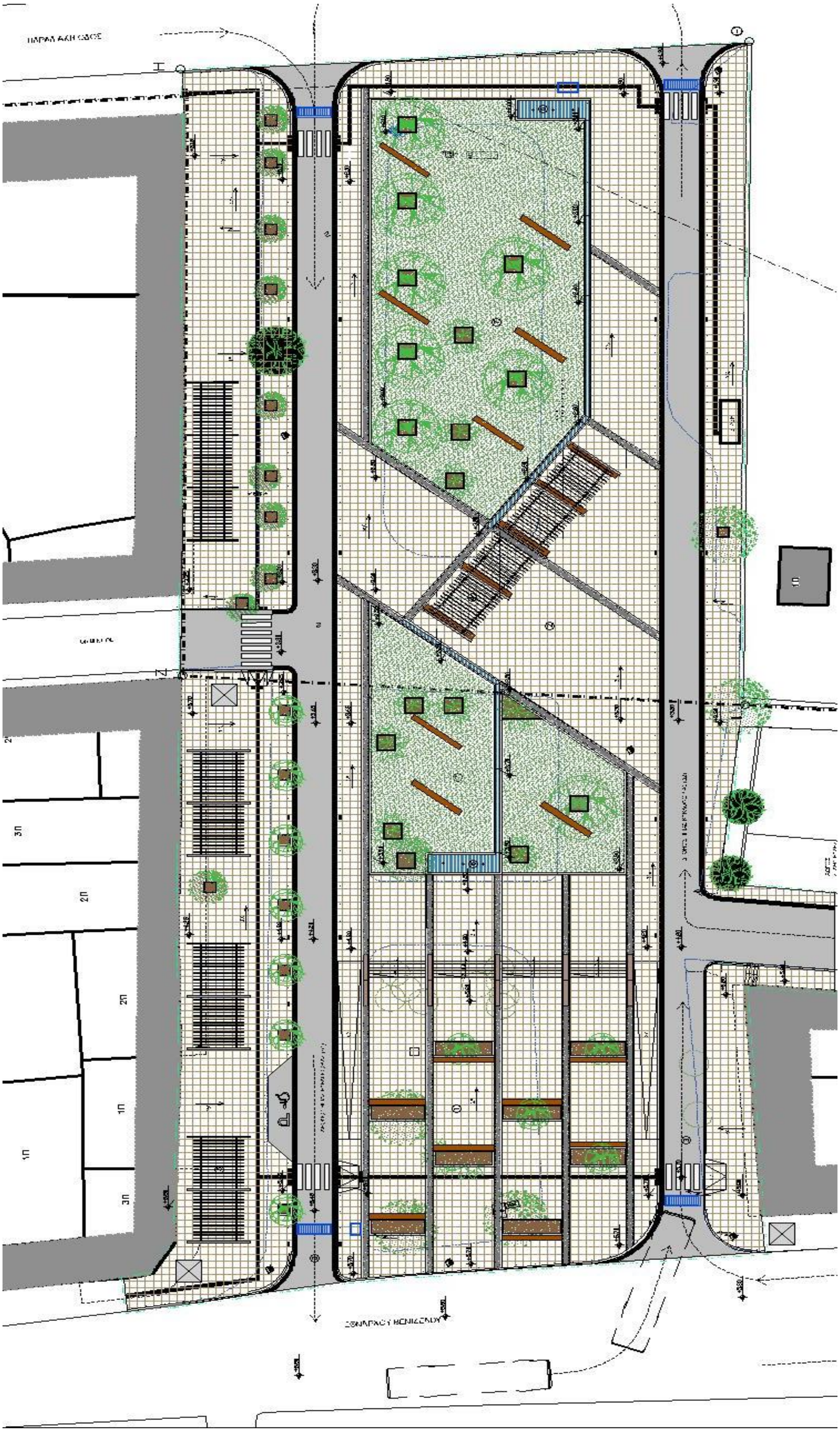
| | |
|---|---|
| **Architectural design** | M. TSITOURA |
| | M. MICHAILIDOU |
| **Electrical - Mechanical design** | TECHNICAL SERVICES DEPARTMENT OF MUNICIPALITY OF CHANIA |
| **Greenery design** | GREENERY DEPARTMENT OF MUNICIPALITY OF RETHYMNON |
| **Topographic - Transportation study** | TECHNICAL SERVICES DEPARTMENT OF MUNICIPALITY OF RETHYMNON |
| **Bioclimatic and innovation study** | M. TSITOURA specialist in bioclimatic urban design |

Picture 37 : Photos of the existing area, Souda.


Picture 38: Existing area topographic diagram.

Picture 39: Proposed design representations of Souda square.

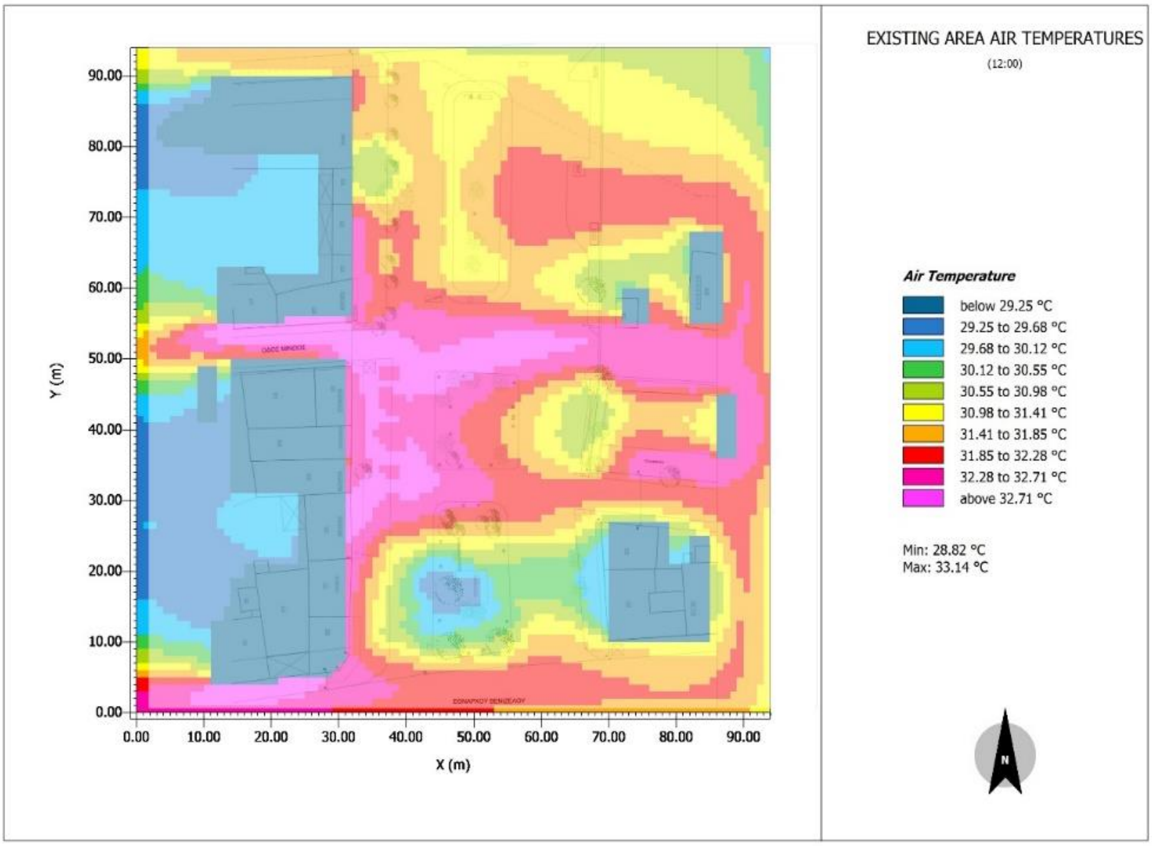
In the process of the new design, the proposed methodology was fully applied, and several greenery, pavement and design scenarios were simulated. The proposed design according to Table 19 is expected to reduce ambient temperature about 2.5$^{o}$C in high pick hours and especially in the Northside in order to improve thermal comfort conditions and with the addition of sitting areas all over the square to encourage the use of the area. Picture 41 shows a heat-map of the existing area and Picture 42 of the proposed design after regeneration at 12:00, produced by the software Leonardo. As can be observed in the pictures, the existing area has large amounts of thermal heat coming from the port side. The new design has tried to minimize this thermal heat by adding trees and shading elements so as to create viable sitting areas. Also, the water fountains and route are added in order to help with the polluted air and noise from the road especially when a ship arrives or departs. Figure 32 and Figure 33show charts of the surface temperatures percentage at 12:00 that covers all the area surface for both before and after the design application. Figure 32 shows that about 70% of the surface temperatures in the existing area are between 31.5 and 33.0$^{o}$C while in Figure 33the expected improvement the new design can lower them up to 4.0$^{o}$C.



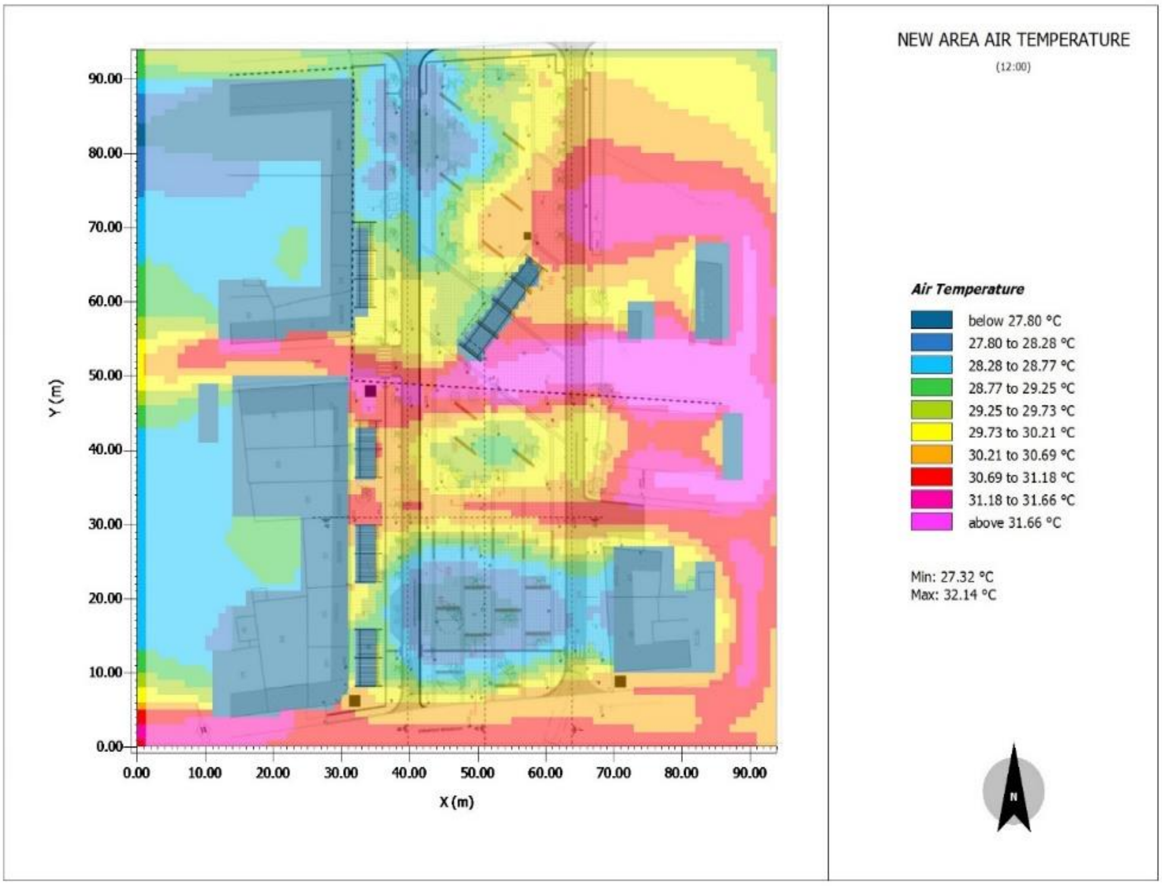
Picture 40: Proposed design.

Table 19: Values of bioclimatic indices before and after the regeneration of Souda square, Chania.

| | Ambient Temperature | | $DH_T$ | | Surface Temperature | | UTCI index | | $DH_{UTCI}$ >26°C | |
|---|---|---|---|---|---|---|---|---|---|---|
| | °C | % | DH | % | °C | % | °C | % | DH | % |
| **North side** | 2.40 | 6.44 | 20.86 | 30.42 | 14.72 | 31.67 | 10.03 | 22.49 | 41.48 | 88.25 |
| **South side** | 2.72 | 7.49 | 18.76 | 34.66 | 6.87 | 17.34 | 3.57 | 9.24 | 12.95 | 7.03 |
| **Eastern pavement** | 2.27 | 5.78 | 17.93 | 24.51 | 7.06 | 12.69 | 1.42 | 2.99 | 10.29 | 15.09 |
| **Southern pavement** | 0.97 | 2.57 | 16.18 | 22.39 | 17.51 | 31.63 | 1.98 | 4.79 | 21.07 | 32.72 |




Picture 41: Heat-map of the existing configuration of Souda square.




Picture 42: Thermal map of the new design proposal of Souda square

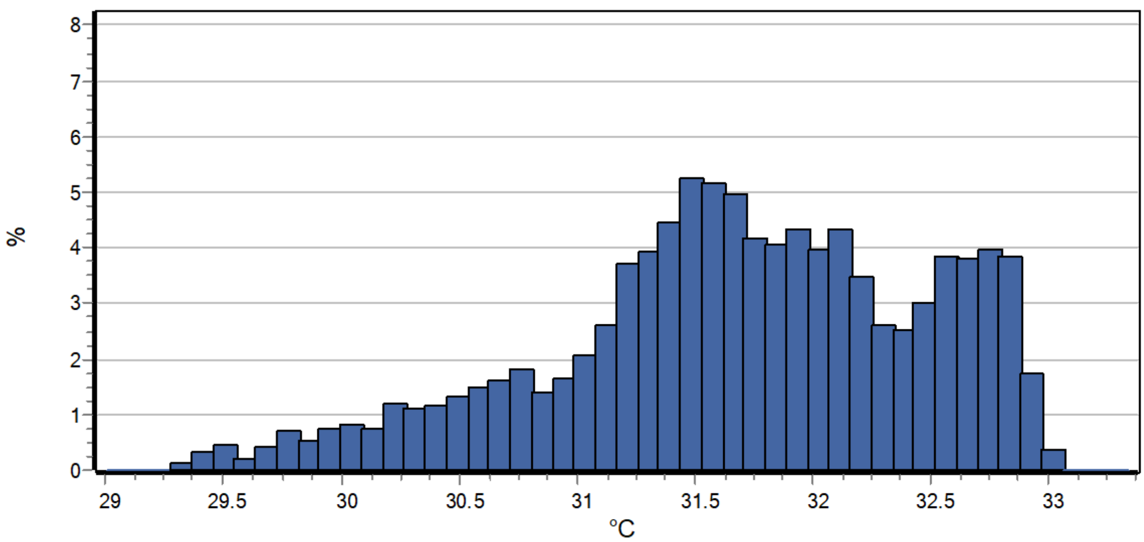



Figure 32: Percentage frequency distribution graph of surface temperatures at 12:00 of the current design of Souda square.

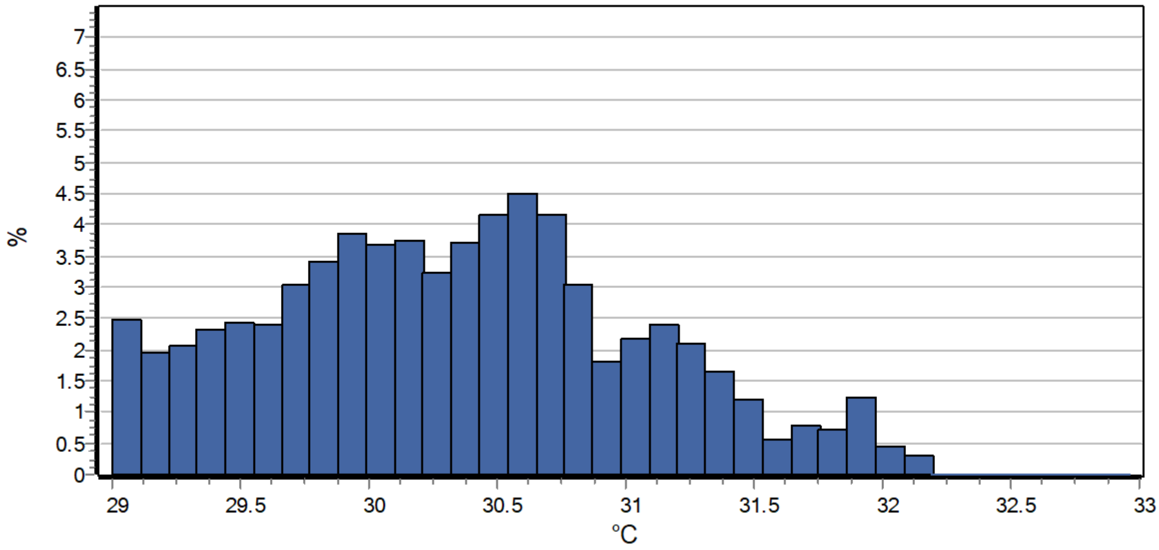



Figure 33: Percentage frequency distribution graph of surface temperatures at 12:00 of the proposed design.

## 8. Building energy savings from bioclimatic urban open space design

Nowadays 40% of energy consumption comes from the building sector. According to trends, the fraction of people expected to live in city centers by 2050 will be almost 70%. Furthermore, the energy demand fraction of the cities will follow the same pattern. For the years 1970-2010 the average increase in cooling loads of typical buildings is about 23% (Santamouris 2014). For these matters, there major interest in increasing energy efficiency and reduction of energy demands within the city centers. The energy demand of buildings not only depends on its construction and use but also on its location, microclimatic conditions, and interactions with other buildings due to shading effects (Moonen et al. 2012; Tsitoura et al. 2016; Tsitoura et al. 2014). Studies have shown that by appling passive and active cooling intervations in the outdoor environment such as the use of water, greenery, shade, cool materials, and reflective materials can reduce the ambient temperature up to 2-3$^{o}$C (Santamouris et al. 2017; Rosso et al. 2018; Kolokotsa et al. 2017). Parameters like maximum air temperature, wind speed, sky view factor, radiation, and the greenery coverage have a certain impact on the microclimate of the external environment of the building; therefore they contribute to the energy savings by exploiting the passive cooling effect (Allegrini et al. 2012; Vallati et al. 2015; Kolokotroni et al. 2006; Geros et al. 2005; Ghiaus et al. 2006; Smith & Levermore 2008). Furthermore, we can obtain even larger energy savings if the microclimate control can be combined with smart cooling systems and renewable technologies which can lead to near-zero energy buildings (Kolokotsa 2017).

The current study focuses on the reduction of cooling loads due to a) minimization of the Urban Heat Island phenomenon; b) the bioclimatic design of urban open spaces; c) the use of innovative materials and, d) smart cooling systems (Tsitoura et al. 2017).

Studies comparing the energy efficiency of buildings with different quality of thermal insulation within the urban environment using detailed simulation models showed that the cooling load reduction can be in the range of 5-10% accompanied with the proper parameter management (Wong et al. 2011). Zoras et. all concluded that after CFD simulation analysis in the city of Serres, Greece that is combined with meteorological measurements a reduction of 1$^{o}$C can reduce the cooling loads by 6.9% (Zoras et al. 2017).

Studies comparing buildings energy demand in urban and rural areas showed that on average the cooling load in urban buildings is about 13% higher compared to similar rural buildings

(Santamouris 2014). In Greece, studies that were conducted using measurements from about 30 urban and suburban points in Athens showed that the peak cooling load between the city center and reference areas different about 13.8kWh/ $m^2$ (Santamouris et al. 2001). In hot and arid environments like Bahrain, the domestic urban load is measured at 17%-19% higher than the rural load (Radhi & Sharples 2013). In Beijing, the same percentage is found to be 11.28% while in certain hot days reached 20.4% (Li et al. 2014) while, additionally, a large green space was measured to reduce 60% of the cooling loads (Zhang et al. 2014; Hsieh et al. 2018).

The combination of two different types of simulations or co-simulation techniques makes the calculation of the energy savings from the well-designed microclimate quite difficult. During the last decade, several studies have tried to develop integrated models for calculating the impact of microclimate on the energy demand of buildings (Roset & Vidmar 2013; Bouyer et al. 2011; Tanimoto et al. 2004). The calculations are made either by one model that combines the building and its surrounding microclimate (Mauree et al. 2017; Schwede & Sheng 2017; Huang et al. n.d.) or by combining two different simulation programs into an integrated model (Schwede & Sheng 2017; Yang et al. 2012; Kolokotroni et al. 2010).

The aims of this part of the research are:

- To calculate the energy savings from the cooling loads of the surrounding buildings by changing the microclimatic conditions around them. The case study of an open area within the Mediterranean climate concludes that 15-23% reduction on the summer cooling loads can be achieved with a 1.7$^o$C reduction of the ambient outdoor temperatures;
- To introduce a methodology that could combine outdoor and indoor simulation tools;
- To estimate the energy benefits and the $CO_2$ reduction from bioclimatic design applications on the outdoor space of old cities with buildings constructed from stone and height between 8-12m.

One of the case study examples is a bioclimatic redesign of a 25,000 $m^2$ area in the old part of the city of Rethymnon, Greece (35$^o$22 N, 24$^o$28 E), where microclimatic simulations were conducted with the use of software ENVI-met 3.1, and the model was validated through on-site measurements with weather stations that were located inside the area of interest at a 3m height above ground level. The methodology for the building energy savings calculation followed the described methodology of bioclimatic outdoor design including the following steps:

1. Classification of the surrounding buildings typology, according to their use, construction materials, and placement;
2. Performing distinct building simulations for both before and after their regeneration. For the current research, the surrounding building simulations are conducted using the software OpenStudio 1.9.0 and EnergyPlus 8.3.0;
3. Calculating the energy savings from the cooling loads and the $CO_2$ reduction of each building that is facing the regeneration area.

**8.1. Building typologies**

The selected area is located in the center of Rethymnon city in the old part of the town where all the buildings apply to the certain typology of form and construction materials that must retain even after extended renovations.

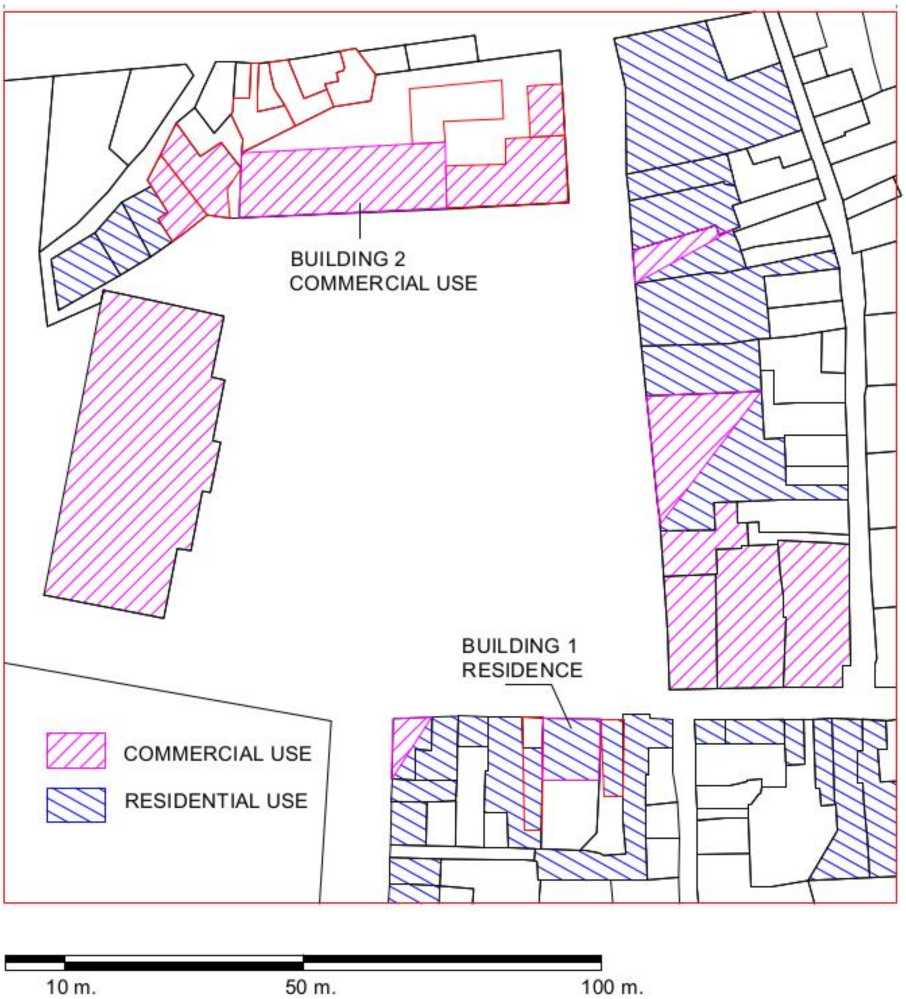
The majority of the buildings are characterized by rectangular shape, attached to each other in a row with common external walls, with windows at similar dimensions and a stable proportion of openings per m$^2$ of facade (Picture 44 and Picture 47). Table 20 shows the typical construction materials and their thermal properties as given by the Greek regulatory agencies of the energy certificates.

Picture 43 indicates the areas of the buildings that will contribute to the calculations, and the type of main use, residential or commercial. As calculated the buildings with residential use cover 7500m$^2$ and the buildings with commercial use cover 6600m$^2$.

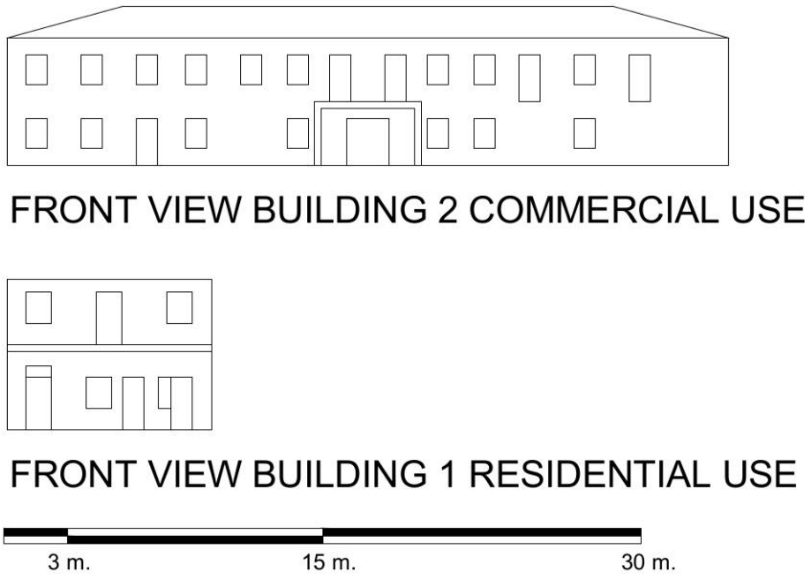
For the building analysis, two typical buildings were selected, one with residential use and one for commercial use. The buildings views on the area are shown in Picture 44 -Picture 48. Building 1 with a residential use is located on the south side of the area, it consists of two floors with a total built area of 200m$^2$ and a measured ceiling height of 4m on the ground floor and 3m on the first floor. The building is recently renovated and is constructed with stone walls without any insulation, and wooden window frames with double glazing. Building 2 with a commercial use is located on the North side of the area, it has two floors with a total built area of 740m$^2$ and a measured ceiling height of 4m on the ground floor and 3m on the first floor. The building is hosting the Police Department and is constructed with stone walls without any insulation, a wooden roof and wooden window frames with double glazing.

Table 20: Typical construction materials and their thermal properties

| Material | Heat conductivity factor U ($W/m^2K$) |
|---|---|
| **Stonewall without insulation** | 3.85 |
| **Brick wall without insulation** | 3.05 |
| **Concrete columns without insulation** | 3.40 |
| **Floor without insulation** | 3.05 |
| **Wooden roof without insulation** | 4.25 |
| **Wooden openings with double glazing** | 2.80 |

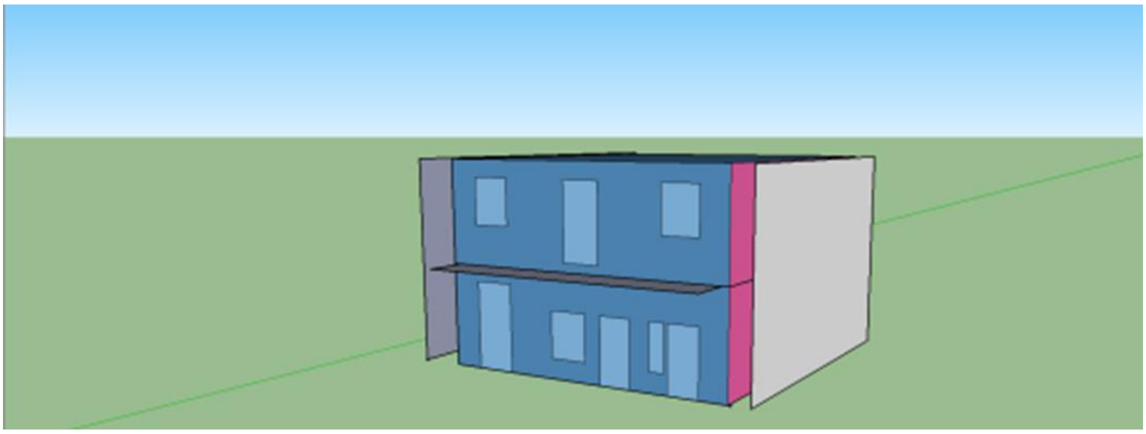



Picture 43: The selected area including the buildings and their uses.



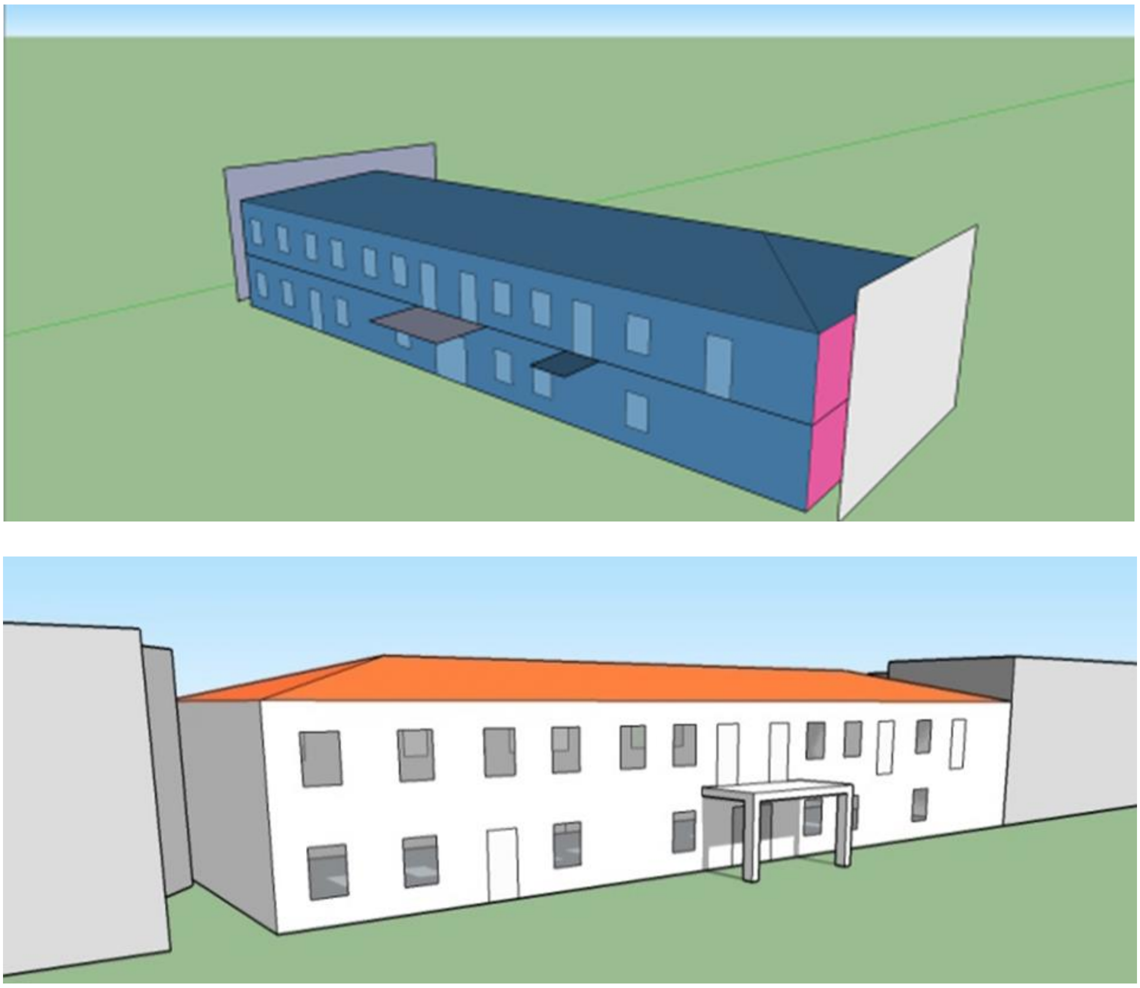

Picture 44: Front view of selected buildings.

Picture 45: Front view of the selected residential building.



Picture 46: Residential building with the software sketch-up plugin open studio.

Picture 47: Front view of the selected commercial building.



Picture 48: Commercial building model with the sketch-up plugin open studio.

### 8.2. Building simulations

The building simulations needed for the calculations of the energy savings for each building typology were conducted with the use of the software OpenStudio 1.9.0. The geometry was inserted from the SketchUp model, the materials, occupancy schedules, and cooling systems for cooling loads calculation were assigned using the OpenStudio plug-in for SketchUp, while the simulation was performed the EnergyPlus 8.3.0. The weather files that are used for the simulations derive from the ENVI-met microclimate simulations for the old and new design as appear in Table 21 and Table 22. Each simulation was performed for four days taking only the last day results for calculating the energy savings. Table 23 shows information that is set to the simulation model according to the Greek standards as described by the regulation for energy calculations such as operating schedules and other important simulation parameters. All the selected buildings are cooled with split air condition units with COP 2.5 with cooling setpoint of 26°C.

Table 21: Microclimatic data for building simulation with the old square design.

| HH:MM | Dry Bulb Temperature (°C) | Dew Point Temperature (°C) | Relative Humidity (%) | Atmospheric Pressure (Pa) | Radiation (Wh/m²) | Wind Direction (°) | Wind Speed (m/s) |
|---|---|---|---|---|---|---|---|
| 1:00 | 25.85 | 18.4 | 72 | 100700 | 0 | 0 | 4.8 |
| 2:00 | 25.65 | 18.1 | 73 | 100700 | 0 | 0 | 5.1 |
| 3:00 | 25.54 | 17.8 | 73 | 100700 | 0 | 0 | 4.8 |
| 4:00 | 25.23 | 17.5 | 73 | 100700 | 0 | 0 | 4.4 |
| 5:00 | 25.00 | 17.2 | 72 | 100700 | 0 | 0 | 4.1 |
| 6:00 | 25.25 | 18.2 | 72 | 100800 | 2 | 0 | 4.4 |
| 7:00 | 25.80 | 19.1 | 72 | 100800 | 165 | 0 | 4.8 |
| 8:00 | 26.00 | 19.9 | 72 | 100900 | 432 | 0 | 5.1 |
| 9:00 | 27.80 | 19.8 | 65 | 100900 | 680 | 0 | 5.1 |
| 10:00 | 29.60 | 19.6 | 59 | 100900 | 892 | 0 | 5.1 |
| 11:00 | 30.58 | 19.5 | 54 | 101000 | 1054 | 250 | 5.1 |
| 12:00 | 31.34 | 19.8 | 54 | 100900 | 1155 | 250 | 4.4 |
| 13:00 | 31.60 | 20 | 54 | 100900 | 1187 | 250 | 3.8 |
| 14:00 | 32.00 | 20.2 | 55 | 100900 | 1148 | 190 | 3.1 |
| 15:00 | 31.36 | 19.7 | 54 | 100900 | 1042 | 190 | 4.8 |
| 16:00 | 30.80 | 19.2 | 54 | 100900 | 875 | 190 | 6.5 |
| 17:00 | 30.00 | 18.6 | 54 | 100900 | 659 | 170 | 8.2 |
| 18:00 | 29.68 | 19.3 | 60 | 100900 | 408 | 170 | 6.7 |
| 19:00 | 28.86 | 20 | 66 | 100900 | 140 | 170 | 5.1 |
| 20:00 | 28.40 | 20.6 | 72 | 101000 | 0 | 140 | 3.6 |
| 21:00 | 27.36 | 19.5 | 69 | 101000 | 0 | 140 | 2.4 |
| 22:00 | 27.00 | 18.3 | 65 | 101000 | 0 | 140 | 1.2 |
| 23:00 | 26.59 | 17 | 61 | 101000 | 0 | 0 | 1 |
| 24:00 | 26.30 | 17.1 | 64 | 101000 | 0 | 0 | 0.7 |

Table 22: Microclimatic data for building simulation with the new square design.

| HH:MM | Dry Bulb Temperature (°C) | Dew Point Temperature (°C) | Relative Humidity (%) | Atmospheric Pressure (Pa) | Radiation ($Wh/m^2$) | Wind Direction (°) | Wind Speed (m/s) |
|---|---|---|---|---|---|---|---|
| 1:00 | 25.5 | 8.8 | 55 | 101900 | 0 | 0 | 4.8 |
| 2:00 | 25.0 | 9.1 | 55 | 101900 | 0 | 0 | 5.1 |
| 3:00 | 24.9 | 9.0 | 56 | 101900 | 0 | 0 | 4.8 |
| 4:00 | 24.7 | 8.9 | 56 | 101900 | 0 | 0 | 4.4 |
| 5:00 | 24.5 | 8.8 | 56 | 101800 | 0 | 0 | 4.1 |
| 6:00 | 25.1 | 8.7 | 55 | 101900 | 0 | 0 | 4.4 |
| 7:00 | 25.6 | 8.6 | 53 | 101900 | 73 | 0 | 4.8 |
| 8:00 | 26.1 | 8.6 | 64.8 | 101900 | 336 | 0 | 5.1 |
| 9:00 | 27.7 | 7.6 | 61.1 | 101900 | 588 | 0 | 5.1 |
| 10:00 | 29.4 | 6.5 | 57.7 | 101900 | 799 | 0 | 5.1 |
| 11:00 | 30.0 | 5.6 | 54.9 | 101800 | 957 | 250 | 5.1 |
| 12:00 | 30.7 | 4.9 | 52.2 | 101800 | 1049 | 250 | 4.4 |
| 13:00 | 30.5 | 4.2 | 49.6 | 101700 | 1070 | 250 | 3.8 |
| 14:00 | 30.2 | 3.6 | 47.3 | 101700 | 1019 | 190 | 3.1 |
| 15:00 | 31.0 | 3.1 | 45.7 | 101600 | 898 | 190 | 4.8 |
| 16:00 | 29.6 | 2.9 | 44.6 | 101600 | 716 | 190 | 6.5 |
| 17:00 | 29.3 | 3.6 | 46.8 | 101500 | 486 | 170 | 8.2 |
| 18:00 | 28.0 | 4.1 | 43 | 101600 | 223 | 170 | 6.7 |
| 19:00 | 27 | 9.1 | 45 | 101600 | 13 | 170 | 5.1 |
| 20:00 | 27.2 | 8.9 | 48 | 101600 | 0 | 140 | 3.6 |
| 21:00 | 26.5 | 9.2 | 52 | 101600 | 0 | 140 | 2.4 |
| 22:00 | 26.0 | 9.4 | 56 | 101600 | 0 | 140 | 1.2 |
| 23:00 | 26.1 | 9.6 | 61 | 101700 | 0 | 0 | 0 |
| 24:00 | 25.0 | 8.1 | 57 | 101600 | 0 | 0 | 0.7 |

Table 23: Configuration of the simulation parameters.

| Parameters | Use | Value |
|---|---|---|
| **Dry Air inserted ($m^3/h/m^2$)** | Residential use | 0.75 |
| | Commercial use | 3 |
| **Illumination (lux)** | Residential use | 200 |
| | Commercial use | 500 |
| **Internal Gains ($W/m^2$)** | Residential use | 4 |
| | Commercial use | 80 |
| **Operating Time** | Residential use | 18 |
| | Commercial use | 10 |

## 8.3. Energy savings from cooling loads

The energy savings from the cooling loads were calculated by the difference between the two simulations of the old and the new design. The simulations were conducted with the same thermal models using two different weather files. Each of them contains microclimatic data extracted from the ENVI-met simulations of the area for 4 days of the summer season.

The cooling demand for both simulations according to different uses in relation to the ambient temperature of the ENVI-met simulations is shown in Figure 34 and Figure 35. Taking into account, the simulation results of the last day as shown in Table 24 and Table 25 the cooling energy demands $E_{CD}$ (kWh) and the energy cooling demands per area (kWh/$m^2$) are demonstrated.

As can be assumed from Figure 34 and Figure 35 the largest energy savings take place during the afternoon. Such results are justified because the new materials have higher albedo and reflectance values; therefore, the total thermal mass of the area is smaller and release less heat during the afternoon hours.

The cooling energy demand of the residence building was reduced by:

$$E_{CD(old)} - E_{CD(new)} = 16.70\ kWh/day\ or\ 0.08 kWh/m^2/day$$

The whole area includes buildings with residential use of about 7,500$m^2$ that reduce the cooling demands by:

$$7{,}500 \cdot 0.08 = 600\ \mathrm{kWh/day}$$

The cooling energy demand of the commercial building was reduced:

$$E_{CD\ (old)} - E_{CD\ (new)} = 37.28 kWh/d\ or\ 0.05 kWh/m^2/day$$

The whole area includes buildings with commercial use of about 6,600$m^2$ that reduce the cooling demands by:

$$6{,}600 \cdot 0.05 = 330\ \mathrm{kWh/day}$$

All the buildings that are included in the area, have reduced cooling demands by:

$$600 + 330 = 930\ \mathrm{kWh/day}$$

The energy savings have directly affected the $CO_2$ emissions from energy consumption. According to the Greek regulation agency for energy certificates, the coefficient of the $CO_2$ reduction for every kWh of electricity is 0.989 (kg$CO_2$/kWh).

According to the energy savings calculated the $CO_2$ reduction for the residence building is:

$$0.08 \cdot 0.989 = 0.079\ \mathrm{kgCO_2/\ m^2/day}$$

and for all buildings with residential use is in total:

$$600 \cdot 0.989 = 593.4 \text{ kgCO}_2\text{/day}$$

Also, the $CO_2$ reduction for the commercial building is in total:

$$0.05 \cdot 0.989 = 0.049 \text{ kgCO}_2\text{/m}^2\text{/day}$$

and for all buildings with commercial use is:

$$330 \cdot 0.989 = 326.37 \text{ kgCO}_2\text{/day}$$

All the buildings that are facing the area, have reduced the cooling demands by:

$$593.4 + 326.37 = 919.77 \text{ kgCO}_2\text{/day}$$

The case study concluded that 15-20% reduction on the summer cooling loads can be achieved with 1.70°C reduction of the ambient outdoor temperatures. Taking into account that the old towns in certain areas of the Mediterranean zone, have similar characteristics regarding the building construction materials and height as well as open space typology pattern. The calculated results from the case study can be used for the estimation of the cooling demands reduction of commercial and residential buildings in such areas. These results are based on detailed simulations. For further research, measurements of the energy loads of the buildings need to be taken to validate the methodology and the real effect of the regeneration. Furthermore, the research indicates that the buildings have large interactions with their surrounding environment. It is for everyone's benefit to implement bioclimatic principles in urban open space design.

Table 24: Cooling energy demands for the residential building.

| **Time** | **Cooling energy needed with the old design [kWh]** | **Cooling energy needed with the old design per m² [kWh/m²]** | **Cooling energy needed with the new design [kWh]** | **Cooling energy needed with the new design per m² [kWh/m²]** |
|---:|---:|---:|---:|---:|
| 1:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 5:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 6:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 7:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 8:00 | 0.45 | 0.00 | 0.10 | 0.00 |
| 9:00 | 2.80 | 0.01 | 1.73 | 0.01 |
| 10:00 | 5.42 | 0.03 | 3.79 | 0.02 |
| 11:00 | 7.52 | 0.04 | 5.75 | 0.03 |

| | | | | |
|---|---|---|---|---|
| 12:00 | 8.86 | 0.04 | 7.34 | 0.04 |
| 13:00 | 9.48 | 0.05 | 8.47 | 0.04 |
| 14:00 | 9.29 | 0.05 | 8.81 | 0.04 |
| 15:00 | 8.51 | 0.04 | 8.05 | 0.04 |
| 16:00 | 6.98 | 0.03 | 5.81 | 0.03 |
| 17:00 | 5.03 | 0.03 | 2.41 | 0.01 |
| 18:00 | 3.21 | 0.02 | 1.25 | 0.01 |
| 19:00 | 1.79 | 0.01 | 0.33 | 0.00 |
| 20:00 | 0.90 | 0.00 | 0.00 | 0.00 |
| 21:00 | 0.29 | 0.00 | 0.00 | 0.00 |
| 22:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 23:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 24:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | 70.53 | 0.35 | 53.83 | 0.27 |

Table 25: Cooling energy needs for the commercial building.

| Time | Cooling energy needed with the old design [kWh] | Cooling energy needed with the old design per m² [kWh/m²] | Cooling energy needed for the new design [kWh] | Cooling energy needed with the new design per m² [kWh/m²] |
|---|---|---|---|---|
| 1:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 5:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 6:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 7:00 | 0.00 | 0.00 | 0.04 | 0.00 |
| 8:00 | 0.04 | 0.00 | 0.04 | 0.00 |
| 9:00 | 4.87 | 0.01 | 4.27 | 0.01 |
| 10:00 | 11.36 | 0.02 | 9.54 | 0.01 |
| 11:00 | 18.90 | 0.03 | 15.59 | 0.02 |
| 12:00 | 25.21 | 0.03 | 21.32 | 0.03 |
| 13:00 | 29.12 | 0.04 | 25.77 | 0.03 |
| 14:00 | 31.47 | 0.04 | 29.29 | 0.04 |
| 15:00 | 31.46 | 0.04 | 30.19 | 0.04 |
| 16:00 | 29.45 | 0.04 | 27.48 | 0.04 |
| 17:00 | 25.58 | 0.03 | 20.04 | 0.03 |
| 18:00 | 19.95 | 0.03 | 12.62 | 0.02 |
| 19:00 | 13.99 | 0.02 | 7.93 | 0.01 |
| 20:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 21:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 22:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 23:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 24:00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | 241.39 | 0.33 | 204.11 | 0.28 |

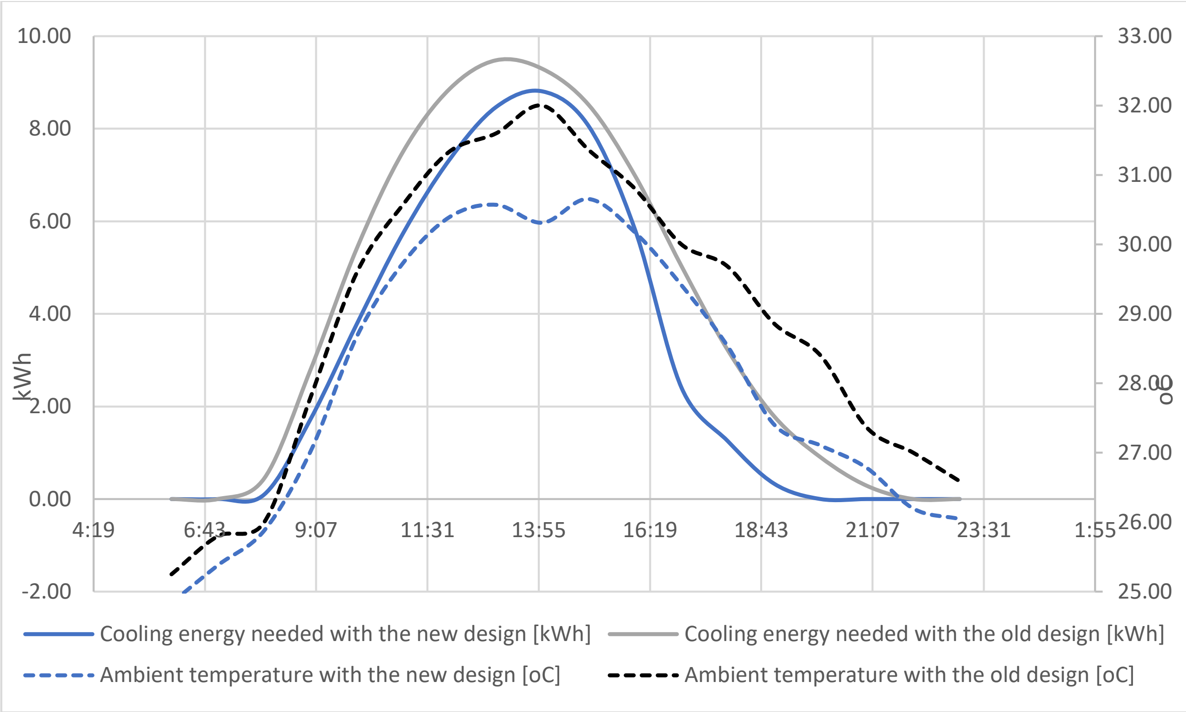



Figure 34: Cooling energy demands in both old and new design for a typical residential building.

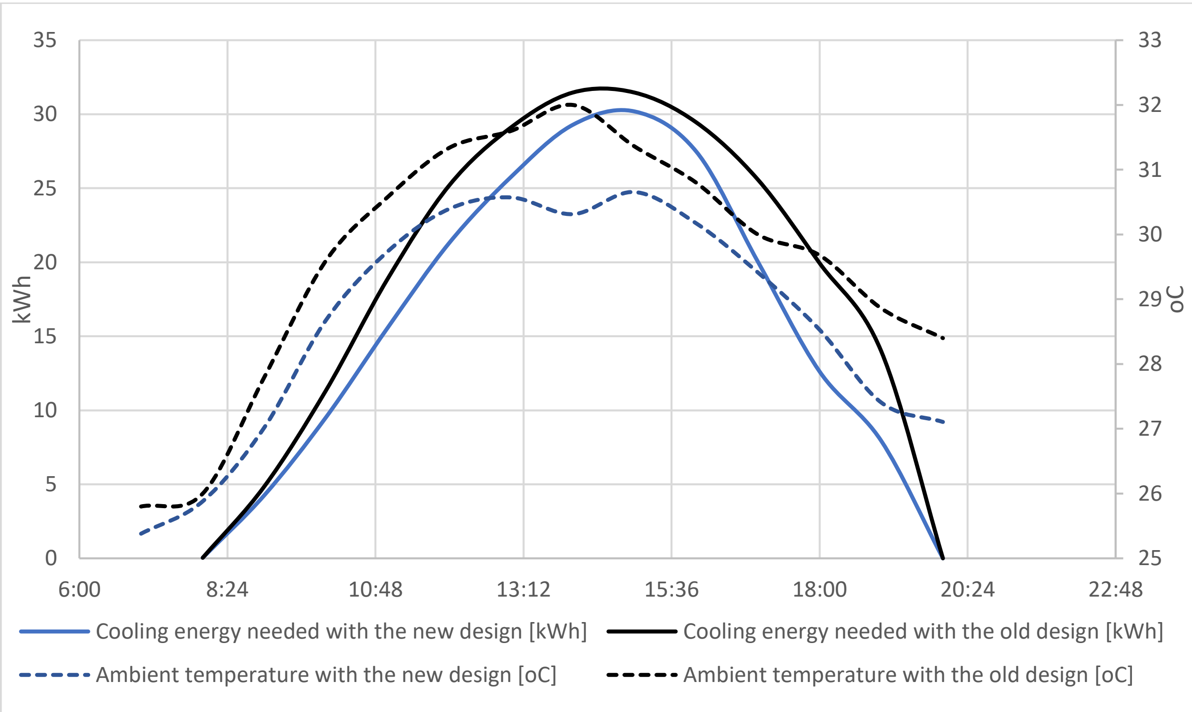



Figure 35: Cooling energy demands in both old and new design for a typical commercial building.

## 9. Conclusion

Many European cities have demonstrated their commitment to reducing their environmental impact by joining the Covenant of Mayors for climate and energy. Initially, signatories pledged to cut their carbon emissions by at least 20% by 2020 (in line with the Europe 2020 strategy). In October 2015, a renewed covenant was agreed, and new signatories pledged to reduce their carbon emissions by at least 40% by 2030, while providing formal plans for how they intend to implement the reduction of their carbon footprint. The described methodology and the designed tool intend to guide the design team to follow a bioclimatic approach and to implement an environmental design relevant to urban open spaces. This approach offers to the designers new possibilities such as to evaluate their decisions before the construction by implementing the "research on design" principles.

The methodology applied in all the case studies followed the steps described in the previous chapters and are:

1) Location and area analysis;
2) Use of the bioclimatic design tool. The tool intends to guide the design team to follow a bioclimatic approach regarding the design of urban open spaces. This approach provides a new dimension on the initial design decisions and introduces a new palette of possible solutions;
3) Microclimatic parameters measurements on certain spots within the existing squares;
4) Microclimate simulation model with the software "ENVI-met". The input parameters include data from measurement in hot days without clouds.
5) Model calibration and validation of the simulation results with the real-time measurements, the model must be able to calculate the microclimate parameters with high accuracy;
6) Final architectural design proposal considering all the microclimatic parameters described (shading, greenery, properties of cover materials). The greenery includes trees that could ensure the sufficient shading needs and could minimize the air and surface temperatures;
7) New area simulation model and analysis so as to calculate the new microclimatic parameters and to be able to compare the final design with the old square.;

8) Calculation of the sustainability indexes that were described in the previous chapter in order to quantify the improvement (Maximum Air Temperature, Maximum Surface Temperature, UTCI, $DH_{UTCI}$, PMV, $DH_T$;
9) Classification of the surrounding buildings according to their use, construction year, materials, and placement;
10) Separate simulations for every building typology both before and after the regeneration. For the current research, the surrounding buildings simulations are conducted with the use of the tools OpenStudio 1.9.0 and EnergyPlus 8.3.0;
11) Calculations of the energy savings from the cooling demands and the $CO_2$ reduction for each different use and in total for all the buildings that relate to the area.

The methodology consists of different simplicity levels steps. Someone with no expertise can proceed until step 2 and use the bioclimatic decision-making tool for setting the design goals. Urban microclimate is a complex environment where all the city uses take place, therefore a methodology that tries to quantify the design regarding thermal comfort demands certain expertise in outdoor simulation models, continuous measurements and calculations.

**9.1. The innovation of the study**

The methodology analysed is referred to the Mediterranean zone where the thermal comfort conditions during summer are crucial. The starting point of this research was the demand for creating a sustainable urban open space that can be used by citizens and visitors as many hours as possible. One basic fact that is adopted and further analysed is the correlation between the use of the urban open space by the citizens and the thermal comfort conditions. The proposed way of managing this is by introducing bioclimatic guidelines during the design process.

The innovative aspects of the described methodology are based on the fact that:

- The introduced tool is easy to use and provides the necessary information to the design team to design sustainable urban open spaces. In this way, the microclimate conditions will be inserted into the design process as a new design parameter;
- The measured microclimate parameters are used as a guide for the new design, as validation data of the simulation model, and as verification that the applied design after construction will achieve the desired comfort conditions;

- The methodology can be applied in any area regardless of the location and the climate;
- Any type of design pattern, type of greenery or construction material can be used since its properties can be added to the software's material library;
- The results include both the heat-maps with the spots that are affected by the comfort conditions during the day, and the energy consumption of the surrounding buildings;
- The methodology includes open access software;
- All the new design projects of public urban open space in Greece demand that the energy profit and the sustainability of the new proposal are demonstrated with the calculation of measurable indexes as a condition in order to be financed by public resources (see Annex);
- The proposed methodology follows a linear process that begins from the concept design of an urban project, by defining the bioclimatic design objectives and continues further on the evaluation of the proposed design using simulation tools and on-site measurements.

The above methodology has been already applied to new projects in Greece and its results have been already evaluated by the users. All new projects of urban open space in Greece demand that the energy profit and the sustainability of the new design are verified with the calculation of measurable indices, as a condition to be financed by public and European resources. Some of these projects are:

1. Western coastal zone regeneration design in the city of Rethymnon, Crete, Greece (constructed project);
2. Melissinou street in Rethymnon, Crete, Greece (under construction);
3. Playground and sports area in the village Platanias, Chania, Crete, Greece;
4. New design of the central square of Souda, Chania, Crete, Greece (funded for construction);
5. New design of Agelou Sikelianou street and square of Saint George Rethymno that additionally included playground and parking (funded and under construction);
6. New design of central roads within the centre of Chania city (roads Tzanakaki, Giannari, Skalidi) (funded for construction);
7. Playground and schoolyard area in the village Kalives, Chania (under construction);
8. Apostolaki street in Rethymnon, Crete, Greece (under construction)
9. Kolokotroni street in Rethymnon city (under design);

10. A number of streets within the Rethymnon city center (under design).

### 9.2. Recommendations for future research

The main objective of this research study was to establish a bioclimatic design methodology that can be applied to urban open spaces. Nevertheless, the proposed methodology needs more optimization and automation techniques that can help the decision process. Since the urban fabric and its and microclimate follow certain patterns, future research should define a classification of typologies and bioclimatic design guidelines for urban areas. Some detailed evaluation of the constructed projects would be very useful to achieve that goal.

The proposed analysis tool includes models and measurements that are also the restrictions of the application scale. In order to insert bioclimatic criteria in bigger scale such as city planning procedures, a new variety of analysis and simulation tools should be added that include GIS-based models and measurements in relation with satellite maps of the microclimatic analysis.

One of the main limitations of the proposed tool and methodology was that it excluded the wind speed and direction from the results. Considering the wind factor as a profitable parameter of comfort in the hot-summer Mediterranean climate it was excluded from the bioclimatic indices and analysis. In this study, the wind was defined as a static parameter. Additionally, due to this decision, it was hard to deal with pollution dispersion and distribution since these factors are mainly affected by the wind. The extended analysis of wind speed formation and certain patterns within the city level and the ability of techniques for pollutant dispersion on certain public areas should be the main factor for further research. Pollution can be researched as another aspect that should be added to the open space design palette tools. The creation of pollution-free pedestrian routes and minimization of the pollution caused by vehicles within city centres is something that can be combined with bioclimatic criteria for creating the sustainable cities of the future.

Another factor that plays important role in quality of urban living is noise pollution. The study has not included any analysis of noise pollution; therefore, no criteria and indices are added to the proposed tool and methodology. In the interest of a percentage of disabled users that rely most on the soundscape of the city, the reduction of the annoyance due to noise pollution should be a good objective for future related research.

The study has a certain scale of application. It is mostly referred on a small part of the city covering few building blocks, such as a road or a square while on the contrary, larger scale application would demand city scale analysis. Proposing environmental design indices in city level that would use measurements, simulations and validations of the results would be beneficial for creating certain comfort routes, applying road characterization (car, pedestrian, bus or bike roads). Also, in the city level analysis, other aspects of the urban environment could be analysed like energy management of the city and energy demand covered by renewables. Finally, as it has been pointed, the selected software ENVI-met takes into account building thermal properties but excludes the thermal gains from external units of the HVAC systems and façade surfaces of the surrounding buildings. ENVI-met's approach towards building energy analysis is incomplete and it does not allow direct evaluation of the energy demands.

The scientific area of the study is relatively new, and many research components need further investigation and introduction of new tools and methodologies.

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## Table of Pictures

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## Appendix

Table 26: Tool's simulation cases

| CASE | No of open sides | CANYON WIDTH (m) | BUILDING HEIGHT (m) | H/W | MATERIAL MEAN ALBEDO | SVF | PERCENTAGE OF TREES (%) | PERCENTAGE OF GRASS (%) | placement of trees/ grass | Orientation |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 15 | 16 | 1.07 | 0.25 | 0.3 | 0 | 0 | center | North - South |
| 2 | | | | 1.07 | 0.25 | 0.3 | 0 | 0 | center | East - West |
| 3 | 2 | 15 | 16 | 1.07 | 0.21 | 0.13 | 25 | 0 | center | North - South |
| 4 | | | | 1.07 | 0.21 | 0.13 | 25 | 0 | center | East - West |
| 5 | 2 | 15 | 16 | 1.07 | 0.19 | 0.09 | 45 | 0 | center | North - South |
| 6 | | | | 1.07 | 0.19 | 0.09 | 45 | 0 | center | East - West |
| 7 | 2 | 15 | 16 | 1.07 | 0.15 | 0.3 | 0 | 45 | center | North - South |
| 8 | | | | 1.07 | 0.15 | 0.3 | 0 | 45 | center | East - West |
| 9 | 2 | 15 | 8 | 0.53 | 0.25 | 0.45 | 0 | 0 | center | North - South |
| 10 | | | | 0.53 | 0.25 | 0.45 | 0 | 0 | center | East - West |
| 11 | 2 | 15 | 8 | 0.53 | 0.21 | 0.15 | 25 | 0 | center | North - South |
| 12 | | | | 0.53 | 0.21 | 0.15 | 25 | 0 | center | East - West |
| 13 | 2 | 15 | 8 | 0.53 | 0.19 | 0.1 | 45 | 0 | center | North - South |
| 14 | | | | 0.53 | 0.19 | 0.1 | 45 | 0 | center | East - West |
| 15 | 2 | 15 | 8 | 0.53 | 0.15 | 0.45 | 0 | 45 | center | North - South |
| 16 | | | | 0.53 | 0.15 | 0.45 | 0 | 45 | center | East - West |
| 17 | 2 | 10 | 16 | 1.60 | 0.23 | 0.19 | 0 | 0 | center | North - South |
| 18 | | 10 | 16 | 1.60 | 0.23 | 0.19 | 0 | 0 | center | East - West |
| 19 | 2 | 10 | 16 | 1.60 | 0.19 | 0.03 | 25 | 0 | center | North - South |
| 20 | | 10 | 16 | 1.60 | 0.19 | 0.03 | 25 | 0 | center | East - West |
| 21 | 2 | 10 | 16 | 1.60 | 0.16 | 0.01 | 45 | 0 | center | North - South |
| 22 | | 10 | 16 | 1.60 | 0.16 | 0.01 | 45 | 0 | center | East - West |
| 23 | 2 | 10 | 16 | 1.60 | 0.16 | 0.19 | 0 | 45 | center | North - South |
| 24 | | 10 | 16 | 1.60 | 0.16 | 0.19 | 0 | 45 | center | East - West |
| 25 | 2 | 10 | 8 | 0.80 | 0.23 | 0.33 | 0 | 0 | center | North - South |
| 26 | | 10 | 8 | 0.80 | 0.23 | 0.33 | 0 | 0 | center | East - West |
| 27 | 2 | 10 | 8 | 0.80 | 0.19 | 0.06 | 25 | 0 | center | North - South |
| 28 | | 10 | 8 | 0.80 | 0.19 | 0.06 | 25 | 0 | center | East - West |
| 29 | 2 | 10 | 8 | 0.80 | 0.16 | 0.02 | 45 | 0 | center | North - South |
| 30 | | 10 | 8 | 0.80 | 0.16 | 0.02 | 45 | 0 | center | East - West |
| 31 | 2 | 10 | 8 | 0.80 | 0.16 | 0.33 | 0 | 45 | center | North - South |
| 32 | | 10 | 8 | 0.80 | 0.16 | 0.33 | 0 | 45 | center | East - West |
| 33 | 0 | 60 | 16 | 0.27 | 0.3 | 0.45 | 0 | 0 | sides | North |
| 34 | 0 | 60 | 16 | 0.27 | 0.3 | 0.45 | 0 | 0 | sides | South |
| 35 | 0 | 60 | 16 | 0.27 | 0.3 | 0.45 | 0 | 0 | sides | East |
| 36 | 0 | 60 | 16 | 0.27 | 0.3 | 0.45 | 0 | 0 | sides | West |
| 37 | 0 | 60 | 16 | 0.27 | 0.3 | 0.65 | 0 | 0 | sides | Center |
| 38 | 0 | 60 | 16 | 0.27 | 0.23 | 0.27 | 25 | 0 | sides | North |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **39** | 0 | 60 | 16 | 0.27 | 0.23 | 0.27 | 25 | 0 | sides | South |
| **40** | 0 | 60 | 16 | 0.27 | 0.23 | 0.27 | 25 | 0 | sides | East |
| **41** | 0 | 60 | 16 | 0.27 | 0.23 | 0.27 | 25 | 0 | sides | West |
| **42** | 0 | 60 | 16 | 0.27 | 0.23 | 0.4 | 25 | 0 | sides | Center |
| **43** | 0 | 60 | 16 | 0.27 | 0.26 | 0.41 | 25 | 0 | center | North |
| **44** | 0 | 60 | 16 | 0.27 | 0.26 | 0.41 | 25 | 0 | center | South |
| **45** | 0 | 60 | 16 | 0.27 | 0.26 | 0.41 | 25 | 0 | center | East |
| **46** | 0 | 60 | 16 | 0.27 | 0.26 | 0.41 | 25 | 0 | center | West |
| **47** | 0 | 60 | 16 | 0.27 | 0.14 | 0 | 25 | 0 | center | Center |
| **48** | 0 | 60 | 16 | 0.27 | 0.23 | 0.45 | 0 | 25 | sides | North |
| **49** | 0 | 60 | 16 | 0.27 | 0.23 | 0.45 | 0 | 25 | sides | South |
| **50** | 0 | 60 | 16 | 0.27 | 0.23 | 0.45 | 0 | 25 | sides | East |
| **51** | 0 | 60 | 16 | 0.27 | 0.23 | 0.45 | 0 | 25 | sides | West |
| **52** | 0 | 60 | 16 | 0.27 | 0.23 | 0.65 | 0 | 25 | sides | Center |
| **53** | 0 | 60 | 16 | 0.27 | 0.26 | 0.45 | 0 | 25 | center | North |
| **54** | 0 | 60 | 16 | 0.27 | 0.26 | 0.45 | 0 | 25 | center | South |
| **55** | 0 | 60 | 16 | 0.27 | 0.26 | 0.45 | 0 | 25 | center | East |
| **56** | 0 | 60 | 16 | 0.27 | 0.26 | 0.45 | 0 | 25 | center | West |
| **57** | 0 | 60 | 16 | 0.27 | 0.14 | 0.65 | 0 | 25 | center | Center |
| **58** | 0 | 60 | 8 | 0.13 | 0.3 | 0.7 | 0 | 0 | sides | North |
| **59** | 0 | 60 | 8 | 0.13 | 0.3 | 0.7 | 0 | 0 | sides | South |
| **60** | 0 | 60 | 8 | 0.13 | 0.3 | 0.7 | 0 | 0 | sides | East |
| **61** | 0 | 60 | 8 | 0.13 | 0.3 | 0.7 | 0 | 0 | sides | West |
| **62** | 0 | 60 | 8 | 0.13 | 0.3 | 0.83 | 0 | 0 | sides | Center |
| **63** | 0 | 60 | 8 | 0.13 | 0.23 | 0.35 | 25 | 0 | sides | North |
| **64** | 0 | 60 | 8 | 0.13 | 0.23 | 0.35 | 25 | 0 | sides | South |
| **65** | 0 | 60 | 8 | 0.13 | 0.23 | 0.35 | 25 | 0 | sides | East |
| **66** | 0 | 60 | 8 | 0.13 | 0.23 | 0.35 | 25 | 0 | sides | West |
| **67** | 0 | 60 | 8 | 0.13 | 0.23 | 0.4 | 25 | 0 | sides | Center |
| **68** | 0 | 60 | 8 | 0.13 | 0.26 | 0.57 | 25 | 0 | center | North |
| **69** | 0 | 60 | 8 | 0.13 | 0.26 | 0.57 | 25 | 0 | center | South |
| **70** | 0 | 60 | 8 | 0.13 | 0.26 | 0.57 | 25 | 0 | center | East |
| **71** | 0 | 60 | 8 | 0.13 | 0.26 | 0.57 | 25 | 0 | center | West |
| **72** | 0 | 60 | 8 | 0.13 | 0.14 | 0.01 | 25 | 0 | center | Center |
| **73** | 0 | 60 | 8 | 0.13 | 0.23 | 0.7 | 0 | 25 | sides | North |
| **74** | 0 | 60 | 8 | 0.13 | 0.23 | 0.7 | 0 | 25 | sides | South |
| **75** | 0 | 60 | 8 | 0.13 | 0.23 | 0.7 | 0 | 25 | sides | East |
| **76** | 0 | 60 | 8 | 0.13 | 0.23 | 0.7 | 0 | 25 | sides | West |
| **77** | 0 | 60 | 8 | 0.13 | 0.23 | 0.83 | 0 | 25 | sides | Center |
| **78** | 0 | 60 | 8 | 0.13 | 0.26 | 0.7 | 0 | 25 | center | North |
| **79** | 0 | 60 | 8 | 0.13 | 0.26 | 0.7 | 0 | 25 | center | South |
| **80** | 0 | 60 | 8 | 0.13 | 0.26 | 0.7 | 0 | 25 | center | East |
| **81** | 0 | 60 | 8 | 0.13 | 0.26 | 0.7 | 0 | 25 | center | West |
| **82** | 0 | 60 | 8 | 0.13 | 0.14 | 0.83 | 0 | 25 | center | Center |

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