EVALUATING AND ENHANCING OUTDOOR THERMAL PERFORMANCE IN MODERATELY WARM -WET CLIMATE ZONE

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APPROVAL SHEET

This dissertation proposal entitled evaluating and enhancing outdoor thermal performance in moderately warm-wet climate zone submitted by Mohammad Suleiman Albdour for the degree doctor of philosophy has been examined and approved for proposal hearing.

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ABSTRACT

Climate change is expected to bring rising temperatures and to increase the frequency and severity of extreme heat events in Central-Europe, and thus in Hungary. Combined with the peculiar climate of cities characterized by increased temperature and reduced ventilation in the summertime. Furthermore, heat waves are expected to have greater impact on urban environment. Nonetheless, the main target of this research is investigating the possibility of enhancing the outdoor thermal comfort in central European city of Pecs. In simple words is to determine how designers could modify climatic conditions in urban spaces for thermal comfort and develop a better understanding of the relationship between outdoor thermal comfort, urban design, and microclimate in an attempt to improve the pedestrians ‘thermal perception.

A representative study area was chosen for the research. The outdoor thermal performance in the study area was quantitatively and qualitatively evaluated through conducting a field questionnaire and numerical assessment respectively. In this evaluation study (*computational fluid dynamics*) software "*ENvi-met*" was used and a sample of occupants were interviewed. This study identified many issues associated with outdoor thermal and indicated its poor performance within the study area. A number of outdoor thermal design measures were formulated based on the literature review and considering the evaluation study results along with the research context nature. The proposed outdoor thermal design measures were applied to the selected study space and their effectiveness in terms of enhancing the outdoor thermal performance was quantified via "*Envi-met*". Furthermore, the numerical results reported that the proposed outdoor thermal design measures could significantly enhance outdoor thermal performance. However, it can be concluded that the final design of the study public space can alleviate the heat stress on outdoor spaces and reach the research main aim and objectives.

keywords: Evaluating, Enhancement, Outdoor thermal comfort, moderately warm-wet climate zone.

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Mohammad Suleiman albdour

To …

My beloved country ……Jordan-(Shoubak)

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THESIS ORGANIZATION

The thesis is organized in seven chapters divided into three parts in addition to the preliminaries; abstract, thesis organization, acknowledgment, dedication, table of content, list of figures, list of tables, and the appendices. The appendices were enclosed in a CD as they contain media files. Nonetheless, others main figures were attached to this work in appendix section. Nevertheless, *Fig.1.1* illustrates the research organization in terms of parts, chapters, tasks, and main aim.

THESIS ORGANISATION

Parts	Ch	Tasks	Main aim
Part 1: The research outline and scientific background	Ch 1-3	Presenting an overview of the thesis outline	**Investigating the possibility of enhancing the outdoor thermal comfort**
Part 2: Study site analysis and evaluation	Ch 4-5	Choosing a representative study site as well as quantitatively and qualitatively evaluation of the outdoor thermal comfort	
Part 3: Enhancing outdoor thermal comfort performance in the study space	Ch 6-7	Formulating possible design measures and quantifying their effect in terms of enhancing thermal comfort	
Summary of conclusions, further work, and Indices	Ch 8 Ch 9	Summarizing the findings and proposing the future work	

Fig.1.1. Thesis organization

Part 1: The research outline and scientific background

Research context, problems and objectives

1.1. Chapter one introduction

The thesis is aimed at investigating the outdoor thermal performance of a central European urban space in a moderately warm-wet context of Pecs-city in Hungary, Public spaces which have always played a central role in the social life of cities. They have served three vital functions since they act as meeting places, marketplaces, and spaces for connection [1].

This chapter is divided into twelve core sections, starting with the thesis organization and introduction, then follows by the geographical and climatic characteristics. Next, the research background is shown, then the previous literature relevant to the research problem within the Hungarian context and the research main aim, objectives, hypotheses and question, as well as the scope and limitations sections are identified. Finally, general research methodology is outlined. Nevertheless, this chapter's purpose is to presenting a general understanding of the whole research.

1.2. Research geographical context

Hungary is a mostly flat country, dominated by the Great Hungarian Plain east of the Danube. The plain includes approximately 56% of the country's land. The terrain ranges from flat to rolling plains. The land rises into hills and some low mountains in the north along the Slovakian border. The highest point, located in the Matra Hills, is Mt Kekes at 1,015m. The lowest spot is 77.6 m above sea level, located along the Tisza River in the south of Hungary, near Szeged. The Danube is the major river, as it divides the country almost in half, and is navigable within Hungary for 418 km. Additional rivers include the Drava and Tisza. Hungary has three major lakes. Lake Balaton, the largest at 78 km long and from 3 to 14 km wide, has an area of 592 sq. km. It's central Europe's largest freshwater lake. However, *Fig.1.2* shows the central European country of Hungary [2].

Fig.1.2. A satellite image shows the georgical location of Hungary [3].

1.3. Research climatic context and classification

Hungary is situated between the 45°45'N and 48°35'N latitudes, about halfway between the Equator and the North Pole, in the temperate climatic zone according to the solar climatic classification. Its climate is very erratic. One of the main reasons for this is the fact that Hungary is situated in between three climatic zones: the oceanic climate with less varying temperature and more evenly dispersed precipitation; the continental climate with more extreme temperature and relatively moderate rainfall; also, a Mediterranean effect with dry weather in summer, and wet one in winter, for a shorter or longer period of time, any of these types can become prevailing. Due to these reasons, significant differences can occur in the weather of the country, despite its lower altitudes and relatively small extent.

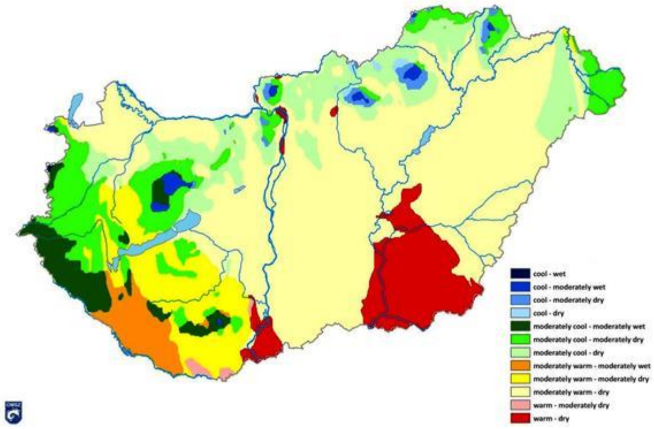

Fig.1.3. The Hungarian climatic design regions classification [4].

The other main determinant is orography. As the country is lain in the Carpathian Basin, more than half of its surface plains below 200 meters, and the area above 400 meters is less than two percent, primarily the effect of the Carpathians should be underlined. Hungary is about halfway from the ocean to the inner parts of the Eurasian continent. In the summer half-year, the dominating air masses are of oceanic origin, in the winter mostly continental ones. The NW-SE distribution of the meteorological variables shows the effect of the Atlantic Ocean, while the SW-NE distribution the effect of the Mediterranean Sea. Hungary is on the conveyor belt of the Westerlies, due to the location of the country is surrounded by the Alps and Carpathians, the prevailing wind direction is northwestern, while the southern wind has a secondary maximum prevailing wind. Hungary’s climate cannot be classified using one of the global climate classifications (e.g. Köppen or Trewartha) to describe the differences within the country adequately. Another classification method must be found. This could be done based on the work of a Hungarian climatologist György Péczely, who has taken into his account the aridity index and the growing season length-separated sixteen climatic zones, from which twelve can be found in Hungary. Following this classification, the greater part of the country has a moderately warm-dry climate. The area of the rivers Körös and Maros, the lower part of the river Danube is warm-dry. The northeastern region of Hungary (Nyírség) is more likely moderately cool-dry, while the nearby Plain of Szatmár is moderately cool-wet. In the Southern Transdanubia region is moderately warm-dry, while in the Western Transdanubia is moderately cool-dry, and moderately cool-wet climate zones are typical. Higher altitudes of the mountains have a moderately cool-dry, and moderately cool-wet climate, only the Mountains of Kőszeg near the western borders with Austria has a cool-wet climate zone [4].

1.4. Research background

With global warming becoming an unavoidable fact, summer heat waves in central Europe are going to become more frequent and more intensive over the next decades. The situation is aggravated in cities with their complex microclimate, normally referred to as the urban heat island effect [5]. Moreover, Climate change is expected to bring rising temperatures and to increase the frequency and severity of extreme heat events in Central-Europe, and thus in Hungary. Combined with the peculiar climate of cities characterized by increased temperature and reduced ventilation in the summertime. Furthermore, heat waves are expected to have greater impact on urban environment [6], [7]. Taking into account that three quarter (73%) of the European population already lives in urban areas, and by 2050 this proportion is expected to rise over 80% [8], mitigating the impact of extreme heat events is one of the most important issues in urban planning. However, without adaptation to heat waves, people will experience both deteriorating thermal comfort and decreasing work efficiency due to the increased heat stress. Additionally, heat stress intensification is expected to increase the mortality rates of urban dwellers, especially among the vulnerable groups, like infants, elderly people and those with cardiovascular diseases [6], [9].

1.5. Previous work

The review of the previous works that investigated climatic responsive and design in particular outdoor thermal in central European context were found to be very limited.

Some of these studies were shallow, in terms of climatic design, and their results need to be verified due to the lack of accuracy sometimes and the lack of reliable methodologies other times. Moreover, below are some of the related studies for this work.

1.5.1. Investigation of human thermal comfort by observing the utilization of open-air terraces in catering places – a case study in szeged.

The observation of the attendance of open-air terraces in restaurants, taverns and cafés provides an indirect way to estimate human reactions on thermal conditions. This paper reports the use of this human biometeorological survey method in two taverns located in Szeged (Hungary) in order to investigate the correlation between the relative attendance of outdoor places and the actual thermal conditions. The latter was quantified by the most popular human comfort index, Predicted Mean Vote (PMV), calculated by the bioclimate model RayMan from measured meteorological parameters influencing the thermal comfort sensation. In a 6-week long period, the relative attendance of the beer gardens of two taverns offering different microclimatic environments was observed in the afternoon hours (between 12 and 3 p.m.). The results proved that the attendance of outdoor places increases up to a specified PMV value, then decreases due to the intensified heat stress. This tendency is not only in harmony with the common human attitude, but also confirms the correctness of the applied bioclimate index (PMV) [10].

1.5.2. Urban greening and cool surfaces: the effectiveness of climate change adaptation strategies within the context of Budapest.

Regional climate projections for Central and Eastern Europe indicate a rise in summertime temperatures along with an increase in the frequency of warm temperature extremes by the end of the next century. In the case of Hungary, models indicate a 1.7–2.6°C rise in summer temperatures in the near future, and a 3.5–6.0°C increase is projected for the end of the twenty-first century based on the A1B scenario. Besides rising temperatures, long term projections also signal a 20–40% decrease in summer precipitation in Hungary. In Budapest, the existing urban heat island (UHI) intensity of 4–8°C is expected to make these already adverse projections worse. Since the combined influences of these phenomena will be most pronounced in the densely built and populated areas of the city, identifying effective heat mitigation and climate change adaptation strategies for these areas is of primary importance. Within this context, a research goal has been set to evaluate the effectiveness of popular heat mitigation strategies (cool roofs, cool pavements and different tree canopy cover ratios) on the urban canopy layer climate in different urban environments. Since the effectiveness of such strategies is highly context specific, the research argues for a sensible approach that start with the analysis of existing conditions and proceeds with the assessment of mitigation approaches. This paper presents the preliminary results of this study [11].

1.5.3. An initial assessment of the bioclimatic comfort in an outdoor public space in Lisbon

This paper describes the application of a methodology designed to analyze the relationship between climatic conditions and the perception of bioclimatic comfort. The experiment consisted of conducting simultaneous questionnaire surveys and weather measurements during two sunny spring days in an open urban area in Lisbon. The results showed that under outdoor conditions, thermal comfort can be maintained with temperatures well above the standard values defined for indoor conditions. There seems to be a spontaneous adaptation in terms of clothing whenever the physiological equivalent temperature threshold of 31°C is surpassed. The perception of air temperature is difficult to separate from the perception of the thermal environment and is modified by other parameters, particularly wind. The perception of solar radiation is related to the intensity of fluxes from various directions (i.e. falling upon both vertical and horizontal surfaces), weighted by the coefficients of incidence upon the human body. Wind was found to be the most intensely perceived variable, usually negatively. Wind perception depends largely on the extreme values of wind speed and wind variability. Women showed a stronger negative reaction to high wind speed than men. The experiment proved that this methodology is well-suited to achieving the proposed objectives and that it may be applied to other areas and in other seasons [12].

1.5.4. The influence of bioclimatic urban redevelopment on outdoor thermal comfort.

One of the greatest environmental challenges for the sustainability of future cities is the mitigation of the urban heat island phenomenon and thus, improvement of outdoor comfort conditions for people. The emphasis of this work is to analyze how mitigation techniques in a dense urban environment affect microclimate parameters and outdoor thermal comfort. The quantitative differentiation of outdoor thermal comfort conditions through bioclimatic urban redevelopment for an area in the city of Serres, Greece is investigated. The main bioclimatic interventions concern the application of cool paving materials, the increase of vegetated areas and the creation of water surfaces. The analysis and comparison are per-formed on a hot summer day with the ENVI-met model. Software simulations regarding microclimatic and outdoor thermal comfort conditions are performed on the daytime period 06.00–20.00 (14 h) at the height of 1.8 m from the ground. The examined parameters are air temperature, surface temperature and mean radiant temperature (MRT). The evaluation of outdoor thermal comfort conditions is conducted using the index PMV (Predicted Mean Vote), adapted for outdoor conditions. The results of simulations are discussed regarding the assessment of bioclimatic interventions [13].

1.5.5. Simulations of the Influence of the Vegetation in the Urban Microclimate in Carmen Alto Place, Arequipa

The lack of green urban spaces affects the majority of cities, producing a serious environmental problem, as for all the city inhabitants. The world population, at present time is concentrated in the big cities; through half of the population of the world this increase of urban housings lives in cities in 2008, according to the report of the United Nations, inside the cities, being the urban design, the factor that determines the presence or absence of green spaces and having the vegetation effects on the quality of urban air on having turned the carbon dioxide into oxygen and glucose, acting also like sewer pipe of CO2 and particulate matter. There is realized a field measurement of the principal variables that affect the urban microclimate and located in the urban area in Arequipa named Carmen Alto and modeling the measured by a microclimatic simulation, using the software ENVI-MET. The numerical model Envi-Met is compared with the observed field measurements, considering his advantages and limitations for potential studies of urban climate on having justified the presence of urban vegetation, in order to regulate the microclimate at level of street and city, helping in improving the quality of the urban air [14].

Through presenting the previous researches, to help in formulating the research main problem and aim, it is noteworthy that: Firstly; most researchers did not demonstrate the ways by which the findings can be applied to the contemporary design. ***Secondly; a few studies went more deeply in studying thermal comfort matters in the central European context and introduced verified results through clearer methodologies. Regardless of the study's context, all these studies almost used the same methodology (parametric analysis using computer simulation) in improving thermal comfort in their case studies. Although the in-depth analysis done in these works, not enough attention was given to outdoor thermal measures and parameters as a holistic approach. Finally; most studies confirmed certain aspects and neglected***

others. Generally, the previous studies dealt with the topic in a fragmented way. Furthermore, in all previously reviewed cases above and beyond, there is no comprehensive approach of the subject or on outdoor thermal performance in moderately warm-wet climate zone. However, this gap in the body of knowledge was identified and is being pursued in this research to be bridged.

1.7. Research problem context

Without an understanding of the urban microclimate measures and parameters and how landscape elements will affect them, designers are at risk of creating urban landscapes, which will perform poorly or even have a negative impact on the microclimate [15], [16]. Landscape architects and urban planners do not integrate the accumulated knowledge of climatology into applicable planning guidelines and tools as a way to improve the microclimate of the outdoor built environment [17]. Most researches are published in scientific literature and are not accessible to the majority of landscape designers and planners. Moreover, the design implications of the results are rarely extracted in a usable form. Therefore, developing a landscape and urban design strategies for outdoor environment in moderately warm-wet climate zone based on bioclimatic principals. In order to provide landscape architects with design guidelines that can improve the microclimate and conserve energy.

1.8. The research main aim and objectives

The main target of this research is investigating the possibility of enhancing the outdoor thermal comfort in central European city of Pecs in summer. In simple words is to determine how designers could modify climatic conditions in urban spaces for thermal comfort and develop a better understanding of the relationship between outdoor thermal comfort, urban design, and microclimate in an attempt to improve the pedestrians ‘thermal perception. However, to achieve this aim, the following objectives were derived:

1-Quantitively and qualitatively evaluating the outdoor thermal performance in Pecs city.

2-Formulating design measures that could enhance the outdoor thermal performance

3-Quantifying the effect of different design measures that could possibly enhance Outdoor thermal performance.

4-Providing the designers and decision makers with a comprehensive framework for use in evaluating or predicting the effect of different design measures and their parameters in modifying the outdoor microclimate.

1.9. Hypothesis and research question

In accordance with the thesis background, research problem, as well as the research main aim and objectives in this research, the following hypotheses will be investigated:

-Utilizing plantation as an outdoor thermal comfort strategy has a significant impact on air temperature, relative humidity, as well as wind speed and can increase the level of thermal satisfaction.

-Utilizing passive cooling strategies as waterbody in outdoor public spaces is considered a very effective strategy which can greatly help in achieving outdoor thermal comfort and mitigating heat stress in the summertime.

-Utilizing proper street canyon direction and geometry play an important role in accelerating wind speed and offer better ventilation.

In order to understand the hypotheses, the study also generated the following question to be answered:

Which are the main design measures and parameters influencing the urban microclimate and outdoor thermal comfort in a moderately warm-wet climate zone?

1.10. Scope and limitations

The research presented in this study concentrates on how urban design affects the microclimate and outdoor thermal comfort. The research is focused on the effect of different design measures and parameters at different urban levels on improving the outdoor thermal. This work is concerned with alleviating heat stress during the extended summer period in a moderately warm-wet climate zone. The study is limited to the moderately warm-wet climate of Pecs. Although some of the findings may be generalized, the conclusions of the study are not necessarily valid throughout moderately warm-wet climate groups, since there are climatic and considerable variations between different cities in terms of size, planning principles, proximity to the sea, and topography, etc. Moreover, visual and acoustical comfort performance are not investigated here.

1.11. Methodology overview

The general methodology employed in this work in order to fulfill the research objectives and achieve its main goal comprises three main parts. Namely, they are in order; the research outline and scientific background, study space analysis and evaluation as well as enhancing outdoor thermal comfort performance in the study site.

1.11.1. First part: The research outline and scientific background:

This part of the general methodology mainly represents a theoretical study, scientific background of outdoor thermal comfort, as well as a wide review is conducted in an attempt to classify the urban design measures and their parameters that could affect the outdoor thermal performance.

1.11.2. Second part: The evaluation study:

This part is mainly a diagnostic study and aims to investigate the outdoor thermal performance of the central European city of Pecs. A study site from Pecs city was chosen. The outdoor thermal design features in the study area are then analyzed. After that, the outdoor thermal comfort in the study space is evaluated quantitatively through objective assessment and qualitatively through subjective evaluations. The subjective evaluation aims to measure the occupants' response towards the outdoor thermal comfort parameters. The evaluation is conducted by designing a questionnaire that measures the occupant's sensation and numerical simulations that study the issues in the climatic context to be solved later in this work *(Chapter 7)*. By conducting this part of the methodology, the first objective of the research *(Evaluating the outdoor thermal performance)* will be fulfilled. The outcome of this part is considered in the enhancement process in the third part, so determining the problems need to be treated and the way of addressing them.

1.11.3. Third part: outdoor thermal enhancement:

This part of the general methodology mainly aims to enhance the outdoor thermal study for comfort purposes. It includes two main tasks. The first task is a preparatory task and was set to formulate the outdoor design measures that could enhance the thermal comfort in the study area context, in order to be tested in the parametric analysis later on. These measures will be formulated through extracting outdoor thermal measures from the literature review that is conducted in the theoretical part and dealt with the design measures. However, at the end of this task, the second objective of the research (*Formulating the different design measures that could possibly enhance the outdoor thermal performance*) will be fulfilled. In addition, the measures that fulfill the occupants' desires and those which are forced by the research context nature will be implemented and tested. By doing that, the third study site objective will be achieved.

To achieve the research fourth objective which depends on an analytical method with the use of a logical conclusion to reach the desired goal and coming up with results taken from the reality by using an actual numerical method. However, by doing that the last objective will be accomplished.

1.12. Research Structure

The study consists of eight chapters, which represent a theoretical, evaluation, as well as the numerical studies of this work.

1.12.1. Chapter one

In this chapter, the overview of the research project is presented, the research geographical and climatic context are explained, the work background is shown, and the research problem is identified. Furthermore, the chapter reviews the previous literature relevant to the research problem within the Hungarian context. Finally, general research methodology is outlined. In general, this chapter purposes of presenting a general understanding of the whole research.

1.12.2. Chapter two

This chapter presents the related science to outdoor thermal comfort. In terms of impacts and limitations, firstly thermal comfort in outdoor space is identified. Secondly, thermal comfort index is chosen and explained. Finally, Variables influencing thermal comfort are outlined. In general, this chapter aims to build up a scientific background on which the discussion and interpretation of results ' analysis later in this work will be based.

1.12.3. Chapter three

This chapter discusses the design measures and their parameters that might affect outdoor thermal comfort at different scale levels. which in turn, affect the performance of the outdoor thermal strategies that are explained in the chapter six. In general, this chapter of the research, the design measures are comprehensively classified and categorized. This classification expresses these measures in order, starting from the largest scale down to the smallest scale. The measures are grouped under three levels; the macro-level, the intermediate-level and the micro-level.

1.12.4. Chapter four

In this chapter, the criteria used to choose the main study space are presented. It, also, presents a detailed analysis of the study site. The study site design measures and their parameters' settings that could be related to the outdoor thermal comfort performance are highlighted. In general, this chapter aims to identify the research study site and the properties of its design measures in terms of outdoor thermal comfort.

1.12.5. Chapter five introduction

In this chapter, the detailed methodology and results, as well as their discussion of the objective and subjective evaluations, are deeply explained. Firstly, the objective assessment methodology including the questionnaire assessment study is set out. Secondly, the results of the objective assessment are shown and analyzed according to the explained methodology. Then the discussion starts with the results of the study site questionnaire after that proceeds to show the outdoor thermal simulation results.

1.12.6. Chapter six

The work in this chapter aims to formulate the design measures and their parameters that could be used to improve the outdoor thermal comfort performance on the study site. This chapter starts by drawing the design measures and their parameters that are believed to have a positive effect on the outdoor thermal comfort. These measures are extracted in three main levels; the macro design level, the intermediate design level, and the micro design level. A list of possible measures for enhancing the outdoor thermal performance will be then formulated.

1.12.7. Chapter seven

In this chapter, firstly the detailed methodology of conducting the improvement process will be explained. Secondly, the results of the composed simulation cases for applying the selected measures to enhance outdoor thermal comfort in the case study are presented, analyzed and discussed. Thirdly; the air temperature, relative humidity, wind speed, mean radiant temperature, predicted mean vote, and CO_2 performance in the original base case are explained. Finally; the results of each set of the selected measures and their parameters within the macro, intermediate and micro design levels are studied in order to add the optimum chosen measures' parameters to the original base case which leads to the final enhanced case. Moreover, the final enhanced scenario will be compared to the original base case in an attempt to quantify the effect of the different design measures on improving the outdoor thermal performance of the case study.

1.12.8. Chapter eight

This chapter summarizes the research conclusions and findings, presents the general research findings, as well as highlights the proposed further work.

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Chapter 2: The science and strategic design of outdoor thermal comfort

2.1. Chapter two introduction

This chapter presents the related science to outdoor thermal comfort. In terms of impacts and limitations. Firstly thermal comfort in outdoor spaces is identified, secondly, thermal comfort index is chosen and explained, and finally, Variables influencing thermal comfort are outlined. In general, this chapter aims to build up a scientific background on which discussion and interpretation of results' analysis later in this work will be based.

2.2. Thermal Comfort in Outdoor Space

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines human thermal comfort as the state of mind which declares satisfaction with the nearby environment [1]. Human thermal comfort is merely the zone where a person acquires a comfortable thermal sensation due to many parameters defined by previous researchers. The air velocity, the ambient air temperature, the mean radiant temperature, and the relative humidity are the physical factors that attain the thermal comfort sensation. There are psychological factors that also influence the thermal comfort levels of human which is the clothing type and activity levels. Researchers found that a combination of physiological in addition to psychological parameters compliment to obtain the ideal comfort zone [2].

Healthy and comfortable urban microclimate qualities are essential for all environments. Human beings are exposed to different kinds of stress in outdoor spaces. The most important one is the microclimatic qualities which differ considerably from suburban areas. Latest research illustrated outdoor thermal condition parameters such as wind speed, air temperature, solar radiation and relative humidity influence estimation of satisfaction, thermal perception and thermal comfort [2],[3].

2.2.1. Predicted Mean Vote thermal comfort index

Thermal comfort is defined in the ISO 7730 [4] as "The condition of mind that expresses satisfaction with the thermal environment." Outdoor PMV-PPD model Predicted Mean Vote (PMV) is one of the most recognized indices to evaluate the thermal sensation for space users. The index is based on thermoregulation and heat balance theories developed by Fanger in 1972 [4]. Originally, PMV is designed for indoor use, yet, PMV for outdoor conditions has been developed by Jendritzky and Nübler [5], [6] which is named Klima- Michael –Model. The model counts the outdoor long and short-wave complex factors in terms of radiant temperature. The index combines the majority of microclimatic analysis factors. It takes into account the effect of shading and radiation flux [5], [7]. The index predicts thermal sensation of people through a point scale developed by ASHRAE *Fig.2.1*. This scale represents the vote of a large space user group for their thermal sensation. It considers that the person is constantly exposed to the same climatic condition for a long time that may reach to 20 minutes. Typically, the scale ranges from (+4) hot too (-4) cold, where (0) is considered a neutral value that represents comfort level. Values can exceed (4) or be below (-4) depending upon the local climatic conditions [5].

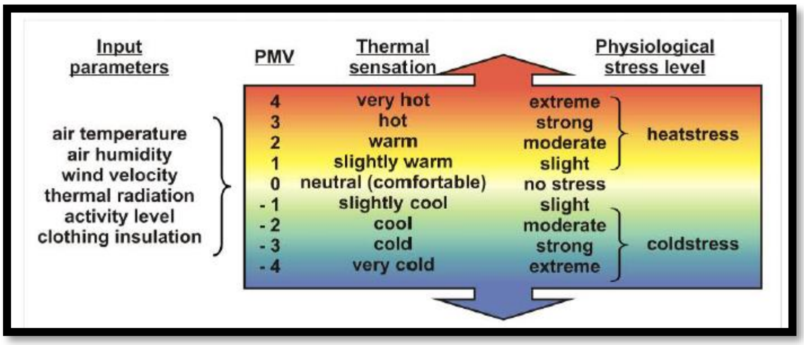

Fig.2.1. Input parameters for the calculation of PMV and the PMV ranges for different human thermal sensations and stress levels [8]

2.2.3. Variables influencing thermal comfort

Four basic environmental parameters are affecting overall thermal comfort: air temperature, radiation, air humidity, and wind velocity. Additionally, two personal variables also influence thermal comfort: clothing insulation and the level of activity as metabolic rate [10]. These factors might be independent of each other, but together they contribute to a body‘s thermal comfort.

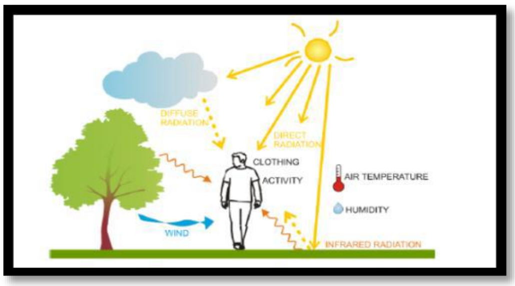

Fig.2.2. The Parameters of outdoor thermal comfort [10]

2.2.4. Environmental parameters

2.2.4.1. Air Temperature

Air temperature is defined as the dry-bulb temperature in the shade, it is perhaps the most important for thermal comfort, where it affects the rate of convective and evaporative body heat loss. If the air temperature exceeds the surface temperature of the clothed body, or of the exposed skin, there will be convective heat gain and vice versa. There is a fairly wide range of temperatures that can provide comfort when combined with the proper combination of relative humidity, mean radiant temperature (MRT), and air flow. As any one of these conditions varies, the dry-bulb temperature must be adjusted in order to maintain comfort conditions [9]. However, the thermal comfort threshold temperature that mentioned above, which an overheating sensation is likely to occur using the thermal neutrality model adopted by ASHRAE is illustrated below.

Table 2.1. Comfort lowest and highest temperature according to ASHRAE standard 55 comfort model [1]

Less than 20.3 ºC	20.3 ºC winter lowest	24.3 ºC winter highest	26.7 ºC summer highest	More than 26.7 ºC

2.2.4.2. Airspeed

Airspeed describes the speed of air moving across the body and may help cool the body if it is cooler than the environment. Air velocity is an important factor in outdoor thermal comfort as it significantly affects body heat transfer by convection and evaporation. It accelerates convection and increases evaporation of sweat from the skin, thus producing a physiological cooling effect. The higher the wind speed, the greater the rate of heat flow by both convection and evaporation.

The wind-driven ventilation strategies cannot be effective unless the wind speed is greater than (2.5 m/s). This huge effect is due to the exponential proportionality between the wind force and the wind speed square. It was found that natural airspeed lies in the range between (0 m/s) and (25 m/s) [11]. The different effects of various airspeed on human sensation and comfort were presented in "*Beaufort scale* "(Fig.*2.3).*

Beaufort number	Wind speed (m/s) (measured 10 m above sea or ground level)	Airspeed (measured 1.75 m height in extended land)	Description	Land condition	comfort
0	0 – 0.5	0.0 – 0.1	Calm	Smoke rises vertically	No noticeable wind
1	0.5 – 1.5	0.2 – 1.0	Light air	Smoke drifts	
2	1.6 – 3.3	1.1 – 2.3	Light breeze	Leaves rustle	Wind felt on face
3	3.4 – 5.4	2.4 – 3.8	Gentle breeze	Wind extends flags	Hair disturbed, clothing flaps
4	5.5 – 7.9	3.9 – 5.5	Moderate breeze	Small branches in motion. Rises dust and loose paper	Hair disarranged
5	8.0 – 10.7	5.6 – 7.5	Fresh breeze	Small trees in leaf begin to sway	Force of wind felt on body
6	10.8 – 13.8	7.6 – 9.7	Strong breeze	Whistling in telegraph wires, large branches in motion	Umbrellas used with difficulty. Difficult to walk steadily. Noise in ears
7	13.9 – 17.1	9.8 – 12.0	Near gale	Whole trees in motion	Inconvenience in walking
8	17.2 – 20.7	12.1 – 14.5	Gale	Twigs broken from trees	Progress impeded. Balance difficult in gusts
9	20.8 – 24.4	14.6 – 17.1	Strong gale	Slight structural damage (chimney pots and slates)	People blown over in gusts
10	24.4 – 28.5		Storm	Seldom experienced inland. Trees up-rooted, considerable structural damage	

Fig.2.3. Beaufort scale for outdoor air velocities and its effect on human sensation and comfort [11].

2.2.4.3. Mean radiant temperature (MRT)

MRT is a way of conceptualizing radiant heat exchanges between a person and the surrounding physical environment. It is defined as the uniform blackbody temperature of an imaginary enclosed room, where radiant heat transfer between a person and the room is equivalent to the total radiant transfers in the actual non-uniform enclosure and represents an area-weighted mean temperature of all surrounding objects. In the outdoor context, there is no enclosure, and the radiant heat exchanges occur with all surrounding surfaces in the heterogeneous environment. The body receives radiation from multiple sources that can be seen in *Fig.2.5*, such as from direct and diffuse shortwave radiation, as well as long-wave radiation from building, vegetation and ground surfaces [12].

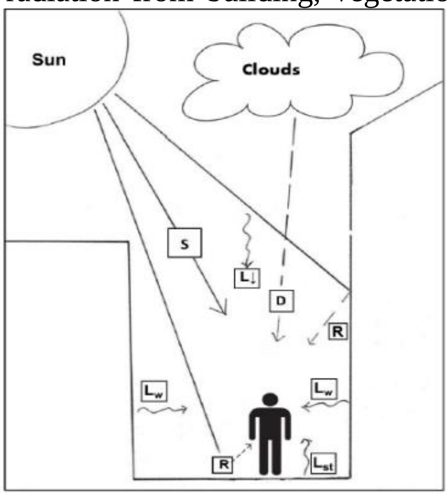

Fig.2.5. In the outdoor setting, a person is exposed to direct (S), diffuse (D), and reflected (R) shortwave radiation, as well as long-wave radiation from the sky (L↓), and long-wave irradiation from buildings walls (Lw) and street surfaces (Lst) [12], [13].

Radiant heat loss from the body decreases as *MRT* increases. If *MRT* is higher than the body temperature, as might be the case throughout the year in the warm humid tropics, then the body experiences net radiant heat gain. During periods of strong solar input, radiant heat gains can be the most significant source of heat input for the human energy balance. Given the complexities of outdoor environments, *MRT* varies greatly through time and space and is considered the most difficult biometeorological parameters to quantify. Kantor and Unger [14] provide a review of the techniques available for quantifying *MRT*, which include using integral radiation measurements, globe thermometers and modelling of the 3D environment [12].

2.2.4.5. Air humidity

Humidity is defined as the amount of water vapour in a given space. An increase in the air ‘s moisture content, or humidity, can affect the evaporation rate: high humidity restricts the dissipation of heat through sweat evaporation from the skin and respiration, while very low humidity leads to drying out of the mucous membranes as well as the skin, thus causing discomfort. A change in the humidity of the atmosphere affects thermal sensation in that a person feels warmer, sweatier and less comfortable. Especially under warm conditions, when both convective and radiative heat losses are small, sweat evaporation is an important mechanism in maintaining comfort. When the liquid sweat on the skin surface evaporates, latent heat is extracted from the body and a cooling effect is produced. However, Givoni [9] stated that humidity does not influence thermal sensation below a critical level, and he defined this limit to 80% relative humidity for temperatures up to 25°C. This is because, although the evaporative capacity of the air diminishes with increasing humidity, the body compensates for this by spreading the sweat over a larger area of skin, thus maintaining the required evaporation rate. Furthermore, Relative humidity /temperature diagram based on comfort zone according to ASHRAE *(55 Fig.2.6)* shows that relative humidity comfort zone ranges from 23% to 79.5% in the summertime [1].

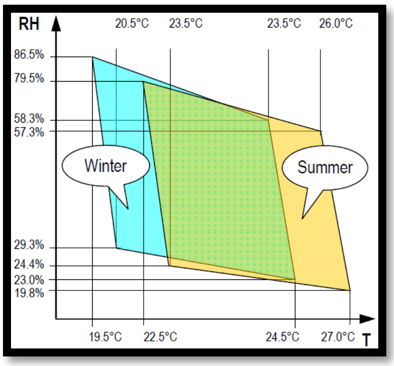

Fig.2.6. Relative humidity /temperature diagram based on comfort zone according to ASHRAE 55.

2.2.5. Personal parameters
2.2.5.1. Metabolic rate (MET)

The metabolic rate is related to the level of physical activity; at higher rates a cooler environment will be preferred to facilitate heat dissipation [1].

2.2.5.2. Clothing insulation (CLO)

Thermal comfort is very much dependent on the insulating effect of clothing on the wearer. Increased clothing insulation leads to a lower temperature difference between the outer surface of the clothed body and the ambient air temperature. Accordingly, the convective *and* radiative heat losses decrease with increasing clothing insulation, and it is considered an important adjustment mechanism if the clothes can be freely chosen. People adapt physically to an environment by a combination of both strategies of clothing insulation and metabolic rate through adjusting how they dress and move, e.g. slow walking in hot climates, and by avoiding exposure to extreme climate situations [9].

2.3. Air quality

The most important and influential pollutant to air quality and temperature is CO2. The level of carbon dioxide before the Industrial revolution was about 280 ppm. This value represents the equilibrium of the flows among the atmosphere, oceans and biosphere. This level of carbon dioxide in the atmosphere increased by 141% of its level before the Industrial revolution in 2011.It is reported that almost 5% of the world's diseases are caused by air pollution [15].

The outdoor air in most locations contains down to about 380 parts per million carbon dioxide. Higher outdoor CO2 concentrations can be found near vehicle traffic areas, industry and sources of combustion. Where indoor concentrations are elevated *(compared to the outside air)* the source is usually due to the building’s occupants. People exhale carbon dioxide the average adult’s breath contains about 35,000 to 50,000 ppm of CO2 (100 times higher than outdoor air). Without adequate ventilation to dilute and remove the CO2 being continuously generated by the occupants, CO2 can accumulate. The concentrations of CO2 found in most schools and offices are well below the 5,000-ppm occupational safety standard (time weighted average for an eight-hour workday within a 40-hour work week) for an industrial workplace. While levels below 5,000 ppm are considered to pose no serious health threat, experience indicates that individuals in schools and offices with elevated CO2 concentrations tend to report drowsiness, lethargy and a general sense that the air is stale. The outdoor air in most locations contains down to about 380 parts per million carbon dioxides [16].

2.4. Albedo

Albedo is measured on a scale of 0-1. A 0 means that the surface of a material absorbs all of the sunlight that hits it. A 1 means that a material reflects all of the light energy that hits it. In other words, a 1 on the albedo scale means 100 percent reflection. A 0 means no reflection. Fresh asphalt, for example, has an albedo of around 0.05, which means that only five percent of the light is reflected. The rest 95 percent is absorbed. In general,, lighter-colored materials reflect more sunlight than darker colors and therefore have a higher albedo. Why do darker materials feel hotter than lighter ones when both are exposed to sunlight for a period of time. When a material absorbs solar radiation, some of that light energy is converted into heat energy, and the material warms up. That is why an asphalt parking lot will feel hot if you walk across it on a sunny day [17].

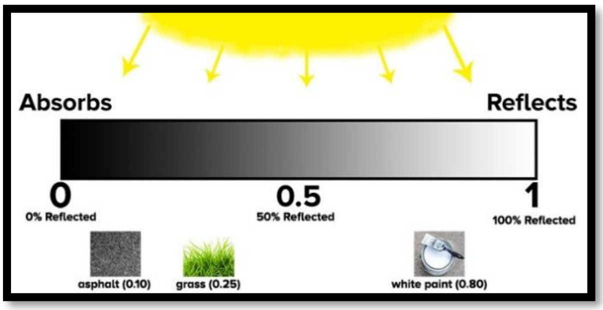

Fig.2.7. Albedo scale and common materials albedo value [17]

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3.DESIGN MEASURES FOR OUTDOOR THERMAL COMFORT: MACRO, INTERMEDIATE AND MICRO LEVELS

3.1. Chapter three introduction

This chapter discusses the design measures and their parameters affecting the outdoor thermal comfort at different scale levels. which in turn, affects the performance of outdoor thermal strategies that explained in chapter number six. In this chapter of the research, the design measures are comprehensively classified and categorized in *Table 3.1*, *Table 3.2*, *Table 3.3.* This classification expresses these measures in order, starting from the largest scale down to the smallest scale. The measures are grouped under three levels; the macro-level, the intermediate-level as well as the micro-level.

3.2. Macro-level design measures

The design measures of site landform**,** heat sinks**,** urban form, and street design are all included and discussed in the macro level.

3.2.1. Site landform

The site landform could be flat, sloping or undulating (*mounds, etc*.). Different local airflow is developed over the site in each case. In flat sites, the prevailing conditions are most likely the same over the entire site with little variation can be identified. However, slopes and depressions could create significant variations in the airflow and air temperatures across the site. In general, on slopes, the temperature decreases by (*0.8o C*) every (*100 m*) increase in the height as shown in *Fig.3.1.* [1], [2].

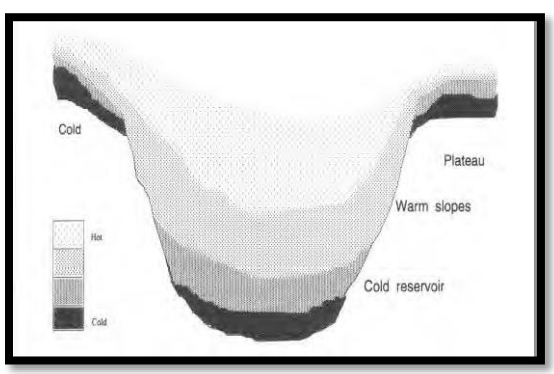

Fig.3.1. Temperature stratification on a mountain slope [1]

3.2.2. Urban form

The measures of urban form and the street design are working in conjunction with each other in order to provide either protection from wind or maximum exposure according to the design proposal. The urban form has a significant role in serving the climatic design generally and designing for ventilation specifically, as it greatly controls the access of the sun and wind to be used in buildings [2]. The urban form could be designed to maximize the air movement through the city level, and thus allow wind access to more buildings for optimum ventilation. Solar orientation should be greatly considered in their design, especially in hot climates, where providing solar shading is given priority over ventilation.

Streets layout and their configurations determine the urban form of the settlement or its districts and neighborhoods. Four main urban forms are shown in *Fig.3.2,* could be identified from the historical background in building cities in order to be adapted to a specific climates' requirements [3].

- *The compact form:* The buildings are arranged in a neat and orderly form in a smaller interval space between dwellings. It responds favorably to both hot-dry and cold-dry climates;
- *The disperse form:* Consists of low-rise detached buildings with wide spaces in between. It is preferable in the hot-humid climate where air movement and ventilation are required. It can also exist in cold-humid climates with some controllable features for winter wind protection;
- *The clustered form:* Consists of small assemblies of buildings, which are built very close to each other. It responds favorably to both hot-dry and cold-dry climates; and in humid climates
- *The combined form:* It is a combination of different of the above forms [1],[4].

Fig.3.2. a) The compact urban form site b) The clustered urban form site c) The disperse (western dotted) urban form site [4]

Fahmy and Sharples [4] studied the airflow and thermal comfort performance of the three forms; compact form, clustered form and disperse form. They took three representative sites in Cairo as case studies *Fig.3.2.* All the buildings in all sites were medium height that varied between 4 and 5-storey height. Their study revealed the suitability of the clustered form for both ventilation and general comfort requirements as it provides enough wind speed and solar access to the site. They advised that the use of the clustered pattern with a different orientation, different aspect ratio as well as using vegetation to provide shading could be the best option for achieving passive cooling in such context. On the other hand, in the compact form, the wind was found to have almost no access to the site. Which in turn, prevents the heat dissipation from the streets at night as well as providing bad environmental conditions.

Although, the disperse form case experienced a good wind flow access, it was found to provide a large exposure to the sun radiation. This in turn, requires much more urban shading to be provided. In addition, it can be considered as excessive land-consuming and sprawl [1].

3.2.3. Street design

Street design includes the design measures of street wind orientation and street canyon geometry. These measures are greatly related to the urban form in terms of air movement and solar shading design.

3.2.4. Street wind orientation

The performance of each urban form, in relation to natural ventilation, greatly depends on the orientation of the streets' grid and the buildings that line them on both sides. Street orientation could be parallel, oblique or normal to the wind direction [1]. When the major streets in a site are oriented parallel to the prevailing wind, the highest velocity could be obtained in the streets and the adjacent open spaces. Generally speaking, the optimal street orientation for ventilation purposes, which is advised by Givoni [5], was found to be oblique to wind direction by approximately 20 – 30o with the narrowest buildings' façades facing the wind, that can be seen in *Fig.3.3.*

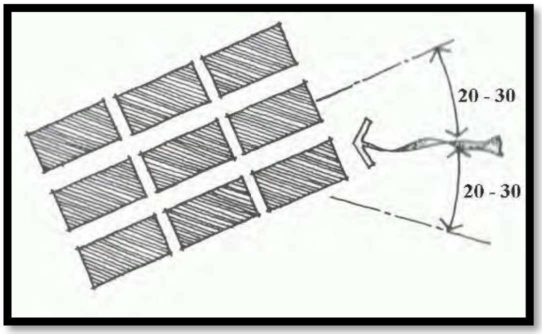

Fig.3.3. The generic optimum street orientation for natural ventilation purposes [1].

3.2.6. Street canyon configurations

The Street canyon can be defined as “the space between blocks distributed on both sides of a street, from the street surface to rooftop level” [6], [7]. Street canyon geometry is also one of the main measures that can have a great impact on air temperature distribution within the street. This, in turn, could affect pedestrian thermal comfort [6], [8]. The geometry of a street canyon is expressed by its ‘aspect ratio’ including the ratio of the height of the building to the width of the street. If the canyon has an aspect ratio of around equal to 1 with no major openings on the walls it is called a uniform street canyon. A canyon with an aspect ratio below 0.5 is a shallow street canyon; and the aspect ratio of 2, represents a deep street canyon. The length of canyon illustrates the road distance between two main intersections subdividing the street canyon into short (L/H= 3), medium (L/H a= 5) and long (L/H = 7) Fig.3.4.It has been proved that the geometry and orientation of the street canyon affect outdoor and indoor environments, solar access inside and outside the buildings, the permeability to airflow for urban ventilation, as well as the potential for cooling of the whole urban system. Therefore, the street design influences the thermal comfort at a pedestrian level as well as the global energy consumption of urban buildings [9]. The design measures affecting outdoor thermal performance at this level are summarized in (*Table 3).1.*

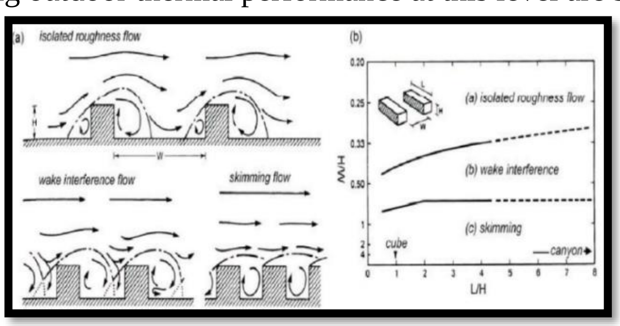

Fig.3.4. Airflow regimes over an array of barriers of the main flow features [9].

Table 3.1. Illustrates the proposed classification of the design measures affecting outdoor thermal performance.

Design level	Design measures	Studied parameter	Best practice
Macro-level	Site landform	Flat, Sloping &Undulating	Middle of the windward facing slope
	Heat sinks (water bodies and forest)	Near & Away	Build the building near to them to benefit from cold sea breeze
	Urban form	Compact, Disperse, Clustered & Combined	Clustered form
	Street wind orientation	Normal, Oblique &Parallel	20o to 30o oblique to wind direction
	Street canyon geometry	H/W < 0.3, 0.3 < H/W < 0.65, H/W =1 & H/W = 1.5	H/W ratio of 0.5 to 0.44

3.3. Intermediate-level design measures

The building arrangement, vegetation, and water body are the design measures that will be discussed in this section.

3.3.1. Buildings arrangement

When locating a building within an urban site, great attention has to be paid to the distance between the building and other buildings in the site. In order to provide maximum wind exposure to a building, it has to be located at a distance from other buildings that is two times larger than its height, However, it could reach five times its height [1].

3.3.2. Vegetation

The vegetation is a modifying factor of the local climate, and it is considered an important design element in improving urban microclimate and outdoor thermal comfort in urban spaces. Although it has been proven that the plantation is considered one of the main tools that can be used in improving the thermal comfort in outdoor spaces, it is being used basically in the urban spaces for aesthetic purposes, utility and recreation in the most cases. The impact they have on the microclimate, the human comfort, and energy aspects are not really taken into account in their design that may be because of poor interdisciplinary work between urban climatology, urban design and landscape architecture. The use of the green as a strategy to mitigate the urban heat island and improve the microclimate has been widely emphasized [10, 11, 12].

For hot climates, the best use of the vegetation should profit from its shading property to mitigate the intense solar radiation in the summer as the overheating is mainly due to the storage of heat by the sunlit surfaces. The evapotranspiration is often weak owing to the lacking water in the soil, unless irrigation is supplied. A sparser vegetation well mixed within the urban structure to produce as much shadow as possible has to be preferred in hot and dry climates. For cold climates using the vegetation as a screen against high winds is more appropriate and dense vegetation located at the urban edges is advisable. Individual trees spaced with large intervals, as is usually the case in an urban street, do not have a significant cooling effect. Therefore, it has been recommended that it is more effective for urban. sites to use several smaller groups of trees. In a dense urban environment, trees can be located in various locations such as in rows along the sidewalks, in parking areas and at street intersections. However, in order to achieve these benefits of urban vegetation, a great attention must be paid to the requirements of appropriately planting and maintaining healthy mature trees in an urban setting to produce the desired shading and cooling effects *Fig.3.5.* [13].

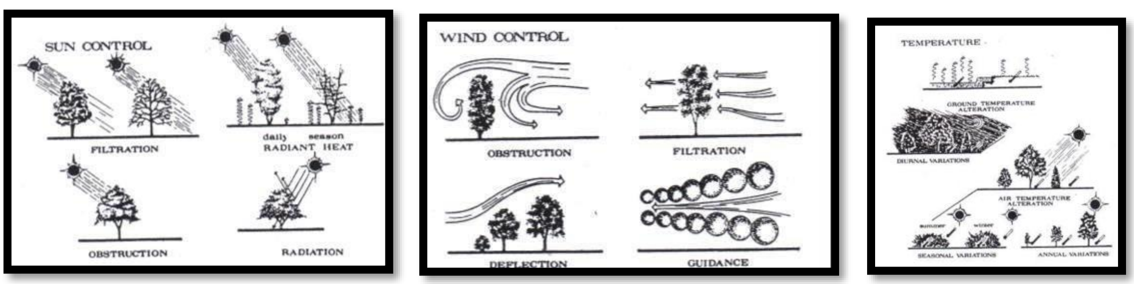

Fig.3.5. Plantation and sun Control Plantation and wind Plantation temperature control [13].

3.3.3. Fountains and ponds

Water bodies have the ability to adjust the surrounding microclimate. The temperature mitigating capacity of water bodies in urban environment can potentially reduce energy consumption, increase outdoor thermal comfort and mitigate the Urban Heat Island effect. Air temperature near bodies of water is found different from that over land. Water bodies are known as the best absorbers of radiation, nevertheless show very little thermal response. Owe to its transparency, large thermal capacity and volume, the incident solar radiation is able to transmitted to considerable depths and be spread throughout large volume. Together with unlimited water for evaporation, bodies of water create an efficient heat sink and further cool the surface layer. Furthermore, from the energy budget point of view, more evaporation increases latent heat (Qh) and affects the energy partitioning of sensible heat (Qe) and the stored energy (Qs), in which reduction of Qe and decrease magnitude of Qs, make its immediate surrounding air temperature lower. Study on the temperature reduction due to water bodies have been conducted by many researchers utilizing various methods. By remote sensing, researchers estimate the cooling effect by analyzing the surface temperature of different land use in urban area and shows cooling effect of up to 5.63°C if urban wetlands are compared to urban area. field measurement study in Singapore found that water features, such as pond and water wall are able to reduce the air temperature up to 1.8°C during sunny clear day. A recent study utilizing numerical simulation study shows that beside the ability to reduce the air temperature the presence of water bodies able reduce the energy consumption and with additional vegetation, it will also provide better outdoor thermal comfort. All of these researches show a clear evidence of water bodies modify the thermal environment by cooling down the surrounding air temperature through evaporation cooling and convection [14].

3.3.4. Green roofs

The adaptation of an Urban Green Infrastructure (UGI) significantly contributes in decreasing the city temperature, and has an important reduction potential on the urban heat island effect as the UGI provides climate regulating effects like evapotranspiration and shading. In related work, Wong and Chen declared that greenery in a built environment could affect all the aspects of the urban life such as the environment, the economic, the aesthetic and the social aspect. Thus, increasing the green areas is an important ecological measure to combat UHI effects and equalize local temperatures. Since transforming residual spaces into green areas still a huge challenge in densely urbanized areas, turning traditional bitumen flat roofs into green ones could be the best solution. The building roofs include a noticeable percentage of the urban area and participate extremely to the intensification of UHI, almost 20 to 25% of the urban surface. Besides, they represent an important component of the buildings when it comes sustainable outputs [15].

3.3.5. Green walls

Green façade (GF) is a passive cooling technique in providing a better sustainable living environment especially in thermal performance. GF acts as an external shield to the building facade avoiding undesirable excessive radiation and reducing heat flux transfer through exterior surface. It also benefits to lessen ambient temperature in between GF and opaque wall and simultaneously decreases heat flux transfer towards indoor environment [16].

When the urban structure is characterized by narrow street canyons, the radiation trapping increases the surface temperature and the reduced airflow recirculation leads to higher air temperatures. A new modeling approach was developed to assess thermal impacts of green walls on buildings in the urban environment. A case study is presented in Djedjig. The simulated urban scene consists of a series of identical buildings and street canyons. Each building is a three-story full-scale building. The cooling load was compared for buildings with different aspect ratios (H/W= 0, 0.5 and 1.0) depending on the width of the streets. The results quantify the progressive effects of streets confinement according to the aspect ratio variation and the potential of green walls to mitigate increased cooling loads. The numerical results show that green walls installed on east and west façades of the studied building reduces by 37% the cooling load of nearby buildings with an aspect ratio equal to one and reduce it by 33% for a secluded building, for Athens summer climate. There is still a lack of experimental data on these effects, so the study focuses on the experimental verification of such results and gives verification data for developed models [17]. However, the design measures affecting outdoor thermal performance at this level are summarized in *Table 3.2*.

Table 3.2. Illustrates the proposed classification of the design measures affecting outdoor thermal performance.

Design level	**Design measures**	**Studied parameter**	**Best practice**
	Buildings arrangement 1-Locating a building in a site	Building location in the site The distance between the building and adjacent buildings = 0.5, 1.0, 1.5 its height	1-The building oriented to the desired wind 2- Distance between them = 1.5 their height
		group of four buildings maximum	arranging the buildings around a central

	2-Arranging small group of buildings		
	3-Arranging a compound	1- Aligned rows arrangement 2- Staggered arrangements	1-Staggered 2-arrangement
	Vegetation	Locations, patterns & functions	Dependent on the design proposal
	Water body	As microclimate modifier	Artificial fountains
	Green roofs	50% & 100% of the roof surface	More than 75% of the roof surface
	Green walls	50% & 100% of the wall surface	More than 75% of the wall surface

3.3. Micro-level design measures

In this level of design, the role and configuration of four design measures in controlling Outdoor thermal performance will be clarified. These design measures include roof shape building height, building envelope materials, heat Transmission.

3.3.1. Roof shape

The building roof shape could be flat, single-slope, double-slope (*Pitched*), dome or vault. In terms of external airflow, the shape of a building roof has a great effect on the size of the downwind eddy as well as the wind pressure distribution over the roof structure itself *Fig.3.6*. However, it was also reported to have a significant role in inducing internal airflow. According to the parametrical study of air pressure distribution over three kinds of roofs (*flat roof, single-slope roof and double-slope roof*) conducted by Grosso [18], it seems that the distribution of pressure over the surfaces of different roof shapes, and consequently their potential use in ventilation [1].

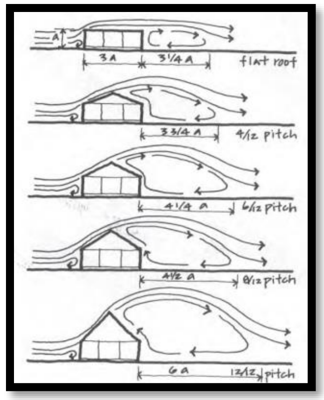

Fig.3.6. The effect of different roof shapes on downwind eddy size [1].

3.3.2. Building height

The height of buildings is an independent design feature that can affect urban density as well as the urban climate in many ways. Studies in Pune, India, showed that the unplanned increase in heights of buildings increases the discomfort level in a city. However, in the case of Colombo, Sri Lanka, it was found that the wide streets with low-rise buildings and no shade trees made the outdoor conditions worse, and the most comfortable conditions were found in narrow streets with tall buildings, especially if shade trees were present. In addition, it was found that a very deep street canyon had considerably lower air temperature than a shallow street canyon [19].

3.3.3. Building envelope materials

When the temperature of the ground surface is warmer than that of the canopy layer air, the direction of sensible heat flux is upward, leading to an increase in near surface air temperature. Unlike many rural areas, where plant cover and evaporation of soil moisture may moderate the increase of surface temperature that occurs when solar radiation is absorbed, a large proportion of urban areas consists of dry impervious materials–pavement or buildings. To mitigate the temperature increase displayed by such surfaces, which results in warmer air temperature, several researchers have suggested that wherever possible, they should have a high albedo. The implicit assumptions of this strategy are that by lowering canopy layer air temperature, cities will enjoy a) reduced air conditioning loads in buildings; and b) improved thermal comfort for pedestrians in outdoor urban spaces. Although use of high-albedo materials in urban surfaces may reduce the air temperature to which pedestrians are exposed, this change has only a small effect on their thermal balance with the environment: The reduction in surface temperatures, which leads to reduced long-wave emission, is offset by increased reflection of solar radiation. The net effect of increasing the albedo of urban surfaces may thus be a small increase in the thermal stress to which pedestrians are exposed – rather than the expected improvement in thermal comfort. Extensive use of high-albedo materials has been advocated as a means of mitigating the urban heat island, especially in warm-climate cities. The implicit assumptions of this strategy are that by lowering canopy layer air temperature, cities will enjoy a) reduced air conditioning loads in buildings and b) improved thermal comfort for pedestrians in outdoor urban spaces [20]. The design measures affecting outdoor thermal performance at this level are summarized in *Table 3.3.*

Table 3.3. Illustrates the proposed classification of the design measures affecting outdoor thermal performance.

Design level	Design measures	Studied parameter	Best practice
Micro-level	building height	1-2 of street width	1.5 of street width
	roof shape	Flat, double-slope (Pitched)	No preference and dependent on orientation
	Building envelope Heat Transmission	With and without Insulation	roofs < 0.25 W/m²K, walls < 0.45 W/m²K
	Building envelope albedo	High reflective materials & Low reflective materials	High reflective material

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PART 2: STUDY SITE ANALYSIS AND EVALUATION

4. STUDY SITE ANALYSIS

4.1. Chapter four introduction

In this chapter, the criteria used to choose the main study space are presented. It also, presents a detailed analysis of the study site. The study site design measures and their parameters’ settings that could possibly be related to the outdoor thermal comfort performance are highlighted. In general, this chapter aims to identify the research study site and the properties of its design measures in terms of outdoor thermal comfort.

4.2. Choosing the study site

Based on Yin [1], [2] definition of the study area, Groat [3] defined it as "an empirical inquiry that investigates a phenomenon or setting within its real-life context." therefore, the study sites are argued to be one of the most important factors that can affect the success of any research project [4]. In this research four main criteria have been driven the choice of the study site. These criteria are:

1-Availability of the data

B-Measurement data

C-Albedo data

D-Weather data

2-Physical accessibility to the study area; and

3-Historical and social value

4-Function and usage

The availability of data as well as social value for the proposed study areas were one of the main factors that controlled the choice of the study site. Three different microclimate spaces were identified in the city of PECS *Fig.4.1*, *Table 4*. These can be presented under the following three microclimate areas:

1- Széchenyi tér

2- Szent István tér

3- Kossuth tér

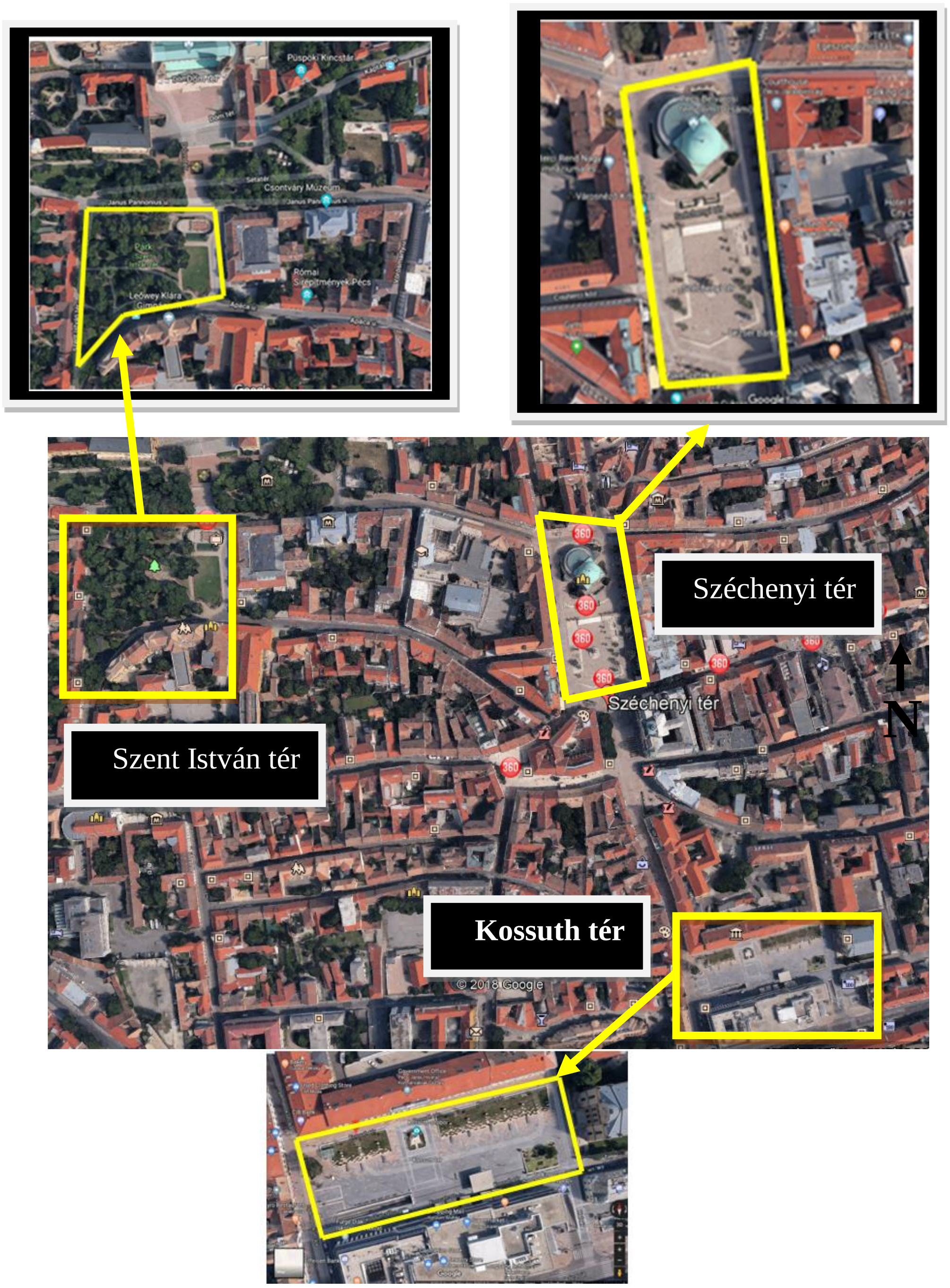

Fig.4.1. Satellite image illustrates each microclimate site and its location in PECS-city [5].

Table 4.1. The available study sites in the research context and the study area choice process with the selected study site highlighted.

Choosing criteria			
Name	Széchenyi tér	Szent István tér	Kossuth tér
Availability of the data	Yes	No	No
Accessibility	Yes	Yes	Yes
Functionality	Main square	Park	Square
Social value	5 star	4 star	4 star
Final choice	Chosen	Excluded	Excluded

4.3. Study area description

Széchenyi square is the main square in the historical center of Pécs, Hungary. In the Middle Ages, it served as the marketplace of the town with the city hall and the parish church. Before the square was named Széchenyi in 1864, it had had several other names like Fórum, Városi piacz (City piazza), Főtér (Main square). The square is one of the central squares of Pécs, full of monuments, and mounting gradually northward. The surface of the square was rebuilt within the scope of the project Pécs 2010 European Cultural Capital.

The square is located in the heart of the old town of Pécs, on the southern side of the Mecsek mountain. Twelve streets run into the square, starting from the south clockwise: Irgalmasok street, Jókai square, Ferencesek street, Ciszterci alley, Janus Pannonius street, Szepessy Ignác street, Hunyadi János street, Megye street, Mária street, Király street, Perczel Miklós street and Munkácsy Mihály street [6].

The study site is located in the middle of the selected city and surrounded by twelve buildings *Fig.4.2*. The total area is almost *11222 m2*, and most buildings are three to four floor height, the case has two water bodies and some plantation nearly 7% of the total area. Moreover, most buildings are built of light-colored brick with red roof tiles. The space serves as an assembly point where locals can meet, chatting, as well as wandering.

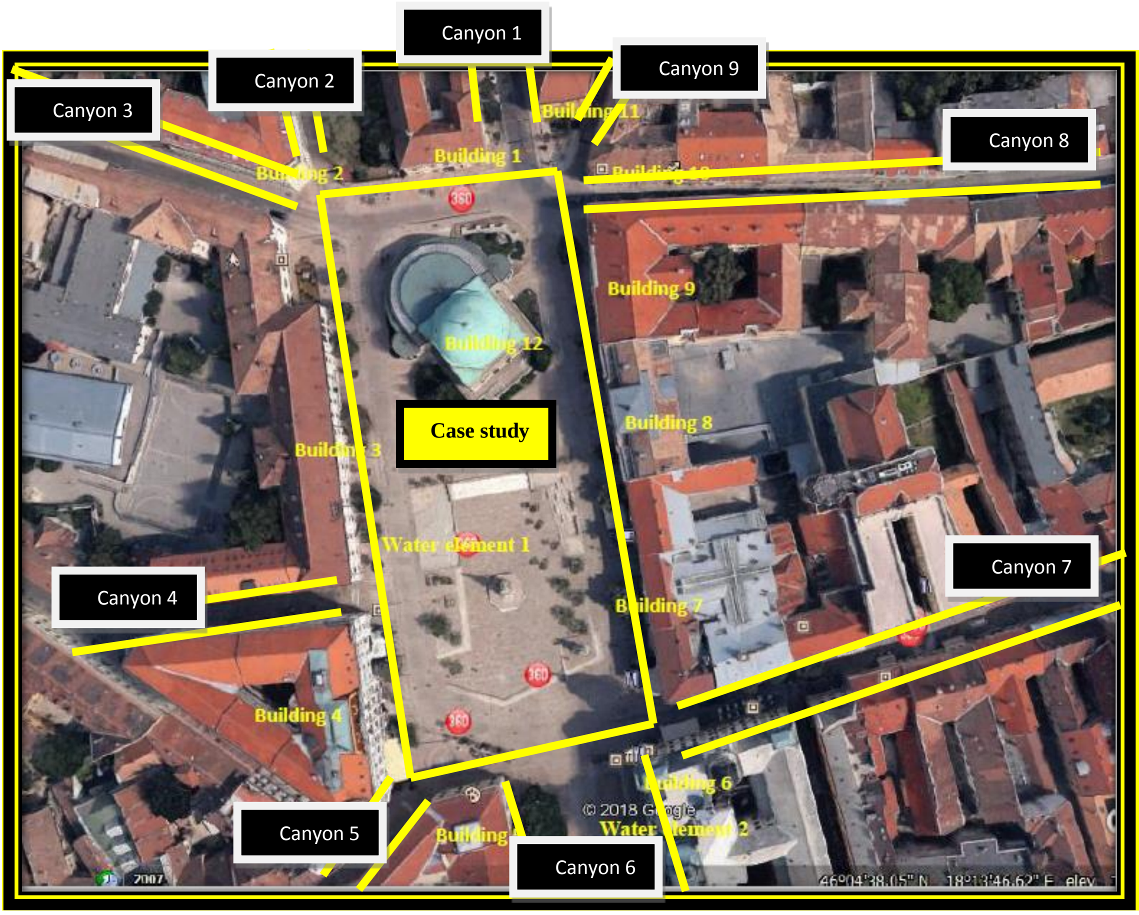

Fig.4.2. The location of the study site, surrounding buildings, and street canyons are highlighted [5].

4.4. Study Site Analysis

4.4.1. Site Analysis

In terms of the landform of the study site, it is flat with no significant difference in levels as can be seen in *Fig.4.3.* However, no heat sinks such as seas, river, and lakes are found near the site within a radius of two *Km*.

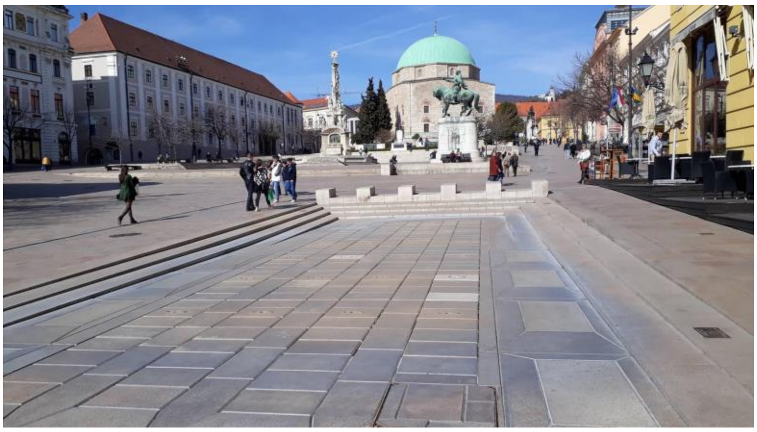

Fig.4.3. The southward sloping terrain profile of the study site.

4.4.2 Street canyon geometries

Analyzing the street geometrical configurations of the study site showed that street width *W* ranges between *6m* and *36m* with the majority of the streets almost more than 40% are having a width of *10m* which can be seen in *Fig.4.4.* The other widths can be found in the site only one or two times maximum. The ratio between height and width was found to be *1.1-1.3* in most cases so more the 60%, in other words, 6 cases out of 9. The H/W in the site ranges from 0.3 to 1.75 and the median is *1.1.* According to the canyon classification mentioned in chapter three and from the site analysis stated above, so it can be reported that the most common canyon configuration across the site is a deep canyon. Also, it can be seen that all canyons within the site are short canyons *Fig.4.4.*

Canyon street No	Height	Width	H/W
Canyon one	8	14.5	0.55
Canyon two	10	7.5	1.3
Canyon three	12	10.5	1.2
Canyon four	14	8	1.75
Canyon five	10	9	1.1
Canyon six	10	36	0.3
Canyon seven	13	11	1.2
Canyon eight	10	7.5	1.3
Canyon nine	7	6	1.2

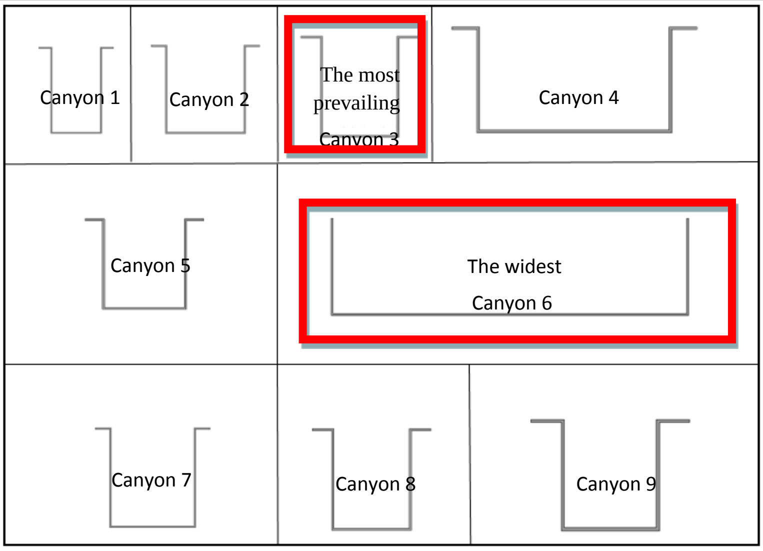

Fig.4.4. Street canyon profile across the study site.

4.4.3. Landscape Analysis

4.4.3.1 Softscape

4.4.3.1.1 Vegetation

From the provided design of the study site's master plan, there are some mature trees and bushes were found. Nevertheless, vegetation is limited to *6-9M* trees with some flowers over the square *Table 4.2*.

Table 4.2. The available plantation of the study site.

Plant name	Plant symbol	Description
Grass	Xx	50cm aver dense
Hedge dense	H	Evergreen, Height 2m, Width 0.6m, Erect, 12-20 L/day
Dense, distinct crown layer	Ds	Deciduous, Height 15m, width 10m, Spreading, 50-70 L/day.

The total vegetation area is 750 *m2*, 7% of the site total area *Fig.4.5*. The flowers are not expected to affect the airflow profile over the site. Nevertheless, they might play a critical role in cooling the air through evaporation.

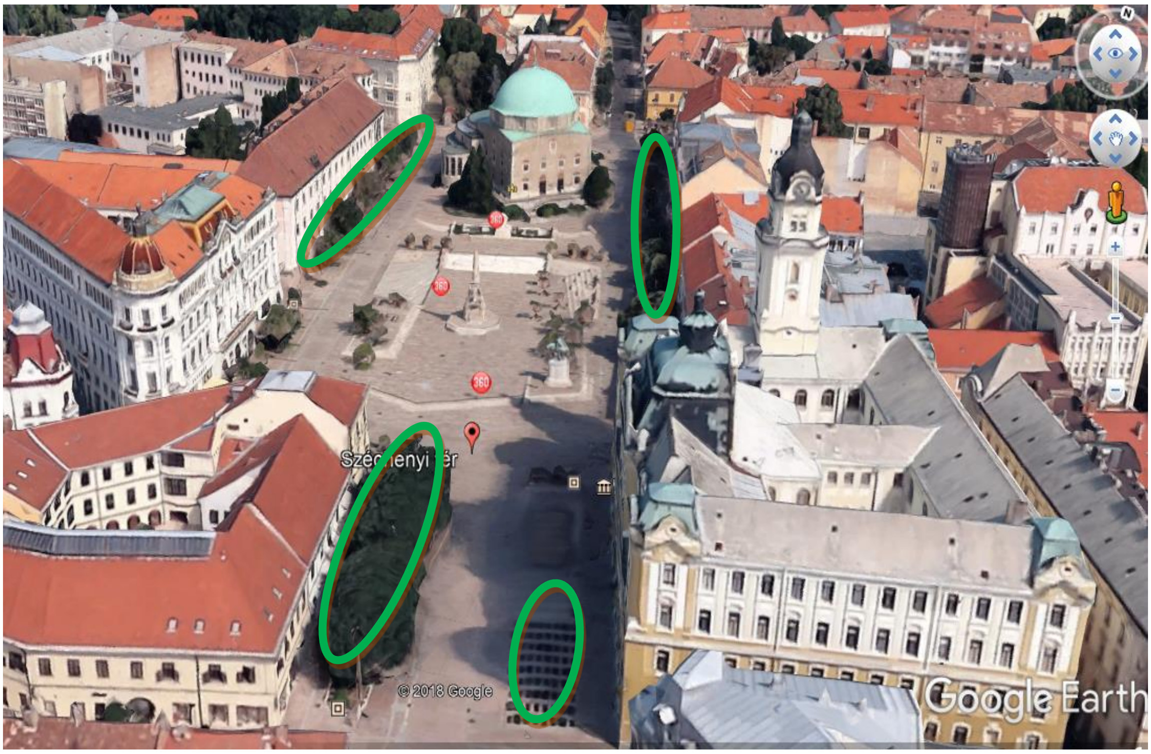

Fig.4.5. The plantation location across the study site [5].

4.4.3.1.2 Water Body

The site analysis also showed that ponds and fountains had been designed to be located on the site in two different places *Fig.4.6*. Furthermore, water constitutes about 3% of the total site *Table 4.3*.

Fig.4.6. The water bodies location of the study site

Table 4.3. The water element analysis of the study site

Water element number	Area m2
1	169
2	120

4.4.3.2 Hardscape

The hardscape such roads, seats, and statuses are found in the location in different places *Fig.4.7.* However, the focus is on material and physical properties as well as dimensions that are more likely to affect the microclimate thermal comfort. Nonetheless, the paving (interlock) is about 86% of the total area while the asphalt roads account for less than 1%, two statues are found in the site with height of *4-6m* as shown in *table 4.4.*

Fig.4.7. The hardscape of the study site

Table 4.4. The Hardscape analysis of the study site.

Material	Material symbol	Description/Albedo
Asphalt road	Kg	Dark, thick, viscous/0.1
Brick road (yellow stone)	S	Light colored brick /0.7
Seating seats	S	
Statues	Building	Height 3-6 m

4.4.4. Climate analysis

4.4.4.1 Wind speed and direction

Wind is distinguished into its direction and speed. The direction of the wind means where the wind blows from. In the upper air of the temperate climatic zone, the prevailing winds are the Westerlies, due to the location of Hungary the prevailing wind is Northwestern, while the southern winds are secondary maxima *Fig.4.8.* The northwestern base flow of the general circulation is more emphasized in Eastern Transdanubia and between the rivers Danube and Tisza, while east of the Tisza the prevailing wind is northeastern. However, due to the different circulation patterns, the wind direction is not permanent, the relative frequency of the most frequent wind is only around 15–35% in Hungary. Thus, in 65–85% of the time the wind does not blow from the prevailing direction [7]. Nonetheless, the wind speed is considerably determined by local effects. Apart from macro scale patterns, the wind speed depends on the relief, the land cover and other objects (e.g. buildings, trees, etc.). Based on the average wind speed, Hungary can be classified as a moderate windy region, the annual means of wind speed are varying between 2 and 4 m/s *Fig.4.8*, *Fig.4.9* but significantly different values can also be measured due to the above-mentioned reasons. The wind speed has a typical intra-annual variability, the windiest period is the first half of spring, while the lowest wind speeds can usually be observed during the beginning of autumn. On average, there are 122 windy days a year in *Pecs* (i.e. When the strongest gust exceeds 10 m/s), from which 35 days are gale (the strongest gust exceeds 15 m/s) *Fig.4.9* [8].

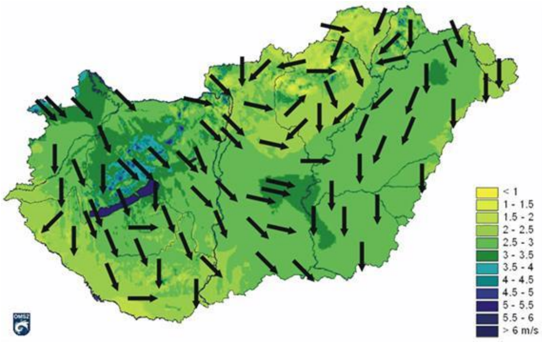

Fig.4.8. The average annual wind speed (m/s) and prevailing directions in Hungary [8].

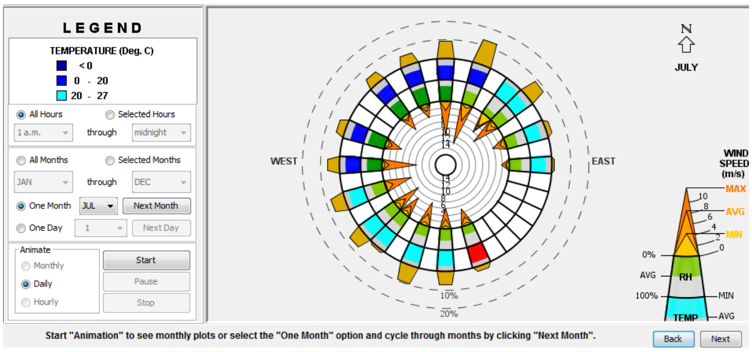

Fig.4.9. The average annual wind speed m/s and prevailing directions in Pecs [9].

- On average the annual wind speed is 2.5 m/s which can be seen in *Fig.4.10;*
- On average the highest wind speed is 4 m/s in April;
- On average the lowest wind speed is 2 in the summertime;
- The Wind direction in degrees in the summertime equals to 0 on June, 20 on July, 0 in August;

The study site is Oriented towards the north direction with the wind in the study site context blows from the north and northwest directions.

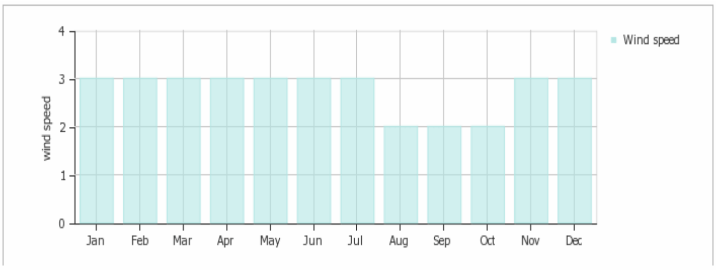

Fig.4.10. The mean monthly wind speed over the year in Pécs (m/s) [8].

4.4.4.2 Relative humidity

Relative humidity: Is the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure [10]. Nevertheless, the following conclusions can be concluded from *Fig.4.11;*

- December is the most humid;
- July is the least humid month;
- The average annual percentage of humidity around 73.0%;
- The summertime percentage of humidity around 71% on average;
- The average Humidity in July around 65%.

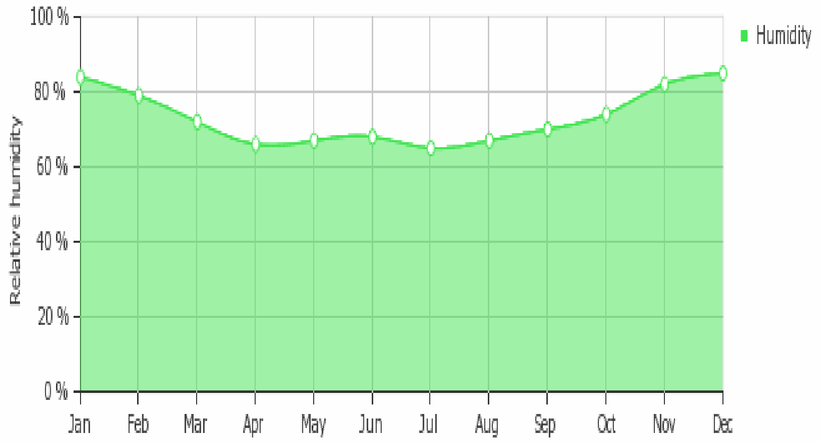

Fig.4.11. The mean monthly relative humidity over the year in Pécs city [8].

4.4.4.3 Temperature range

The temperature of the air surrounding the occupant [10]. However, the following results can be drawn from *Fig.4.12.*

- The warmest month is July *see Fig.4.12*, the mean temperature is *22c* and the average high temperature around 26c.In addition, design temperature is 33c and low design temperature is *15c;*
- The coolest month is January with mean temperature around -*1*, the high design temperature is 6c and the low is -7c;
- The average annual maximum temperature is: *15* Celsius;
- The average annual minimum temperature is: *6.0* Celsius.

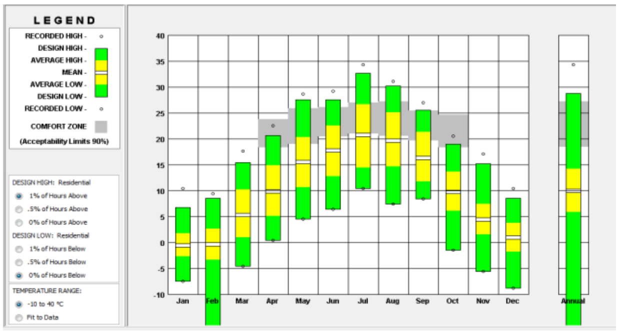

Fig.4.12. The average annual and monthly temperature ranges in Pecs-city [9].

4.4.4.4 Radiation range

Solar radiation is radiant energy emitted by the sun from a nuclear fusion reaction that creates electromagnetic energy. The spectrum of solar radiation is close to that of a black body with a temperature of about 5800 K. almost half of the radiation is in the visible short-wave part of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum. The units of measure are Watts per square meter.

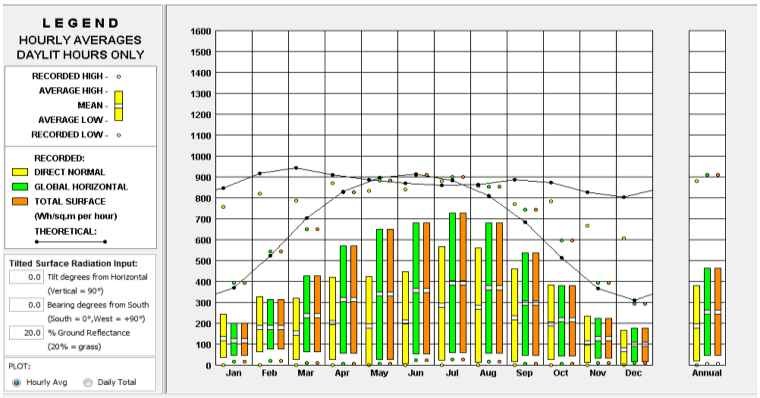

Fig.4.13. The average annual and monthly radiation range [9].

On average July sees the highest radius mean value where direct radius is around 300 w / m2 while the average high radius is 440 w / m2 *Fig.4.13*. However. the average low is 50 w / m2. On average December sees the lowest radiation mean radiation while high average about 100 w / m2, the low average is about 0 w/m2 that means no sun radiation reaches the earth at this time. The annual mean radius 190 w/m2, annual high average around 390 w / m2, annual low average is 20 w / m2 [8].

4.4.5. Building characteristics

4.4.5.1. Heat Transmission

4.4.5.1.1. Walls

All buildings that are surrounded the study space are built of bricks see *Fig.4.14*, *Fig.4.15*. The U-value is almost 1.7 W/m2. K, bearing in mind that minimum value according to Hungarian legislation is 0.45 W/m2. K [11]. However, one building is made of stone with 1.3 W/m2. k U-value *building 12 see Fig.4.14.*

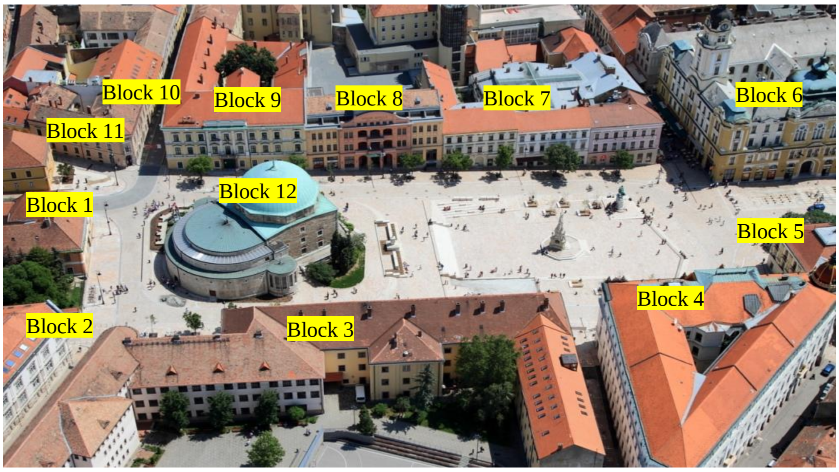

Fig.4.14. The study site [5]

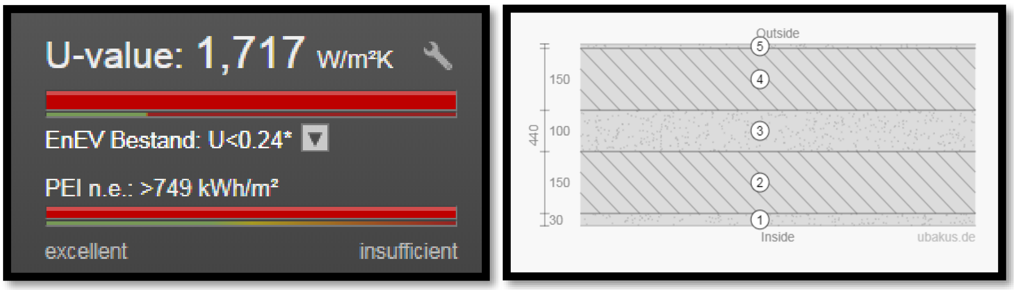

Fig.4.15. The walls heat Transmission value on the study site [12].

3.4.5.1.2 Roofs

Most Roofs in the study space are built of tiles with on insulation, so the U-value is almost 2.2 W/m2 as can be seen in *Fig.4.16*. Nonetheless, the minimum value according to Hungarian legislation is 0.25 [11].

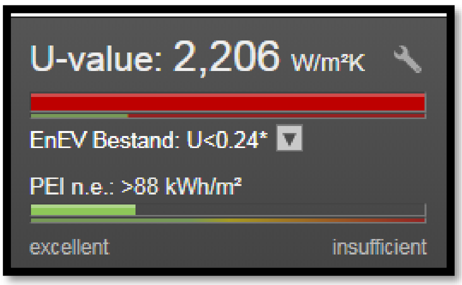

Fig.4.16. The roofs heat transmission value on the study site [12].

4.4.5.2. Albedo

The fraction of the incident radiation that is reflected from the surface is called the albedo [10]. However, the *table 4.5* shows the albedo values in the study site. In addition to, commonly used materials which could be utilized in the next part *(part 3)* to enhance the chosen study space.

Table 4.5. Commonly used materials with their albedo values that used on the study site [13].

Surface	**Albedo**
Streets	
Asphalt (fresh, aged 0.2)	0.05-0.2
Walls	
Concrete	0.10-0.35
Brick/stone	0.20-0.4
Whitewashed stone	0.8
White marble chips	0.55
White colored brick	0.30-0.5
RED brick	0.20-0.3
Dark brick and slate	0.20
Limestone	0.30-0.45
Roofs	
Smooth-surface Asphalt Weathered	0.07
Asphalt	0.10-0.15
Tar and gravel	0.08-0.18
Tile	0.10-0.35
Slate	0.10
Corrugated Iron	0.10-0.16
Highly reflective roof after weathering	0.6-0.7

4.4.5.3. Building envelope properties

Most buildings have light-colored façade with red roof tiles. In other words, the albedo value is approximately the same in most cases as shown in *Table 4.6.* The structures' height ranges from *7m to 14m*.However, Heat transfer does not meet the minimum requirement of the Hungarian energy code, although most buildings are newly renovated. Nevertheless, the *table 4.6,* below shows different building materials, U-value, and albedo values for various walls and roofs in the study site.

Table 4.6. Different buildings materials, color, u-value, as well as albedo values that used on the study site.

Building Number	Height	Albedo		Heat Transmission	Façade materials	
1	8 m	walls	0.5	1.7	Walls	light colored brick

		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo			Façade materials	
2	10 m	walls	0.5	1.7	Walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
3	12 m	Walls	0.5	0.4	walls	light colored brick
		Roof	0.2	0.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
4	14 m	Walls	0.5	1.7	walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
5	10 m	Walls	0.5	1.7	walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
6	10 m	Walls	0.5	1.7	walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
7	13	Walls	0.5	1.7	walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
8	10 m	Walls	0.5	1.7	walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
9	13 m	Walls	0.5	1.7	Walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
10	7 m	Walls	0.5	1.7	walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
11	7 m	Walls	0.5	1.7	walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles
Building Number	Height	Albedo		Heat Transmission	Façade materials	
12	7 m	Walls	0.5	1.3	walls	light colored brick
		Roof	0.2	2.2	Roof	Roof tiles

4.4.6. Clothing Insulation

The increased resistance to sensible heat transfer obtained from adding an individual garment over the nude body. Expressed in clo units [10]. In the summertime, the majority of individuals wear garments that have clothing insulation ranges between 0.5 and 0.67 clo. However, in wintertime clothing insulation increase up to 1.3 col as can be seen in *Fig.4.17*.

Clothing Description	Garments Included[b]	I_{cl} (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

Fig.4.17. The clothing insulation value of different clothing pieces [10].

4.4.7 Metabolic rate

The rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. this rate is expressed in met units [10]. The most common activities in the study site are seated, standing, relaxing and walking. The fewer common activities are dancing and exercising. Nevertheless, the metabolic rate ranges from *1met* to *4.4met*. In other words, from seated to dancing. However, the most popular activities range from *1met (seated) to 2.6met (waking), table 4.7.*

Table 4.7. Metabolic rates for typical tasks [10].

Activity	Met Units	Metabolic Rate W/m2	(Btu/h·ft2)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)

Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	(70)
Miscellaneous Leisure Activities			
Dancing, social	2.4-4.4	140-255	(44-81)
Calisthenics/exercise	3.0-4.0	175-235	(55-74)
Tennis, single	3.6-4.0	210-270	(66-74)
Basketball	5.0-7.6	290-440	(92-140)
Wrestling, competitive	7.0-8.7	410-505	(129-160)

4.4.8. Summary

A representative study site was chosen to be used in this research. The study area was analyzed in this chapter in terms of identifying the properties of its design measures which could affect the outdoor thermal performance.

The results of the study site analysis could be concluded as follows:

1-The site is flat with no slopes nor any nearby heat sinks;

2-The master plan is surrounded by 11 blocks and one in the middle streets that were found to be oriented to the northeast-southwest mostly direction and northwest-southeast direction;

3- The most common canyon configurations within the site were found to be short deep canyons with a width of 6 m, H/W ratio = 1.2;

4- there are some mature trees and bushes were found. Vegetation is limited to 6-9 M trees and flowers over the public open spaces. The total area of the vegetation is 750 m2, i.e., 7% of the site. These flowers are not expected to affect the airflow profile over the site;

5- The site analysis also showed that ponds and fountains had been designed to be located on the site in two different places. Water constitutes about 3% of the total site.

6-The hardscape such roads, seats, and statuses are found on location in different places;

7- The Climate analysis;

- Wind: The average wind speed is 2.5-3 m/s in the summertime.
- The Wind direction in degrees in summertime equals to 0 on June, 20 on July, 0 in August.
- Relative humidity: The average summertime percentage of humidity is around 71%
- Temperature: On average, the warmest month is July, the mean Temperature is 22c, and the average high temperature is around 26c. In addition, design temperature is 33c and low is 15c.
- Radiation: On average July sees the highest radiation mean value where direct radiation is around 300 w/m2 while the average high radiation is 440 w/m2, however. The average low is 50 w/m2.

8-Building characteristics analysis;

- Heat Transmission;
- Walls the U-value is almost 1.7 W/m2. K;
- Roofs the U-value is almost 2.2 W/m2. K;
- Albedo: Walls 0.5, Roofs 0.2.

9-Clothing Insulation analysis: In the summertime, the majority of individuals wear garments that have clothing insulation rages from 0.5 to 67 clo. However, in wintertime clothing insulation increase up to 1.3 col;

10-Metabolic rate analysis: The most common activities in the study site are seated, standing, relaxed and walking. the most popular activity metabolic rates range from 1 met (seated) to 2.6 met (waking).

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OBJECTIVE AND SUBJECTIVE EVALUATION OF OUTDOOR THERMAL COMFORT

5.1. Chapter five introduction

In this chapter, the detailed methodology and the results of the objective and subjective evaluations are deeply explained. Firstly, the objective assessment methodology including a questionnaire assessment study is set out. Secondly, the results of the subjective assessment are shown, and analyzed according to the explained methodology. The discussion starts with the results of the study site questionnaire and then proceeds to show the outdoor thermal simulation results.

5.2. Objective and subjective assessment methodology overview

The subjective and objective assessment studies were conducted in two parts *Fig.5.1*. The first part used a survey approach of the outdoor thermal sensation and measured the predicted mean vote, air temperature, humidity, wind speed, as well as solar radiation. In an attempt to understand the voters' thermal sensation. The second part employed a computer-aided tool to quantitatively investigate the outdoor thermal comfort and its weather parameters on the study site occupants.in order to identify the climatic weather context issues to be addressed in the next chapter. Nonetheless, the methods, techniques, and steps of conducting both parts, are explained in (*Fig.5.1)*.

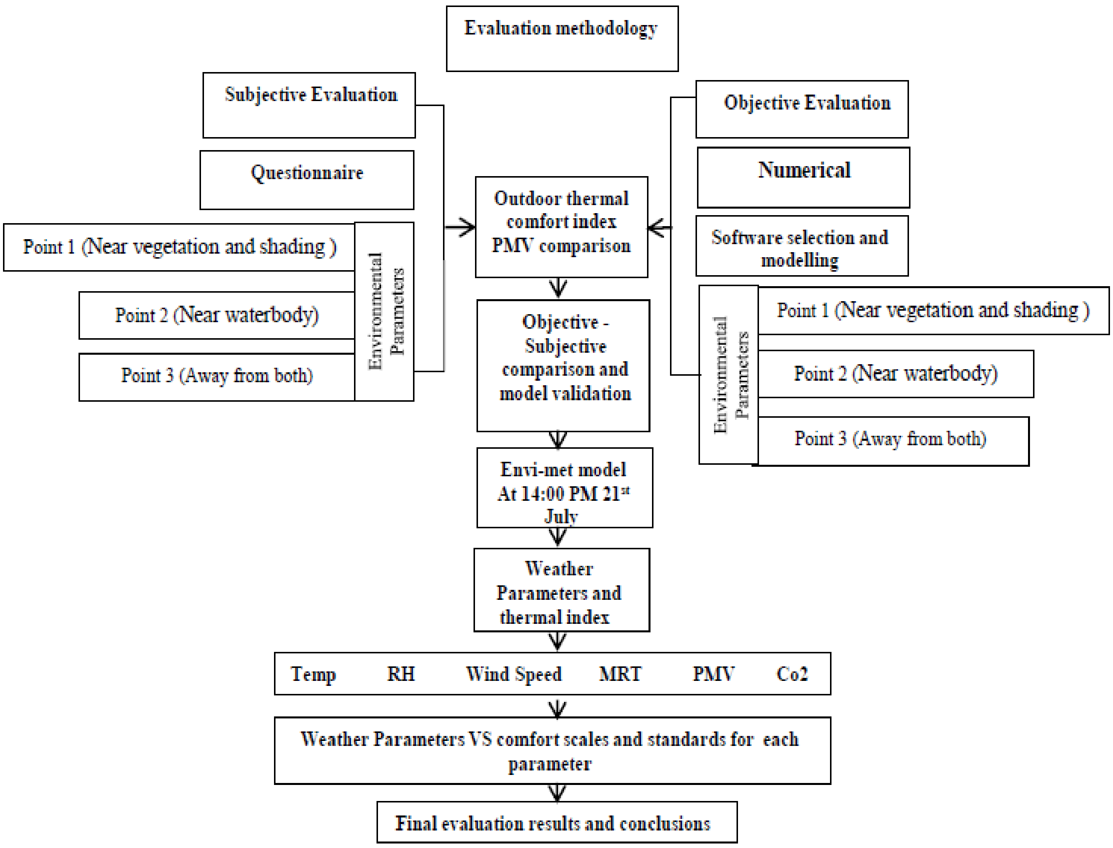


Fig.5.1. The Subjective and objective assessment methodology overview

5.3. Subjective evaluation methodology

The aim of questioning the study space was to assess the performance of outdoor thermal comfort weather parameters in use and investigate their capabilities in achieving the outdoor thermal comfort. Outdoor microclimate has a direct impact on the outdoor thermal comfort of occupants and consequently affects their outdoor activity level [1]. This investigation conducted a field survey that involved microclimatic questionnaire, and activity recording between 12:00 PM and 16:00 PM in the summertime. This survey was completed between September 13, 2018, and September 16, 2018, at Széchenyi square in different areas of the public space. In order to study all other factors that could affect the questionnaire results. It was essential to conduct the questionnaire in different locations at the square, 3 points were chosen as shown in *Fig.5.2.* By doing this, the shade that cast from the trees, vegetation, plus the water body effect can be studied, and their impact on TA, RH, WS, SR, and PMV were studied and analyzed to get a better understanding of outdoor thermal performance. Furthermore, the weather parameters and PMV will be studied even further in the next part of this chapter via a computer-based tool. However, the three mentioned points are:

- Point one (P1): Is near vegetation so the impact of the plantation on outdoor thermal comfort and its parameters can be noticed.
- Point two (P2): Is close to water element in an attempt to understand the effect of the water body on outdoor thermal comfort as well as on weather parameters.
- Point three (P3): Is away from water body and plantation in order to eliminate the softscape effects on the outdoor thermal comfort.

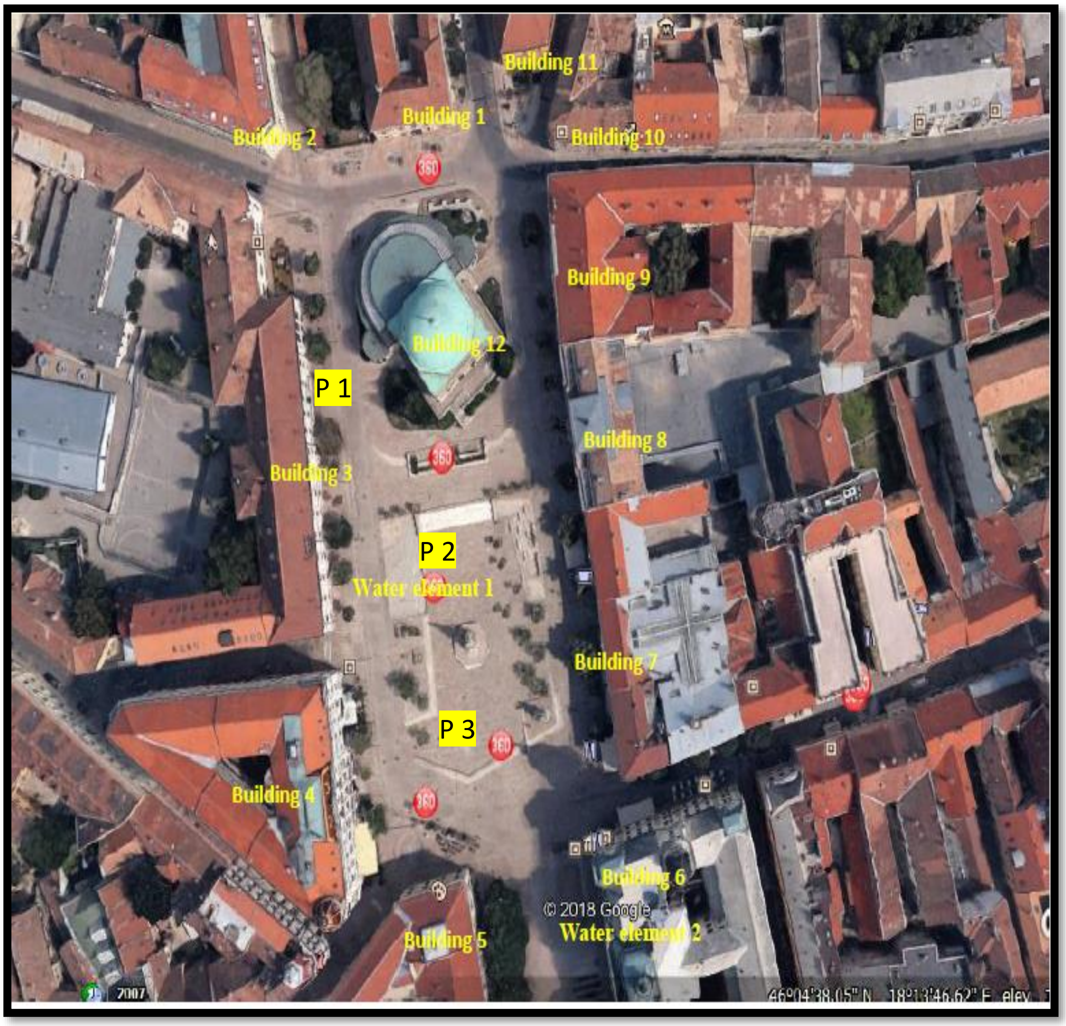


Fig.5.2. The chosen points P1, P2 and P3.

All points have almost the same albedo since most buildings have more or less the same color and materials. Buildings height is about *7-13m*. However, the average height is around *10m* which's classified as low-rise buildings, no significant height around the square.

Fig.5.3 Shows the questionnaire that used to collect subjective data in this investigation. The first part of the questionnaire recorded the personal information, activity level, and clothing level of the subjects. The second section collected data related to their thermal comfort and their preference votes in regard to the weather parameters. Thermal sensation was rated on the ASHRAE seven-point scale for thermal sensation votes. Overall comfort was rated on a three-point scale: uncomfortable, acceptable, and comfortable corresponding to -1, 0, 1 respectively. The four preferred climate parameters, air temperature, global solar radiation, wind speed, and relative humidity, were rated on a three-point scale. Nonetheless, a total of a hundred effective questionnaires were collected in this study [1],[2].

Outdoor Thermal Comfort Questionnaire

Date: **Time:** **Location:**

Gender: **Age:** **Weight:** **Height:**

Current activity:

1-excercising light 2-exercising medium 3- exercising heavy 4-chatting standing
5-chatting seated 6- strolling 7-resting 8-attending to children 9-other specify………

What are you wearing now (multiple choice)?

1-T-shirt (short sleeves) 2-T-shirt (long sleeves) 3-shorts or short skirt 4-long pants or long skirt 5-vest 6-sport skirt 7- Jacket 8-other specify ………

Please describe your current thermal sensation

Cold	cool	Slightly cool	Neutral	Slightly warm	warm	hot	Very Hot
-3	-2	-1	0	1	2	3	4

What's your feeling about the following weather conditions at this moment?

Temperature	Cold	neutral	hot
Wind speed	Weak	neutral	windy
Humidity	Dry	neutral	humid
Solar radiation	Weak	neutral	strong

Please describe your overall comfort level

Uncomfortable	Acceptable	Comfortable
-1	0	1

Fig.5.3. Outdoor thermal comfort questionnaire from according to ASHRAE.

5.3.1. Results and discussion

The field survey was conducted in different locations of the space. The PMV, (Ta), (RH), (WS), (SR) were averaged over the main square and the results in *table 5.1-5.3 (for full results can be found in the appendix A)* have revealed the followings:

- Clothing insulation ranges from *0.5 to 0.67 clo* (summer clothing) see *chapter 3, Fig.4.17*. The mean value of 0.58 *col* was chosen as the mean Clothing insulation value as shown in *table 5.1,table 5.2*;
- The main activities in the square are strolling, relaxing, chatting standing and seated, the metabolic rate ranges from *(1.2 to 2.6) met*. The average value of *1.9 met* was chosen as shown in *table 5.1, table 5.2*;
- The average weight is *75 kg* while height is *174 cm*;
- The vast majority of the voters described the **current thermal sensation** as following: 25%Warm (2), 40% Hot (3) and 30%very hot (4);

- Almost 73% of the total voters **described the overall comfort level** as uncomfortable;

Table 5.1. The PMV value at P1, P2, and P3 on 13-9-2018

Time	P 1	P2	P3	Metabolic rate	clothing Insulation
12.00	2	1	2	1.9	0.58
13.00	3	4	4	1.9	0.58
14.00	4	2	4	1.9	0.58
15.00	3	2	3	1.9	0.58
16.00	2	2	3	1.9	0.58
Mean	2.8	2.2	3.2	1.9	0.58

Table 5.2. The PMV value at P1, P2, and P3 on 14-9-2018

Time	P1	P2	P3	Metabolic rate	clothing Insulation
12.00	2	3	3	1.9	0.58
13.00	3	4	4	1.9	0.58
14.00	2	4	4	1.9	0.58
15.00	2	4	4	1.9	0.58
16.00	2	3	3	1.9	0.58
Mean	2.2	3.6	3.6	1.9	0.58

- Around 25% of the voters described the overall comfort level as acceptable
- Almost less than 2% of the participants described the overall comfort level as comfortable;
- The majority of the voters described temperature as hot, humidity as dry, radiation as strong, as well as wind as neutral as can be seen in *Table 5.3;*

Table 5.3. The weather condition parameters for the entire survey period

Point	Temperature	Humidity	Radiation	Wind speed
P1	Hot	Dry	Neutral	Neutral
P2	Hot	Neutral	Strong	Neutral
P3	Hot	Dry	Strong	Neutral

- P1, P2, and P3 all described as hot. Nevertheless, P3 was the warmest;
- The relative humidity at P2 was described as neutral, dry at P1 and P2;
- The global solar radiation was described as Neutral at P1, strong at P2 and strong at P3;
- The weather parameters for P1: temperature is hot, humidity is dry, radiation is neutral, and wind is neutral;
- The weather parameters at P2: temperature is hot, humidity is neutral, radiation is strong, and wind is neutral;

- The weather parameter at P3: temperature is hot, humidity is dry, radiation is strong, and wind is neutral. However, the *Fig.5.4* shows the average predicted mean vote for entire the survey time.

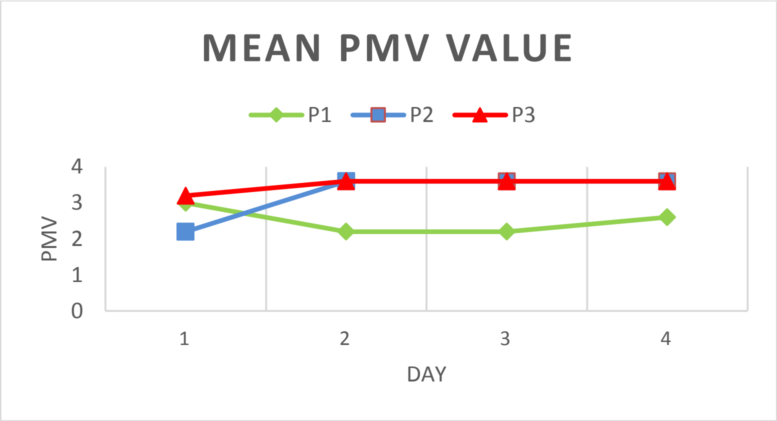


Fig.5.4. Mean PMV Value at point1, point 2, and point 3 for entire the survey period

5.3.2. Summary

- In general, the outdoor thermal sensation is uncomfortable almost two thirds of the Participants felt uncomfortable.
- The temperature is considered to be uncomfortable. Nonetheless, P1 and P2 were described by some voters as warm and hot while P3 was described as hot and very hot.
- On average **14:00 PM** was recorded the highest very hot *(rate 4).*
- Plantation and water body have a profound effect on outdoor thermal comfort.

5.4. Objective evaluation methodology

This part of the objective evaluation aims to evaluate the thermal comfort in the study site. This is important as it allows a better understanding of thermal comfort as well as helps in justifying some questioning results. Two methods of evaluating thermal comfort in outdoor spaces were considered; monitoring, computational fluid dynamics, and using the monitoring method could be performed using techniques such as tracer gas for measuring the rate and data loggers. Both monitoring techniques require costly equipment which is not available to the author. Apart from that and for security reasons the equipment could not be left unattended in the study site. Therefore, it was decided to conduct this study using one of the computational fluid dynamics software.

It is known that the simulation research methods can be effectively used where the experimental work in the real world cannot be performed due to unacceptable ethical, economic or dangerous restrictions [3]. In simple terms, outdoor thermal comfort software code uses a complicated mathematical model that is represented and solved by a computer-based code. The results are graphically presented, usually on a 2D or and 3D. Several computer programs that can predict one or more of the following variables:

- External air movement patterns and airspeed;
- Air Temperature;
- Relative humidity;
- Global solar radiation;
- sky-factor;
- predicted mean vote value;
- Mean radiant temperature;
- CO2 Level.

Several computer-based tools were considered; Rayman, Envi-met, ANSYS package, Autodesk package ,CitySim Pro,TAS, Meteodyn , Honeybee and Ladybug [4-12]. The *tables 5.4-5.7* briefly described below contains detailed tables comparing the features and capabilities of the programs in the following categories:

1. *General criteria* (User interface, reliability and accuracy, cost, operating system, compatibility, visualization and graphics, comfort prediction index);
2. *Specific outputs* (PMV, PET (Physiological Equivalent Temperature), Predicted Percentage of Dissatisfied (PDD), mean radiant temperature, relative humidity, air temperature, wind speed, wind direction, solar radiation, sky-view factor, Carbon dioxide;
3. *Strategies and elements* can be investigated by the tool in outdoor spaces (plantation, materials and albedo, waterbody, green roofs, green walls, shading, streets canyon geometry, streets wind orientation, building form and shape, buildings height, site landform, heat sinks, urban form, building adjacency, buildings arrangement, building envelope, building roof shape, natural ventilation: (inducers, shafts, projections, double skin façade).

Each software tool of the mentioned microclimate simulation tools has certain characteristics and specific outputs and use in outdoor simulation. In order to better understand the specific features of each one, *Table 5.4, Table 5.5, Table 5.6* and *Table 5.7* present a detailed table of the features of each of the software tools stated above.

Table 5.4. Detailed comparison of CFD software serving the scope of research (General criteria and Specific outputs).

Choosing criteria	RayMan	Envi-met	ANSYS	Autodesk® CFD
General criteria				
User Interface	Friendly	Friendly	Extremely complex	Friendly
Reliability & accuracy	High	High	Very high	High
Cost	Free	Low*	Very high	Free
Operating system	Windows	Windows	Windows and MAC	Windows
Compatibility	Low	Moderate	High	Very high
Visualization and graphics	Moderate	High	High	High
Comfort Prediction index	PET	PMV	-	-
Specific outputs				
PMV	Yes	Yes	No	No
PET	Yes	Yes	No	No
PDD	Yes	Yes	No	No
MRT	Yes	Yes	Yes	Yes
Relative humidity	Yes	Yes	Yes	No
Air Temperature	Yes	Yes	Yes	Yes
Wind speed	No	Yes	Yes	Yes
Wind direction	No	Yes	Yes	Yes
Solar radiation	Yes	Yes	Yes	Yes
Sky-view Factor	Yes	Yes	Yes	Yes
CO_2	No	Yes	Yes	Yes

- ENVI-met is capable of predicting and simulating the thermal comfort indices (PMV, PET, MRT , and PDD), meteorological parameters (airspeed, wind direction, air temperature, relative humidity, global solar radiation) with low cost for students *version 4* and *version 3* available for free for any use but not commercial use .Nonetheless, the tool is not capable of modeling the natural ventilation inducers, shafts, projections, and double skin façade.
- RayMan is a free tool with high accuracy *Table 5.5.* However, the tool is not capable of investigating primary design strategies like waterbody, green roofs

and green walls. Furthermore, the computer-aided software is not capable of predicting wind speed with low compatibility, so the tool was excluded.

- Autodesk® CFD is a free tool with high precision and friendly user interface *Table 5.5*. However, the software is not capable of predicting thermal indices in outdoor spaces. As a result, the tool has been excluded.

Table 5.5. Detailed comparison of CFD software serving the scope of the research (Strategies and elements can be investigated by the tool in outdoor environment).

Strategies and elements can be investigated by the tool in outdoor environment				
Plantation	Limited	Yes	No	No
Materials and Albedo	Yes	Yes	Yes	No
Waterbody	No	Yes	Yes	Limited
Green roofs	No	Limited	Limited	Limited
Green walls	No	Limited	Limited	Limited
Shading	Yes	Yes	Yes	Yes
Streets canyon geometry	No	Yes	Yes	Yes
Streets wind orientation	No	Yes	Yes	Yes
Building form and shape	No	Limited	Yes	Yes
Buildings height	Limited	Yes	Yes	Yes
Site landform	No	No	Yes	Yes
Heat sinks	No	yes	Yes	Yes
Urban form	Limited	Yes	Yes	Yes
Building adjacency	Limited	Limited	Yes	Yes
Buildings arrangement	Limited	Yes	Yes	Yes
Building envelope	No	No	Yes	Yes
Building roof shape	No	No	Yes	Yes
Natural ventilation Inducers, shafts, projections, Double skin façade	No	Limited	Yes	Yes
Final results	Excluded	Chosen	Excluded	Excluded

- On one hand Tas and Meteodyn have a relatively low price with friendly User Interface as well as high and moderate Compatibility *Table 5.6*. On the other hand, both tools are not capable of predicting thermal indices in outdoor spaces *Table 5.6.* So were excluded.

- CitySim Pro is a free computer-aided software with friendly User Interface and online operating system. However, its Compatibility with other computer-aided tools is low *Table 5.6.* Therefore, the tool has been excluded.

Table 5.6. Detailed comparison of CFD software serving the scope of the research (General criteria and Specific outputs).

Choosing criteria	CitySim Pro	TAS	Meteodyn	Ladybug and Honeybee
General criteria				
User Interface	Friendly	Friendly	Friendly	Friendly
Accuracy	Moderate	High	Moderate	Very High
Cost	Free	Low	Low	Free
Operating system	Online	Windows	Windows	Windows and mac and Linux
Compatibility	Low	High	Moderate	Very high
Visualization and graphics	Moderate	High	High	High
Comfort Prediction index	PET	PDD	No	SET
Specific outputs				
PMV	No	No	No	No
PDD	No	Yes	No	No
PET	Yes	No	No	No
MRT	Yes	Yes	No	Yes
Relative humidity	No	Yes	No	No
Air temperature	Yes	Yes	Yes	Yes
Wind speed	Yes	Yes	Yes	Yes
Wind direction	Yes	Yes	Yes	Yes
Solar Radiation	Yes	Yes	No	Yes
Sky-view Factor	Yes	Yes	No	Yes
CO_2	No	Yes	No	No

- On one hand the Ladybug and Honeybee tools are free decision-making tools with a friendly user interface and high compatibility *Table 5.7.* On the other hand, the tools are not capable of simulating main thermal indices like the PMV and PET in outdoor spaces neither capable of predicting the relative humidity. For this reason, the tool has been excluded.

Table 5.7. Detailed comparison of CFD software serving the scope of the research (Strategies and elements can be investigated by the tool in outdoor environment).

Strategies and elements can be investigated by the tool in outdoor environment				
Plantation	No	No	No	Yes
Materials and Albedo	No	Yes	No	Yes
Waterbody	No	No	Yes	No
Green roof	No	No	No	Yes
Green wall	No	No	No	Yes
Shading	Yes	Yes	Yes	Yes
Streets canyon geometry	Yes	Yes	Yes	Yes
Streets wind orientation	Yes	Yes	Yes	Yes
Building form and shape	Limited	Yes	Yes	Yes
Buildings height	Yes	Yes	Yes	Yes
Site landform	No	Yes	Yes	Yes
Heat sinks	Yes	Yes	Yes	No
Urban form	Yes	Yes	Yes	Yes
Building adjacency	Yes	Yes	Yes	Yes
Buildings arrangement	Yes	Yes	Yes	Yes
Building envelope	Limited	Yes	No	Limited
Building roof shape	Yes	Yes	No	Yes
Natural ventilation Inducers, shafts, projections, Double skin façade	Limited	yes	Limited	Limited
Final results	Excluded	Excluded	Excluded	Excluded

Among several CFD tools ENVI-met is capable of predicting and simulating the thermal comfort indices (PMV, PET, MRT and PDD), meteorological parameters (airspeed, wind direction, air temperature, relative humidity, global solar radiation) as well as most of the design strategies in outdoor spaces. Therefor ENVI-met has been chosen as the most suitable tool among the eight tools.

5.4.1. Envi-met in a nutshell

ENVI-met as shown in *Fig.5.5* is a holistic three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions not only limited to but very often used to simulate urban environments and to assess the effects of green architecture visions. It is designed for microscale with a typical horizontal resolution from *0.5 to 10 m* and a typical time frame of *24 to 48 hours* with a time step of *1 to 5 seconds*. This resolution allows to analyze small-scale interactions between individual buildings, surfaces and plants. **Exchange processes with the environment**: Vegetation interacts in various ways with the environment: Heat and vapor are exchanged between the plants' leaves and the atmosphere. Transpired water would be if possible, extracted out of the soils hydraulic model using the plant root distribution. A complex raytracing algorithm is used to analyze the plant's impact of solar radiation (shadow casting) and on longwave radiation exchange (thermal shielding).**Numerical methods** :ENVI-met uses the Finite Difference Method to solve the multitude of partial differential equations (PDE) and other aspects in the model. The scheme is explicit depending on the subsystem analyzed. The atmospheric advection and diffusion equations are implemented in a fully implicit scheme, which allows ENVI-met to use relatively large time steps by still remaining numerically stable. This, in the final effect, reduces computing costs and allows the ENVI-met model to run on any normal computer available at your local hardware store [13].

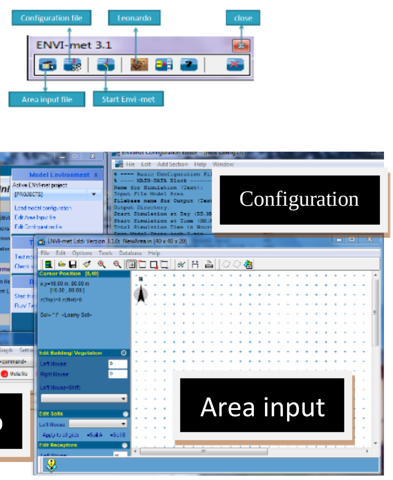


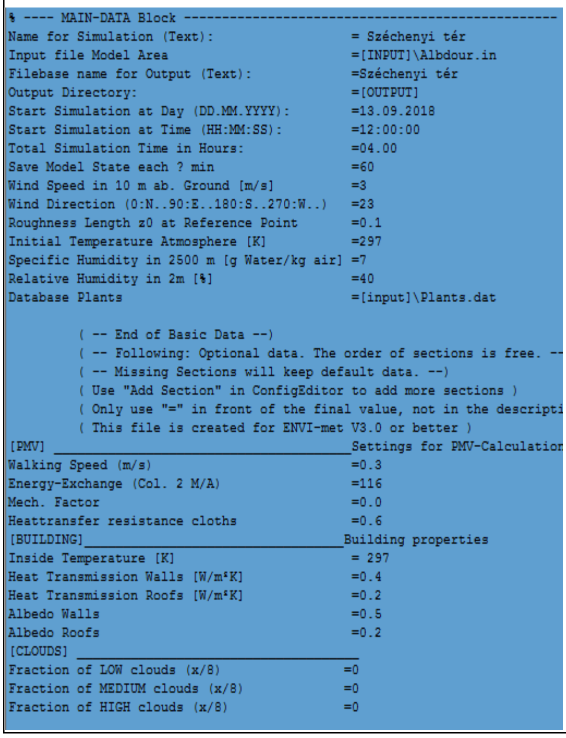
Fig.5.5. Envi-met interface

5.4.2 Objective-Subjective comparison and model validation

The complete and comprehensive validation for the model is generally not possible [14]. No model can have an absolute validity it should be valid for the purpose for which it is constructed [15]. Since this work focuses on outdoor thermal comfort. The Predicted Mean Vote is to investigate as it’s a well-known index of the thermal comfort performance. Validating the accuracy and reliability of the *Envi-met* was focused on this variable. In order to obtain the PMV simulation was conducted between 13.09.2018 and 16.09.2018 At 12:00-16:00. For four consecutive days, the results as followings:

The predicted mean vote has been analyzed using ENVI-met version 3 tool since it is a freeware program and is under constant development [16]. *Fig.5.6-5.9*, and then compared against the questionnaire results *Table 5.1-5.2.* The average PMV value on the 13th of September at point 1 is hot, point 2 is hot, and point 3 is very hot *Fig.5.6.* On average areas close to buildings and covered in shading and vegetation have a lower PMV value than the rest places of the square.

Area	11294 m^2
Number of surrounding buildings	13
Vegetation	750 m^2 (7-8%)
Paving(interlock)	9675 m^2 (86%)
Paving(asphalt)	270 m^2 (2%)
Water body (fountains)	290 m^2 (3%)
Hardscape	200 m^2 (1.5%)



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% ---- MAIN-DATA Block -------------------------------------------------
Name for Simulation (Text):                  = Széchenyi tér
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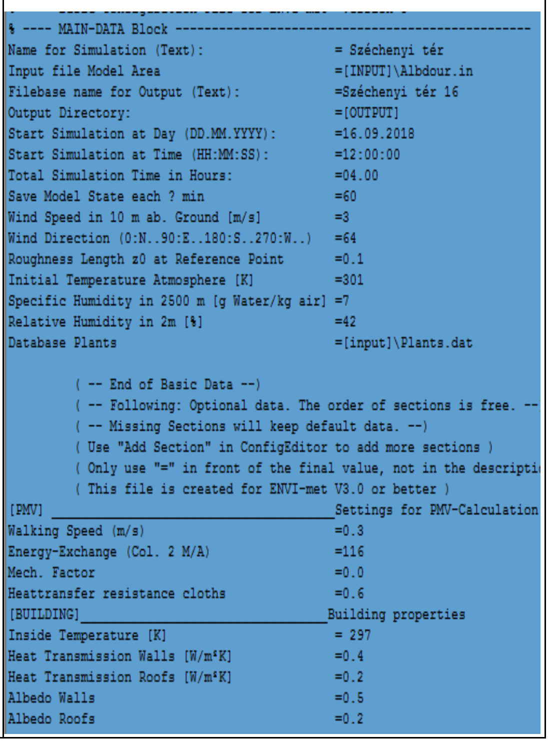
Filebase name for Output (Text):             =Széchenyi tér
Output Directory:                            =[OUTPUT]
Start Simulation at Day (DD.MM.YYYY):        =13.09.2018
Start Simulation at Time (HH:MM:SS):         =12:00:00
Total Simulation Time in Hours:              =04.00
Save Model State each ? min                  =60
Wind Speed in 10 m ab. Ground [m/s]          =3
Wind Direction (0:N..90:E..180:S..270:W..)   =23
Roughness Length z0 at Reference Point       =0.1
Initial Temperature Atmosphere [K]           =297
Specific Humidity in 2500 m [g Water/kg air] =7
Relative Humidity in 2m [%]                  =40
Database Plants                              =[input]\Plants.dat

         ( -- End of Basic Data --)
         ( -- Following: Optional data. The order of sections is free. --
         ( -- Missing Sections will keep default data. --)
         ( Use "Add Section" in ConfigEditor to add more sections )
         ( Only use "=" in front of the final value, not in the descripti
         ( This file is created for ENVI-met V3.0 or better )
[PMV] _______________________________________Settings for PMV-Calculatior
Walking Speed (m/s)                          =0.3
Energy-Exchange (Col. 2 M/A)                 =116
Mech. Factor                                 =0.0
Heattransfer resistance cloths               =0.6
[BUILDING]__________________________________Building properties
Inside Temperature [K]                       = 297
Heat Transmission Walls [W/m²K]              =0.4
Heat Transmission Roofs [W/m²K]              =0.2
Albedo Walls                                 =0.5
Albedo Roofs                                 =0.2
[CLOUDS] _____________________________________
Fraction of LOW clouds (x/8)                 =0
Fraction of MEDIUM clouds (x/8)              =0
Fraction of HIGH clouds (x/8)                =0
```



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Output Directory:                            =[OUTPUT]
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Start Simulation at Time (HH:MM:SS):         =12:00:00
Total Simulation Time in Hours:              =04.00
Save Model State each ? min                  =60
Wind Speed in 10 m ab. Ground [m/s]          =3
Wind Direction (0:N..90:E..180:S..270:W..)   =64
Roughness Length z0 at Reference Point       =0.1
Initial Temperature Atmosphere [K]           =301
Specific Humidity in 2500 m [g Water/kg air] =7
Relative Humidity in 2m [%]                  =42
Database Plants                              =[input]\Plants.dat

         ( -- End of Basic Data --)
         ( -- Following: Optional data. The order of sections is free. --
         ( -- Missing Sections will keep default data. --)
         ( Use "Add Section" in ConfigEditor to add more sections )
         ( Only use "=" in front of the final value, not in the descripti
         ( This file is created for ENVI-met V3.0 or better )
[PMV] _______________________________________Settings for PMV-Calculation
Walking Speed (m/s)                          =0.3
Energy-Exchange (Col. 2 M/A)                 =116
Mech. Factor                                 =0.0
Heattransfer resistance cloths               =0.6
[BUILDING]__________________________________Building properties
Inside Temperature [K]                       = 297
Heat Transmission Walls [W/m²K]              =0.4
Heat Transmission Roofs [W/m²K]              =0.2
Albedo Walls                                 =0.5
Albedo Roofs                                 =0.2
```

Fig.5.6. Area inputs and configurations of the objective models

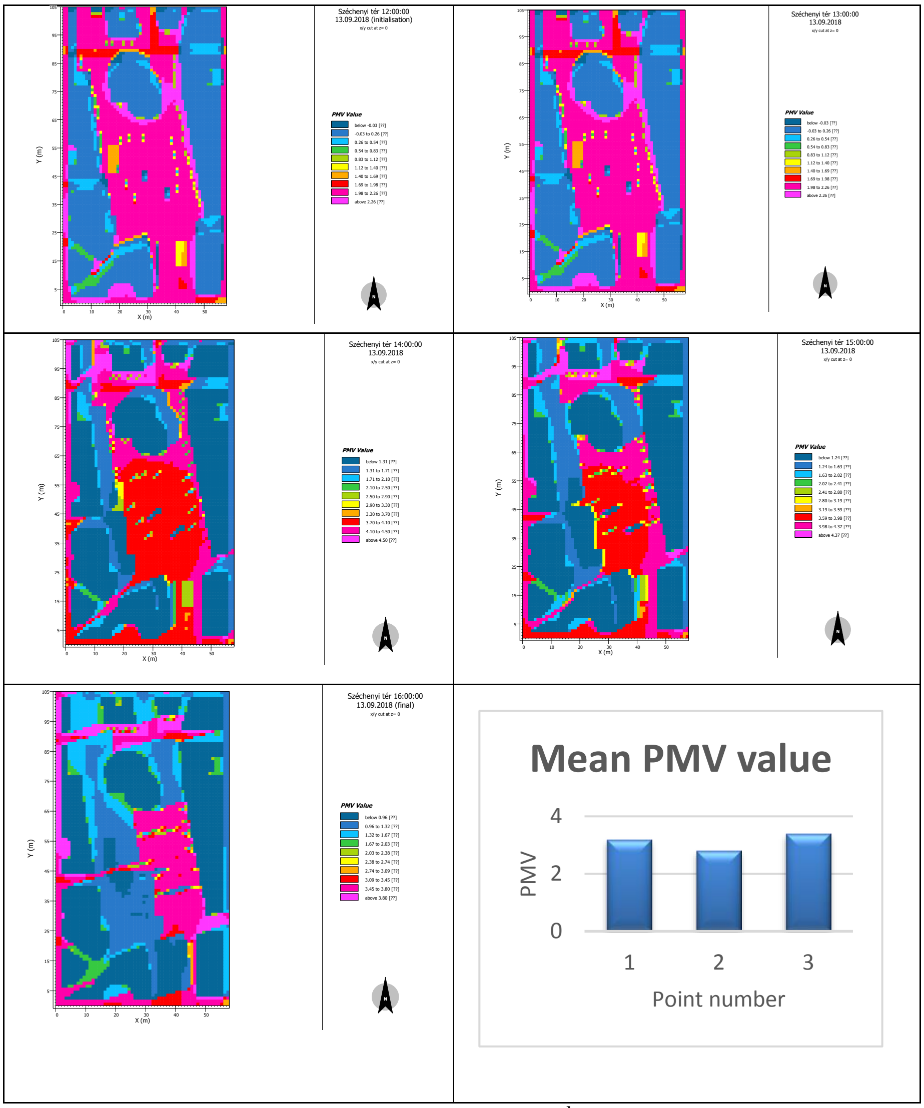
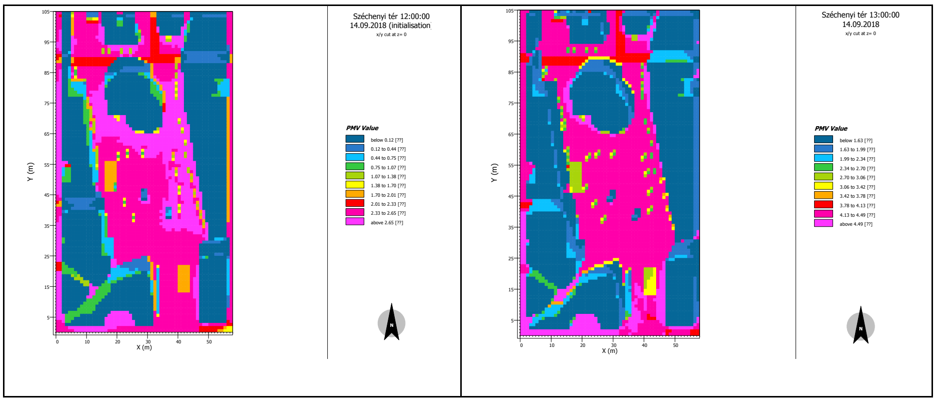


Fig.5.7. The PMV value on 13th of September

The average PMV value on the 14th of September at point1 is very hot, point 2 is hot, and point 3 very hot *Fig.5.7.* On average areas nearby buildings and are casted in shade and vegetation have a lower PMV value than the rest areas of the square.



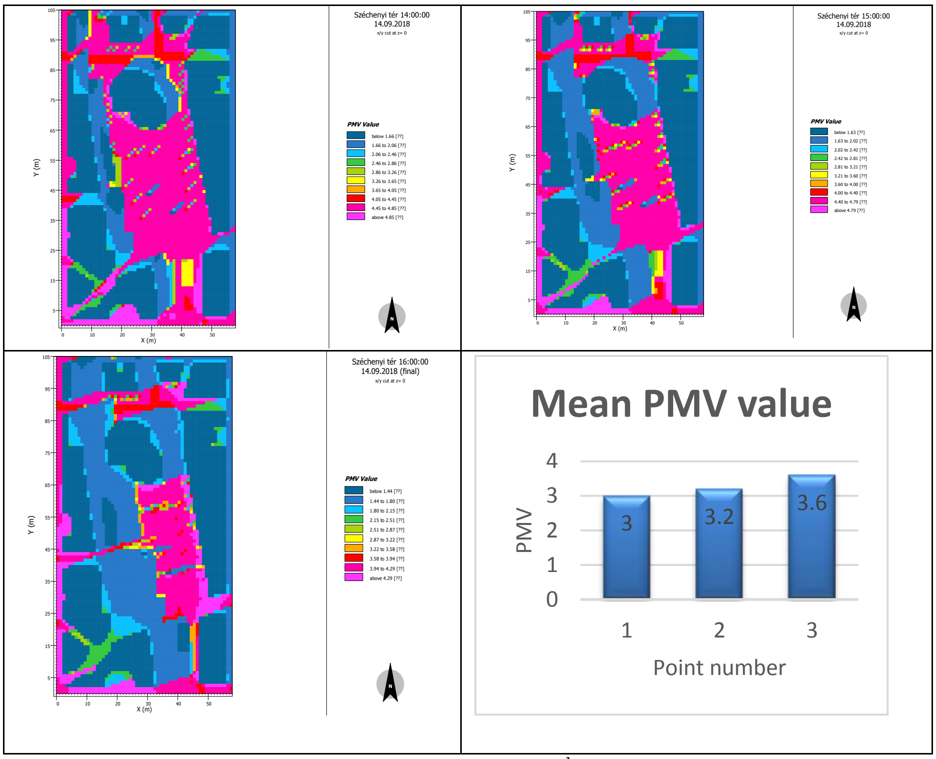
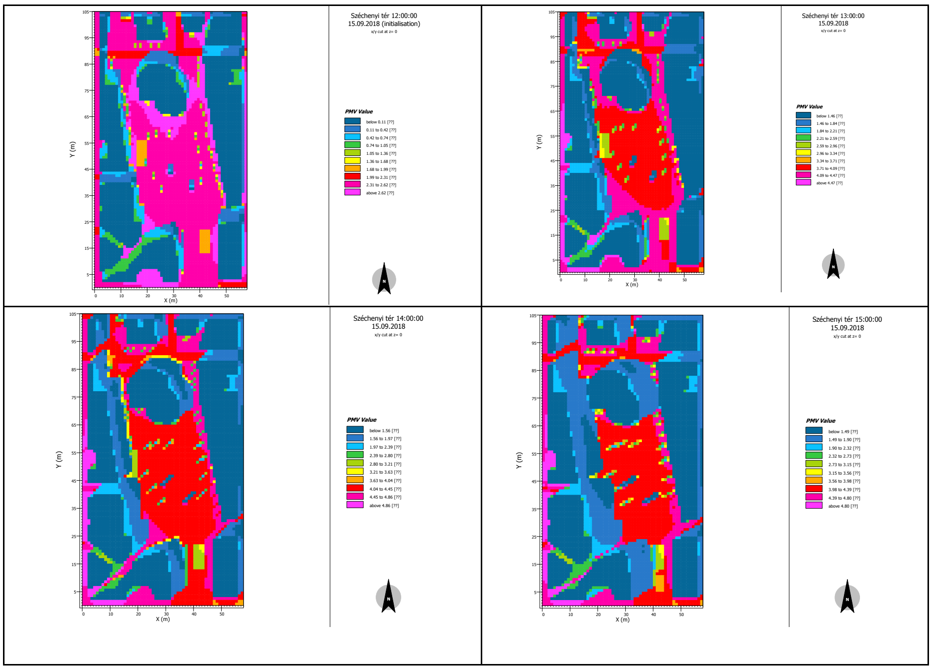


Fig.5.8. The PMV value on 14th of September

The average PMV value on the 15th of September at point1 is hot, point 2 is very hot, and point 3 very hot *Fig.5.8.* On average areas close to buildings and covered in shading and vegetation have a lower PMV value than the rest places of the square.



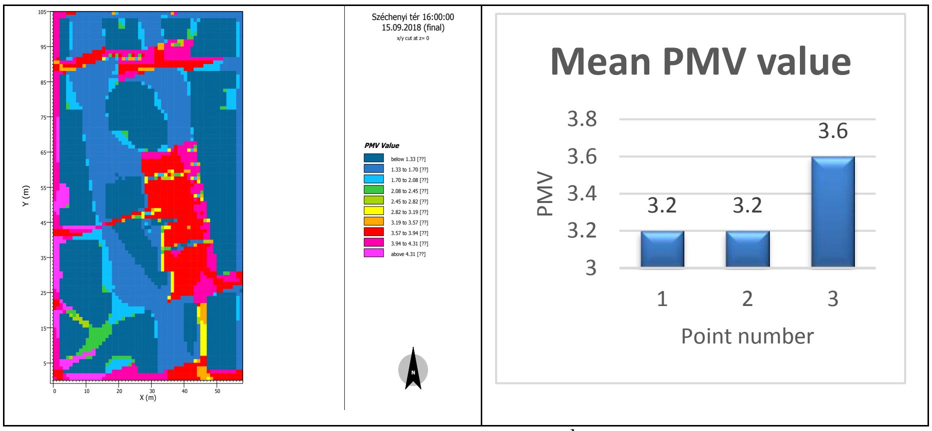


Fig.5.9. The PMV value on 15th of September

The average PMV value on the 16th of September at point1 is very hot, point 2 is very hot, and point 3 is very hot *Fig.5.9*. On average areas close to buildings and covered in shading and vegetation have a lower PMV value than the rest places of the square *Fig.5.9.*

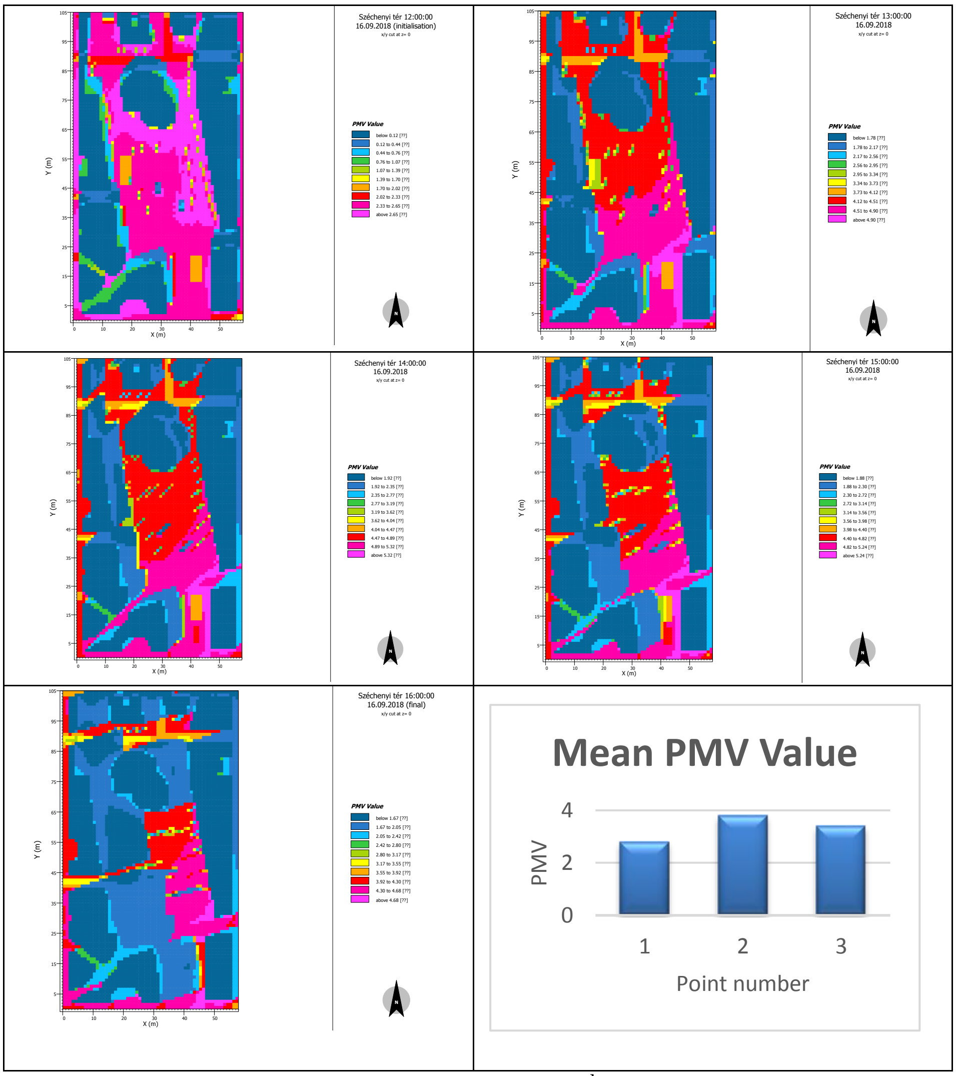


Fig.5.10. The PMV value on 16th of September

In general, the results of simulation and questionnaire *in Fig.5.10*, *Fig.5.11*. prove Envi-met's great reliability in predicting outdoor thermal comfort (*the index that will be adopted in the current work*).

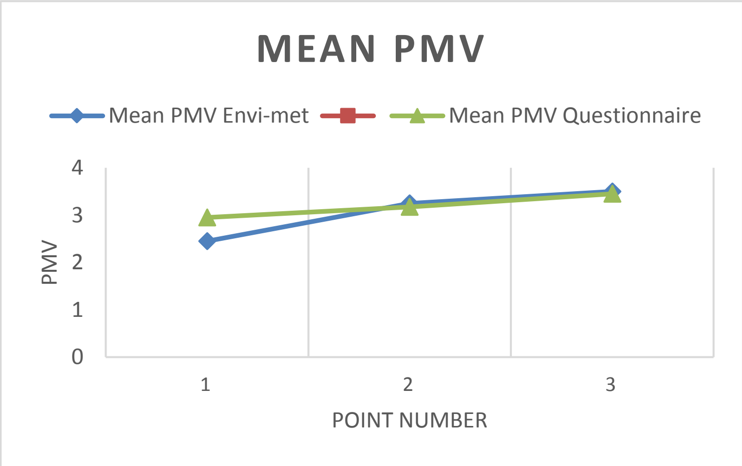


Fig.5.11. The mean PMV value for P1, P2, P3 for the entire period

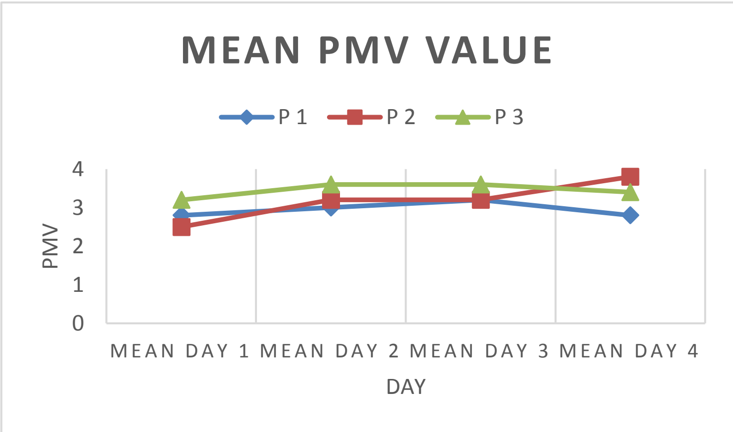


Fig.5.12. The Mean PMV measured at Széchenyi tér in comparison with the mean PMV value output from simulated cases.

5.4.3. Building the study site model

In order to assess the whole site thermal performance, simulations were held at 14:00 on the 21st of July as a representation for the summer period. It is an extreme summer day analyzed by climate consultant 6.0 [17], which is expected to result in high radiant interaction values. It is a research interest of this study to investigate extreme conditions. Nonetheless, taking more than a specific hour will result in excessive scenarios, since the author will be studying 9 design measures with 25 different cases and 6 weather parameters and thermal indices, which means he is studying 150 different scenarios. Moreover, taking more than one hour causes high striking similarities and complexity which are against the research interest. However, A model domain *Fig.5.12* *was modeled*: area: x-grids=58, y-Grids:105, z-Grids=20 Grid size and structures: dx:2 dy:2 dz:2. Geographic coordinates of Pécs, Hungary Latitude: 46°04′59″ N, Longitude: 18°13′59″ E, Elevation above sea level: 153 m.

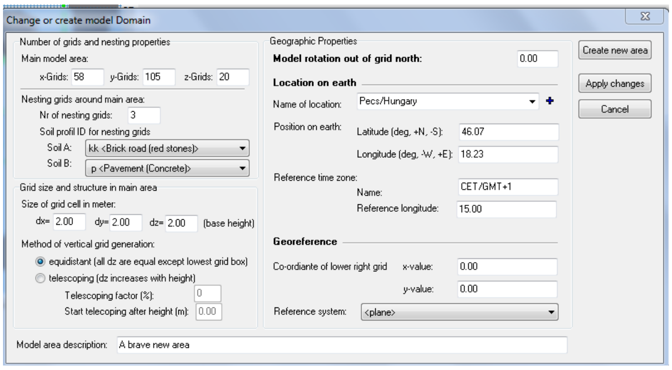


Fig.5.13. Envi-met model domain

5.4.4. Model Area Inputs

The model requires relatively few input parameters and calculates all required meteorological factors, namely air and surface temperatures, wind speed and direction, air humidity, short-wave and long-wave radiation flux as well as the mean radiant temperature needed for comfort analyses [18]. The first task will be to set the space to be tested *Fig.5.13.* This includes the location, the horizontal and vertical dimensions of the architectural environment, the surface materials and the vegetation size, kind, distribution and percentage to non-green areas as can be seen in *Table 5.8.*

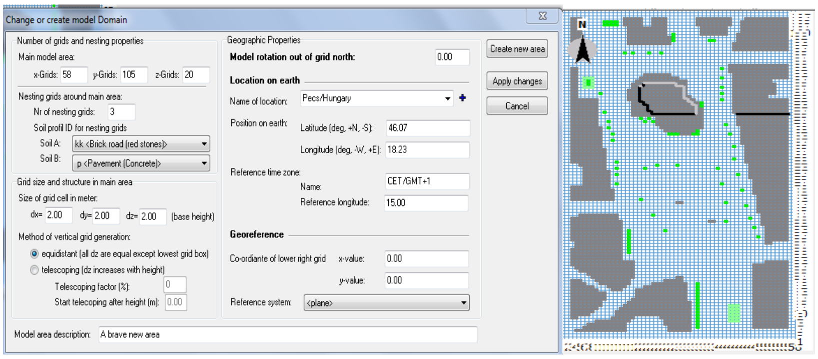


Fig.5.14. ENVI-met model domain and model area inputs for the whole site

Table 5.8. Model area inputs

Area	11294 m^2
Number of surrounding buildings	13
Vegetation	750 m^2 (7-8%)
Paving(interlock)	9675 m^2 (86%)
Paving(asphalt)	270 m^2 (2%)

Water body (fountains) Hardscape	290 m^2 (3%) 200 m^2 (1.5%)

The second step is to gather information about the site location and its climatic data like temperature, wind speed, and humidity. In addition to, databases for soil types and vegetation *Table 5.9.* The simulation using ENVI-met is then processed. The output files are visualized using LEONARDO code [18].

Table 5.9. ENVI-met model configuration

Day	21 July 2018
Start time	13:00 till 14:00
Simulation time	1 hour
Step every	60 Minutes
Wind direction	5
Initial temperature atmosphere	304 K
Heat transfer resistance cloths	0.58
Relative humidity in 2m	44%
Wind speed in 10 m ab. ground	2 m/s
Heat transmission walls	1.7 W/m²K
Heat transmission roofs	2.2 W/m²K
Albedo walls	0.5
Albedo roofs	0.2

5.4.5. Results and discussion

5.4.5.1. Air temperature

On average the air temperature on the 21st of July at 14:00 PM is 305 K, which means the temperature ranges from warm to hot. Areas close to buildings and covered in shade and plantation have a lower temperature 303.55 K than other places of the square 304-306.9 K. Buildings height, orientation and plantation have a significant effect on outdoor thermal comfort. In addition, water bodies play an essential role in mitigating the temperature that can be seen in *Table 5.10, Fig.5.14.*

Table 5.10. Maximum, Minimum and Average air temperature on the 21st of July at 14:00

Average	305 K ~ 31.85 ºC
Maximum	307 K ~ 33.85 ºC
Minimum	303 K ~ 29.85 ºC

The average monthly outside temperature over the month of investigation (July 2018) from the raw climatic data 30.85 ºC [19] was used to calculate the thermal comfort threshold temperature below *Table 5.1*, which an overheating sensation is likely to occur using the thermal neutrality model adopted by the American Society of Heating, Refrigerating and Air-Conditioning [2]. The air temperature has been analyzed using ENVI-met tool and then compared against ASHRAE standards *Fig.5.14*, *Table 5.11*.

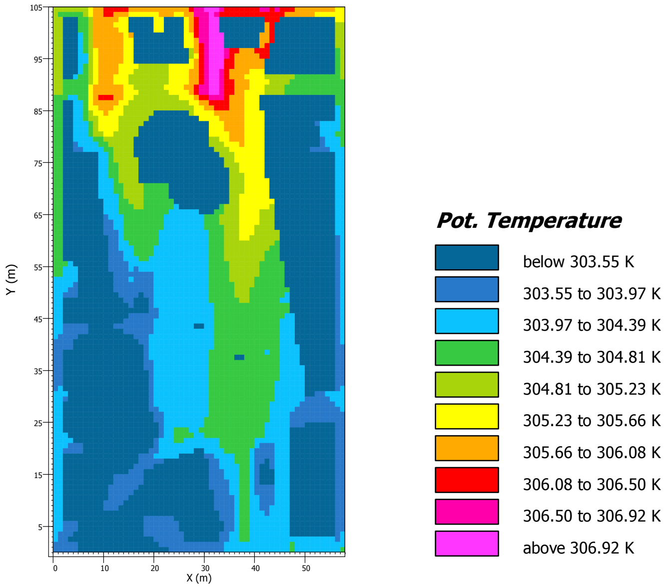


Fig.5.15. Air temperature on 21st of July at 14:00

Table 5.11. Comfort lowest and highest temperature according to ASHRAE standard 55 comfort model [2]

Less than 20.3 ºC	20.3 ºC winter lowest	24.3 ºC winter highest	26.7 ºC summer highest	More than 26.7 ºC

5.4.5.2. Relative humidity

The relative humidity has been analyzed using ENVI-met tool and then compared against ASHRAE relative humidity/temperature diagram based on comfort zone [2]. Nevertheless, the relative humidity falls within the comfort range in the summertime *Table 5.12*. Streets orientation, water bodies, and plantation play a critical role in increasing the relative humidity *Fig.5.15*.

Table 5.12. Maximum, Minimum and average relative humidity on the 21st of July at 14:00

Average Maximum	34.5% 38 % 31 %

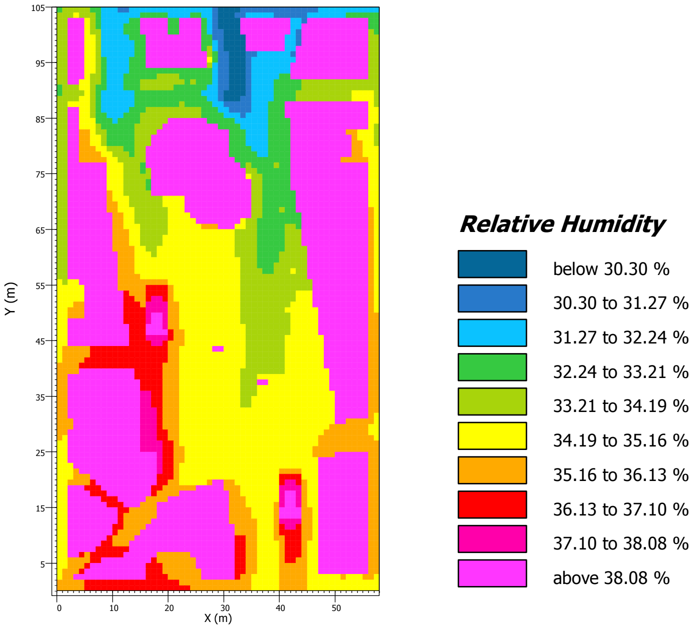


Fig.5.16. Relative humidity on the 21st of July at 14:00

5.4.5.3. Wind speed

The average wind speed is light breeze *1.3 m/s Table 5.13*. Streets orientation and streets canyon geometry have a great role in accelerating the wind speed *Fig.5.16.* The wind speed was analyzed using ENVI-met tool and then compared against the Beaufort wind scale [19] that can be seen in *Table 5.14, Fig.5.16.*

Table 5.13. Maximum, Minimum and average wind speed on 21st of July at 14:00

Average	1.3 m/s
Maximum	2 m/s
Minimum	0.45 m/s

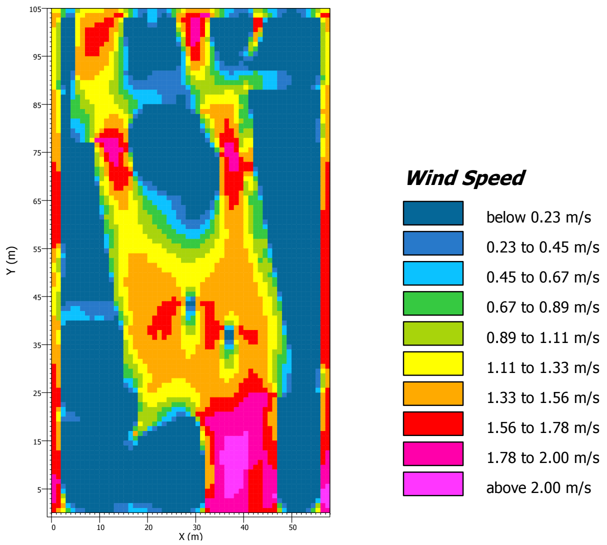


Fig.5.17. Wind speed on the 21st of July at 14:00

Table 5.14. Beaufort wind scale [19]

0.3 m/s Clam	0.3-1.5 m/s Light air	1.6-3.3 m/s Light breeze	3.4-5.5 m/s Gentle breeze	5.5-7.9 m/s Moderate breeze	8-10.7 m/s Fresh breeze

5.4.5.4. Mean radiant temperature

On average the MRT is 333.2 K. Areas close to buildings covered by shade and plantation experienced a lower MRT than the rest areas of the square *Fig.5.17*, *Table 5.15*. Moreover, water bodies play an essential role in mitigating MRT see *Fig.5.17*.

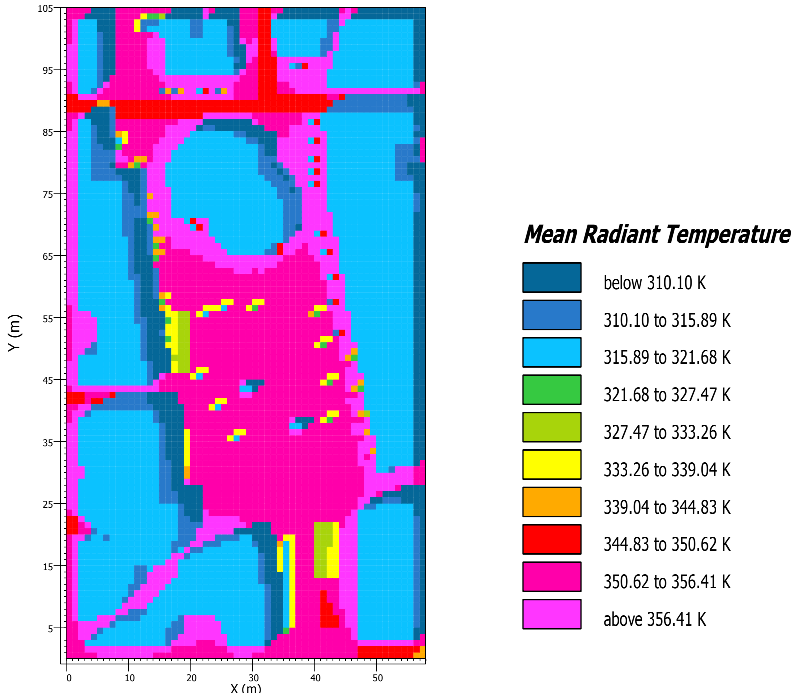


Fig.5.18. Mean radiant temperature on 21st of July at 14:00

Table 5.15. Maximum, minimum and average mean radiant temperature on 21st of July at 14:00

Average	333.2 K
Maximum	356.41 K
Minimum	310.10 K

5.4.5.5. Predicted mean vote

The predicted mean vote was conducted using *ENVI-met* code and then compared with ASHRAE thermal sensation scale *Table 5.17*, *Fig.5.18*, *and Table 5.16*. The average PMV value on the 21st of July at 14:00 PM is very hot. On average areas close to buildings and covered in shading and vegetation have a lower PMV value than the rest places of the square *Fig.5.18*.

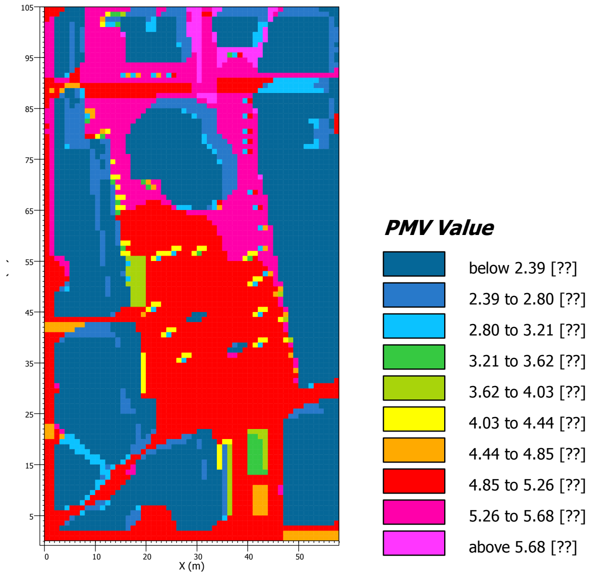


Fig.5.19. Predicted mean vote on the 21st of July at 14:00

Table 5.16. Maximum, Minimum and average PMV on the 21st of July at 14:00 PM

Average	4 (very hot)
Maximum	5.6 (very hot)
Minimum	2.4 (warm)

Table 5.17. ASHRAE thermal sensation scale [2]

-3 Cold	-2 cool	-1 slightly cool	0 neutral	+1 slightly warm	+2 warm	+3 hot

5.4.5.6. Carbon dioxide

The CO2 level was conducted using *ENVI-met* code and then compared with CO2 normal level scale *Table 5.18* [21]. Nonetheless, Co2 level falls within the safe level, Furthermore, Places under the influence of vegetation and water elements experienced a lower level of Co2 than the rest areas of the square see *Fig.5.19.*

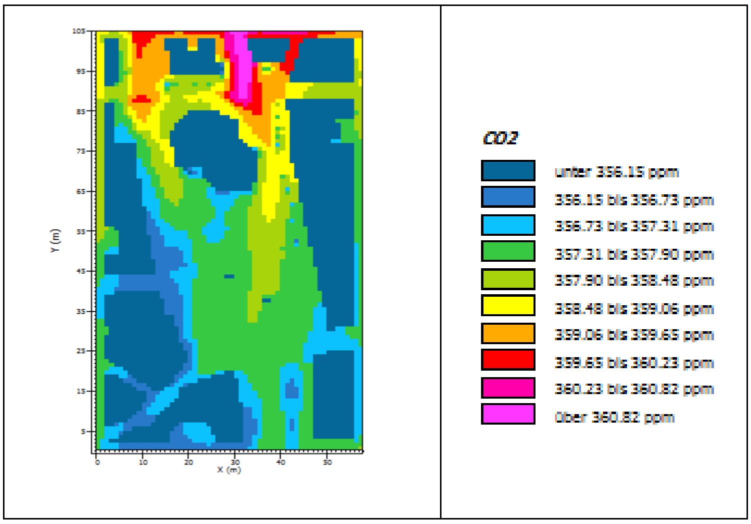


Fig.5.20. Co2 level on the 21st of July at 14:00

Table 5.18. Maximum, Minimum and average CO2 levels on 21st of July at 14:00

Average	358 PPM
Maximum	360 PPM
Minimum	356 PPM

5.5. Conclusions

The study site was modeled to assess the performance of outdoor thermal comfort parameters and investigate their capabilities in achieving the outdoor thermal comfort. However, it was concluded that on average 14:00 PM was recorded the highest very hot (rate 4). Furthermore, areas close to buildings and covered in shading and plantation have less temperature than other places of the square, water bodies play a significant role in mitigating the temperature and decreasing the PMV value. Street orientation, shading, water bodies, as well as plantation play a critical role in increasing or decreasing the outdoor thermal comfort level.

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Part 3: Enhancing the study site outdoor thermal performance

Chapter 6. Formulating possible measures to enhance the study site outdoor thermal comfort

6.1. Chapter six introduction

The work in this chapter aims to formulate the design measures and their parameters that could be used to improve the outdoor thermal comfort performance in the study space. This chapter starts by drawing the design measures and their parameters that are believed to have a positive impact on thermal comfort. These measures are extracted in three main levels, first the macro design level, the intermediate design level, and the micro design level. A list of possible measures for enhancing outdoor thermal performance will be then formulated.

6.2. Possible measures that could be used for outdoor thermal enhancement

Based on the literature review conducted in chapter three, many design measures and their parameters were found to have a significant positive effect on outdoor thermal on macro, intermediate levels, and micro level. Taking into consideration the same classification of the reviewed design measures, the outdoor thermal enhancement measures on macro, intermediate could be extracted with reference to chapter three as in *Table 6.1.*

Table 6.1. A list of possible measures for enhancing outdoor thermal comfort

Design level	Design measures	Studied parameter	Best practice
Macro-level	Site landform	-Flat -Sloping -Undulating	-Middle of the windward facing -slope
	Heat sinks (water bodies and forest)	-Near -Away	buildings near to them benefit from cold sea breeze
	Urban form	-Compact - Disperse - Clustered - Combined	- Disperse form - Clustered form

	Street wind orientation	- Normal - Oblique - Parallel	20o to 30o oblique to wind direction
	Street canyon geometry	-H/W < 0.3 - 0.3 < H/W < 0.65 - H/W =1 - H/W = 1.5	H/W ratio of 0.5 to 0.44
Intermediate-level	Vegetation	Locations, patterns and functions	Dependent on the design proposal
	Water body	As microclimate modifier	Trickle fountains are recommended for cooling air by evaporation
	Green roofs	-50% -100%	50% of the roof surface or more
	Green walls	-50% -100%	50% of the wall surface or more
Micro-level	Building height	(6-20) m (2-7) floor	1.5 of street width
	Building envelope Roof shape	flat, double-slope (Pitched),	No preference and dependent on orientation
	Building envelope Heat Transmission	-With Insulation -Without Insulation	-Roofs < 0.25 W/m²K -Walls < 0.45 W/m²K
	Albedo	-High reflective materials -Low reflective materials	-High reflective material

The list of measures summarized on all design levels *Table 6.1* could not be all applied to the study site enhancement. The nature of the study area and the less possible control over some listed measures hindered the use of them in the enhancement process. In addition, some measures could be only applied to new designs rather than already existing study site. Moreover, the nature of the research context forced some measures to be implemented in the enhancement process.

Therefore, these measures should be discussed, filtered, and modified in order to choose the final list of measures that will be applied to the study site and their effect on outdoor thermal comfort will be investigated in the Enhancement process.

6.3. Selected measures

In this section, all the design measures and their parameters that mentioned in *Table 6.1* will be filtered in order to select the most appropriate measures to be used in the enhancement process. The selection process will be conducted keeping in mind that the proposed measures will be applied to an already designed study area.

6.3.1. On the macro design level

The site landform and heat sinks measures will be excluded from the choice, as the architect does not have any control over their design parameters. In addition, their design parameters seem to be not applicable in the research context. The urban form measures seem to be more suitable to be applied to a newly designed square rather than to an already designed study site. As a result, the urban from measures will not be included.

In terms of street design, the street wind orientation will be studied in eight different directions. The orientations of *0o, 45o,90o,135o,180o,225o,270o, and 315o* were chosen among the orientation parameters to be tested in the enhancement process for the street orientation.

The last design measure at this level *(macro-level)* is the street canyon geometry. The recommended parameters for this measure are H/W of 0.5 to 0.44 *(see chapter three).* On one hand the author does not have any control over their design parameters. Moreover, the city center is a world's heritage site and any redesign or change to the street profile would be impossible. On the other hand, the street canyon geometry is playing an important role in increase outdoor ventilation and thermal comfort as mentioned in *chapter three.* As a result, the street canyon geometry will be listed to be investigated in this work.

6.3.2. On the intermediate design level

The building adjacency measures were excluded, as the study site is already designed. The last design measure at the intermediate level is the vegetation and water element measures. The huge diversity of the vegetation design measures, green walls, green roofs, as well as their parameters are in the heart concern of this research so softscape, hardscape, green roofs, and green walls measures and their parameters will be thoroughly investigated.

6.3.3. On the micro design level

The building mass and form measures will be excluded from the choice, as their design parameters are more suitable for designing a new outdoor space rather than being applied to an already designed and built ones. The research study space has its own fixed form and shape and mass configuration. As long as this work aims to enhance the study site as designed and built, there is no point on studying the impact of these measures. The building envelope design measures including roof shape were included. Furthermore, the building envelope design measures like heat transmission and albedo which could affect the outdoor thermal comfort. As a result, the U-value for walls and roofs with and without insulation as well as materials properties will be included and studied in this research.

Table 6.2. The proposed measures and their parameters for applying in outdoor enhancement.

Design level	Design measures	To be studied parameter
Macro	Street design orientation	0, 45, 90, 135,180,225,270,315.
	Canyon geometry	-H/W 0.65 -H/W 1 -H/W 1.5
Intermediate	Softscape (Vegetation, waterbody)	-Plantation 1-Grass (12%,17%,25%,) 2- Hedge dense (2m) (12%,17%,25%,) 3- Dense district crown (10m)

		(12%,17%,25%,) -Water (6%9%)
		-Green roofs 50%,100% of roof surface -Green walls 50%,100% of wall surface
	Hardscape (albedo)	-Paving Albedo, red stone , and pavement Concrete
Micro	Building envelope Heat Transmission	Walls & roofs (with and without insulation) (with and without insulation)
	Roof shape	Pitched, Flat

The effectiveness of the proposed measures and their parameters that extracted in this chapter on outdoor thermal performance will be quantified according to the detailed methodology in the next chapter.

Note: The building orientation design measure within this design level was dealt with earlier along with the street orientation measure.

Enhancing outdoor thermal performance in the study site

7.1. Chapter seven introduction

In this chapter, firstly the detailed methodology of conducting the improvement process will be explained. Secondly the results of the composed simulation cases to enhance outdoor thermal comfort in the study site are presented, analyzed and discussed. Thirdly the air temperature, relative humidity, wind speed, mean radiant temperature, predicted mean vote, and CO2 in the original base case are explained. Finally, the performance of each set of the selected measures and their parameters within macro, intermediate and micro design levels are studied in order to add the optimum chosen measures' parameters to the original base case which leads to the final enhanced case. Moreover, the final enhanced scenario will be compared to the original base case in an attempt to quantify the impact of the different design measures on improving the outdoor thermal performance of the study space.

7.2. The enhancement detailed methodology

The outdoor thermal enhancement part of this work will be conducted using CFD tool. The effectiveness of the proposed design measures will be quantified through conducting parametric analysis, in which each measure and its parameters will be applied to the base case as shown in *Table 7.1.* Moreover, the effectiveness of each parameter of these measures will be judged in terms of the mean air temperature, mean relative humidity, mean airspeed, mean TMRT, mean PMV across the study site and then the optimum case will be chosen to be added to the final enhanced case. Furthermore, the details of conducting this study, in terms of the determination of the base case and the procedures of conducting the parametric analysis, are explained below.

7.2.1. The base case

The outdoor thermal performance in the study site was evaluated in the previous part of this research. However, when working on the enhancement, A model for the base case was constructed with the same settings and grid configuration as the site model in the evaluation study *(For more information, refer to chapter 5).* Each selected parameter results will be compared to the original base case results to investigate the effectiveness of the parameter on outdoor thermal comfort.

Nonetheless, it should be noted here that this original base case will be dubbed *(The original base case (OBC)* hereinafter.

7.3. Quantifying the effect of the selected measures

To begin with, the enhancement process will deal with the selected measures at the macro and intermediate design levels. The case that achieves the highest TA, RH, WS, MRT, PMV, and CO2 on average in most areas of the square will be chosen as the best case. However, *Table 7.2*illustrates the methodological flow and stages of the enhancement process.

Table 7.1. The methodological stages of the enhancement process

Simulation case	Description	Proposed measures to be quantified
Case (1)	OBC+ Street orientation 0/360	Quantifying the effect of different street orientation parameters
Case (2)	OBC+ Street orientation 45	
Case (3)	OBC+ Street orientation 90	
Case (4)	OBC+ Street orientation 135	
Case (5)	OBC+ Street orientation 180	
Case (6)	OBC+ Street orientation 225	
Case (7)	OBC+ Street orientation 270	
Case (8)	OBC+ Street orientation 315	
Case (9)	OBC + canyon width=14.5	Quantifying the effect of different canyon geometry parameters
Case (10)	OBC + canyon width=10	
Case (11)	OBC + canyon width=6.5	
Case (12)	OBC + 12% hedge dense (2m)	Quantifying the effect of different plantation parameters
Case (13)	OBC + 17% hedge dense (2m)	
Case (14)	OBC + 25% hedge dense (2m)	
Case (15)	OBC + 12% dense district crown (10m)	
Case (16)	OBC + 17% dense district crown (10m)	
Case (17)	OBC + 25% dense district crown (10m)	
Case (18)	OBC + 6% water body	Quantifying the effect of different water body parameters
Case (19)	OBC + 9% water body	

Case (20)	OBC + 50% green roofs	Quantifying the effect of different green roofs parameters
Case (21)	OBC + 100% green roofs	
Case (22)	OBC + 50% green walls	Quantifying the effect of different green walls parameters
Case (23)	OBC + 100% green walls	
Case (24)	OBC + red stones	Quantifying the effect of different materials albedo parameters
Case (25)	OBC + pavement concrete	
Case (26)	OBC + insulation	Quantifying the effect of different Heat transmission parameters
Case (27)	OBC + flat roof	Quantifying the effect of different building shape parameters
FINAL ENHANCED CASE [FEC]	The best parameters to be added to the base case	quantify the amount of enhancement

The best cases of this set will include the best performing parameters among all the tested measures which will be the final enhanced case *[FEC]* that represents the final output of this research work. The performance of this final case will be compared to the performance of the original base case in an attempt to quantify the amount of enhancement achieves in the case study.

7.4. Simulation results, analysis, and discussion

The results of the study site enhancement process and their discussion, according to the methodology that was explained above, are introduced in details in the next section. For the full set of simulations and data, refer to *(Appendix C).*

7.4.1. The original base case performance

The simulation results of the air temperature, relative humidity, wind, MRT, PMV as well as Co2 on the original base case's areas showed;

- On average the air temperature on the 21st of July at 14:00 PM is 305K, which means the temperature ranges from warm to hot;
- The relative humidity is 34.5% which falls within the comfort range in the summertime;
- The average wind speed is light breeze 1.3 m/s;
- The average PMV value is very hot (+4);
- On average the MRT is 333.2 K;
- Co2 falls within the safe level.

It can be clearly seen from the *Fig.7.1*, *Table 7.2 that* areas close to buildings and covered in shading and vegetation have a lower TA, PMV, MRT than other places of the square.

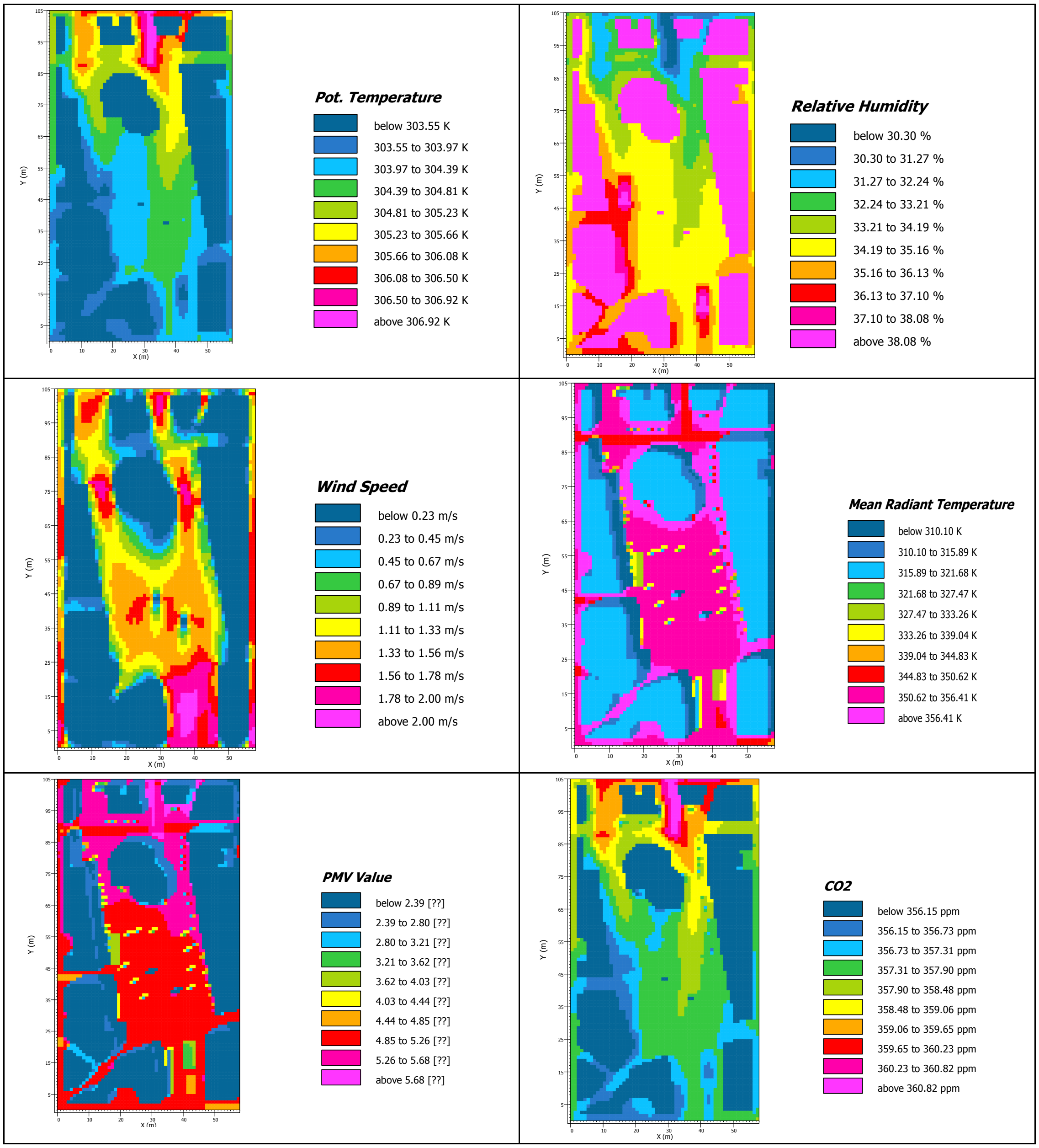


Fig.7.1. The original base case

Table 7.2. The mean Ta, RH, WS, PMV, MRT and Co2 in the original base case

Factor	**Temperature (K)**	**Relative Humidity (%)**	**Wind speed (m/s)**	**PMV value**	**Mean radiant temperature (K)**	**CO2 (PMM)**
Average result	304.8	34.2	1.4	5.2	353	358

7.4.2. The effect of street orientation

In this section, the results of the first 8 cases *Table 7* of orientation effects are discussed. However, it was found that the best method to analyze these cases is to calculate the overall average weather parameters and predicted mean vote that are reached by all cases in most areas of the square. This is in order to extract the optimum case. From *Fig.7.2*, *Fig.7.3*, *Fig.7.4*, *Table 7.2*, *Fig.7.5* some general conclusions could be drawn as follows:

- Case number eight has shown the best thermal performance among the 8 cases;
- Case (8) has achieved the lowest average air temperature *(303k=29.85c)*, highest average relative humidity *35.5%*, highest wind speed *(1.5 m\s)* along with case 5, lowest PMV value 4.8. However, the case directly faces the prevailing wind, and the street orientation is parallel to the wind direction;
- Co2 is almost constant in all scenarios with case 6 achieved the lowest value on average;

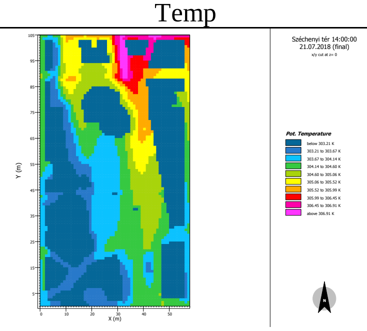
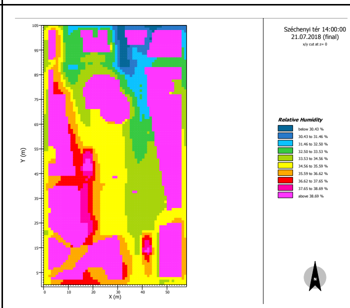
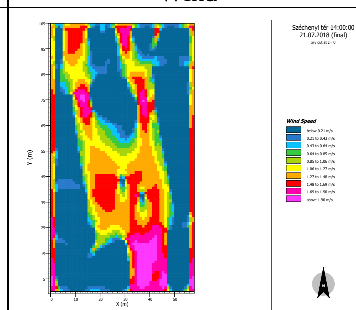
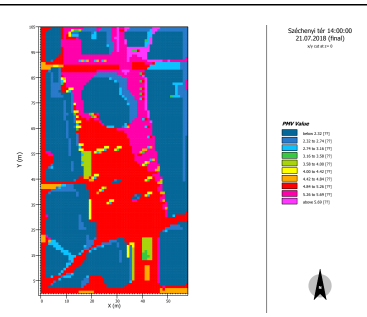
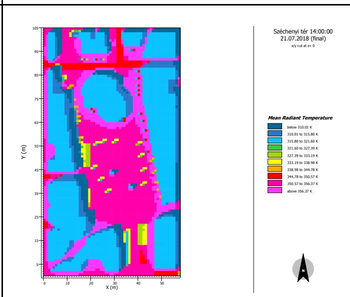
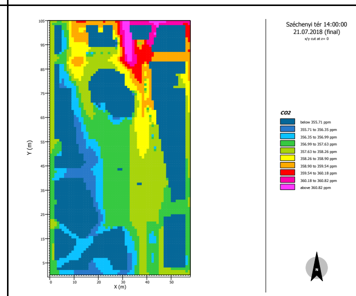
Orientation	Temp	RH	Wind
0/360			
Orientation	PMV	TMRT	CO2
0/360			

Fig.7.2. The mean Ta, RH, WS, PMV, MRT and Co2 in case (1)

- It can be seen from *Table 7.3* that the wind angle of *(315-0)o* achieved the highest total average airspeed that because the case directly faces the prevailing wind;
- In general, the lowest total average airspeed was found in case 4 when the wind Incident angle was 90o that due to no direct access to the prevailing wind;
- Thermal comfort is greatly affected by the wind direction;

- The *Table 7.3 and Fig.7.5* showed that the best airflow pattern over most of the spaces is achieved in case (8) that faces the prevailing wind;

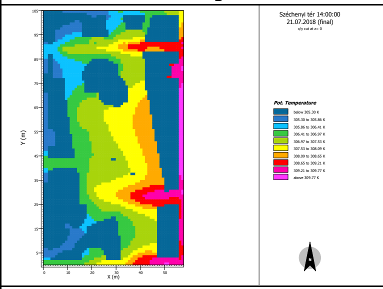
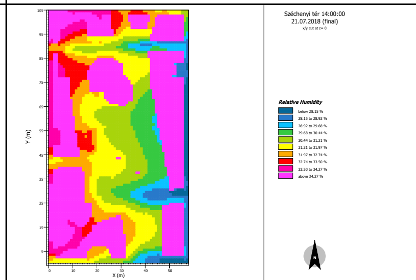
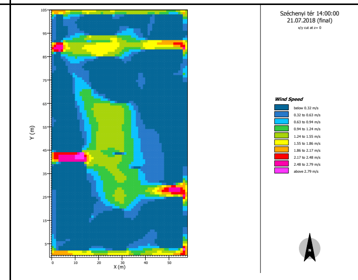
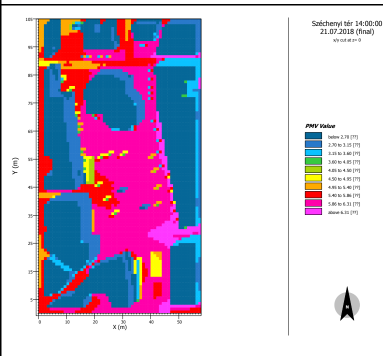
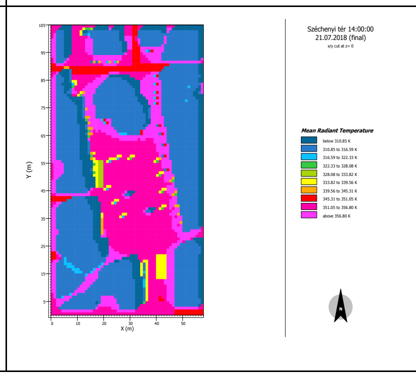
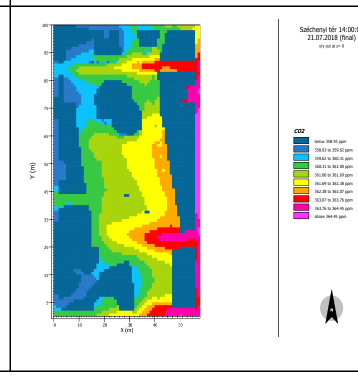
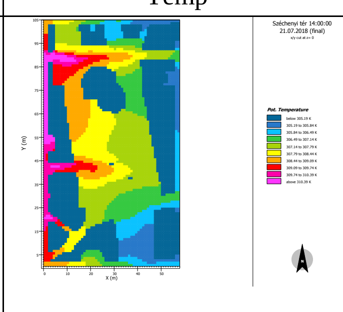
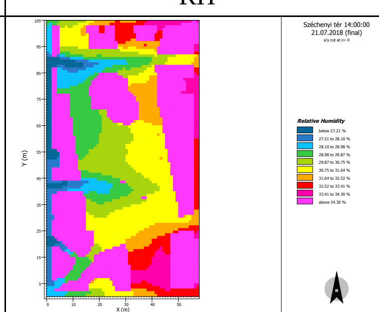
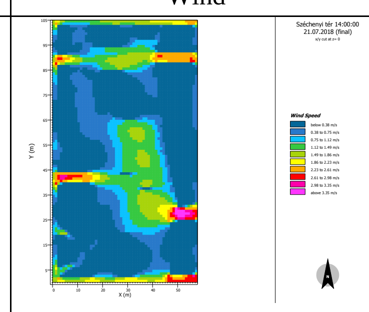
Orientation	Temp	RH	Wind
90			
Orientation	PMV	TMRT	CO2
90			

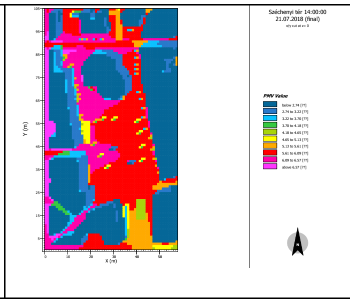
Fig.7.3. The mean Ta, RH, WS, PMV, MRT and Co2 in case (3)

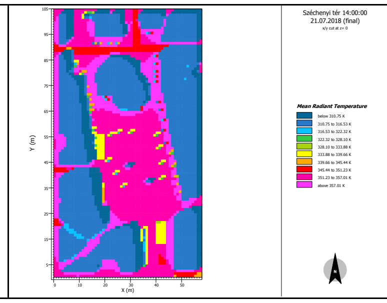
- The case 8 was found to be oblique to wind direction by approximately 20–30o with the narrowest buildings' façades facing the wind. However, the case was found to be the best case;

- When the major streets in a site are oriented parallel to the prevailing wind, the highest velocity could be obtained in the street canyons *Fig.7.4;*

Orientation	Temp	RH	Wind
270			
Orientation	PMV	TMRT	CO2

270





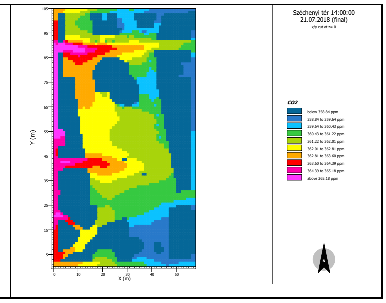
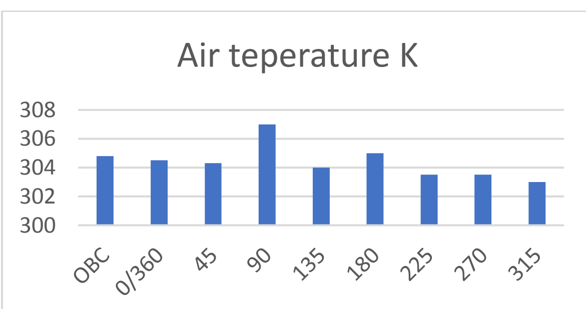


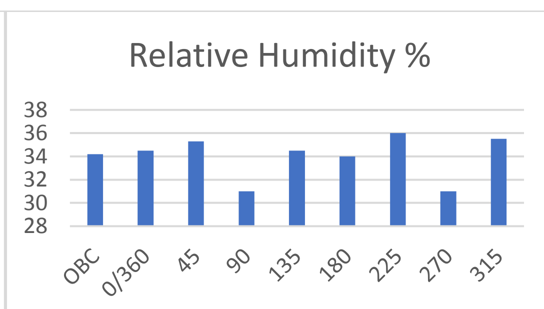
Fig.7.4. The mean Ta, RH, WS, PMV, MRT and Co2 in case (7)

In order to quantify the enhancement effect of these different parameters, the results of the optimum case 8 were compared to the results of the original base case. By comparing the results of *(OBC)* to their counterparts in case 8. These improvements introduced an increase in the outdoor thermal index (PMV) and the weather parameters, from *Table 7.3,Fig.7.5* it can be seen that optimum case 8 has achieved an enhancement in most areas of the square in comparison to the original base case.

Table 7.3. The mean Ta, RH, WS, PMV, MRT and Co2 in cases (1-8)

Street orientation	*Ta*	*RH*	*Wind*	*PMV*	*TMRT*	*CO2*
OBC	304.8	34.2	1.4	5.2	353	358
0/360	304.5	34.5	1.4	5.1	353	358
45	304.3	35.3	1.3	5	353	357
90	307	31	1.1	5.8	353	362
135	304	34.5	1.4	5.1	352	357
180	305	34	1.5	5.3	353	358
225	303.5	36	1.2	5.1	353	356
270	303.5	31	1.3	5	353	362
315	303	35.5	1.5	4.8	353	357





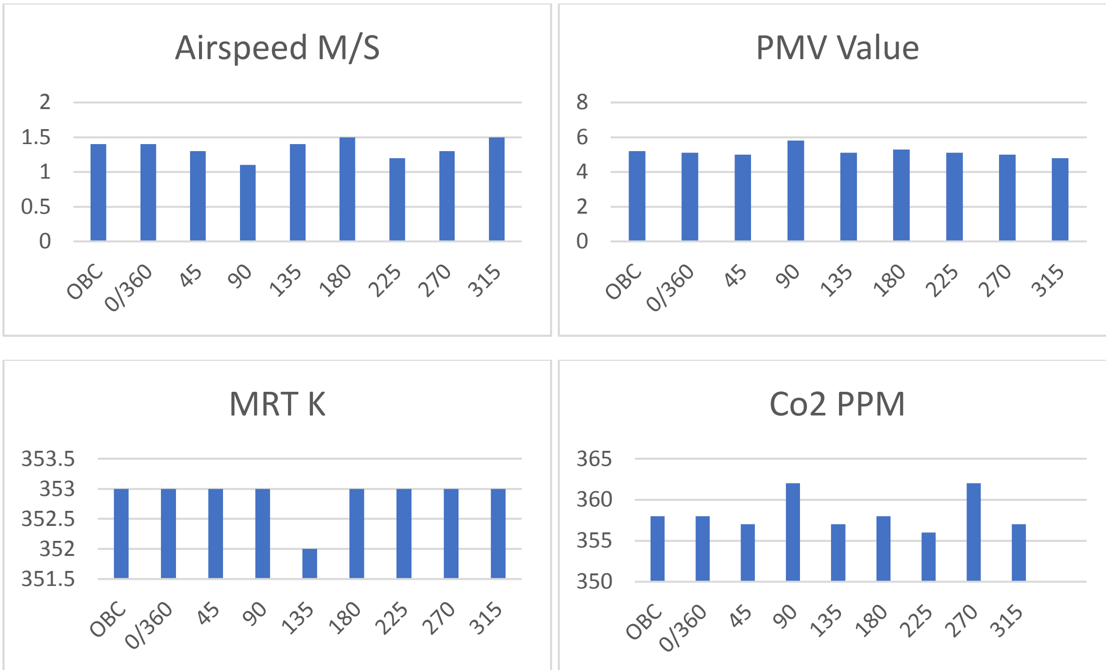


Fig.7.5. The mean Ta, RH, WS, PMV, MRT and Co2 in cases (1-8)

7.4.3. The effect of canyon geometry

The geometry of the street (Height/width ratio) as well as orientation directly influence the airspeed and solar access in urban canyon and as a result thermal comfort at the pedestrian level. This part examined street geometry case study's scenarios with different street geometry and investigate its effect on outdoor thermal comfort as well as weather parameters. However, the vast street canyons with an orientation parallel to the prevailing wind direction achieved the best results. The urban outdoor thermal comfort in this section was performed by studying the relationship between the ratio of building height to street width. Three scenarios with different street geometry were analyzed; *H/W=0.65 Fig.7.6, H/W=1 Fig.7.7, H/W=1.5 Table 7.3.*

When the street orientation is constant, the effect of canyon geometry on outdoor thermal comfort could be measured. However, the air temperature, relative humidity, airspeed, PMV, mean radiant temperature, Carbon dioxide were averaged over the square *Table 7.3*, results from *Fig.7.6* for this particular case study as follows;

- On average the total air temperature is 304k (hot);
- The average relative humidity is 35.3% (comfort);
- On average wind speed is 1.55 *m/s (light breeze);*
- The mean PMV value 5.1 (very hot);

- On average mean radiant temperature is 353K;
- The mean Co2 is 358 PPM (normal range);
- High airspeed was observed in the cases' inner street canyons, as most of the streets are parallel to the prevailing wind direction which allowed a larger amount of air to pass through the streets with high-speed values;

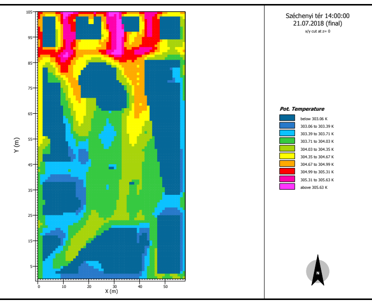
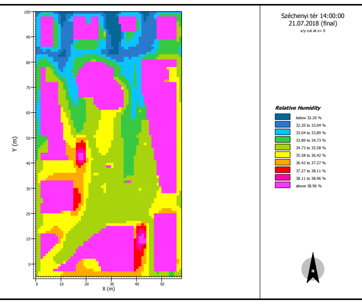
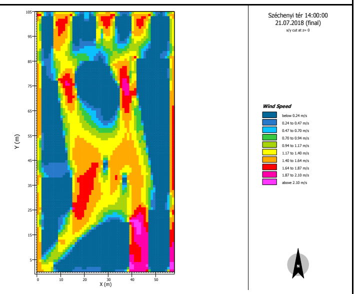
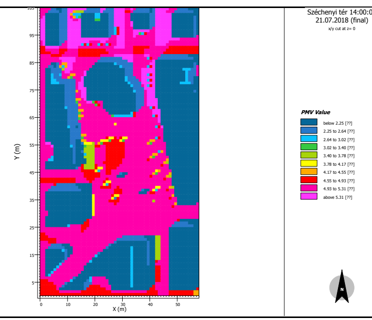
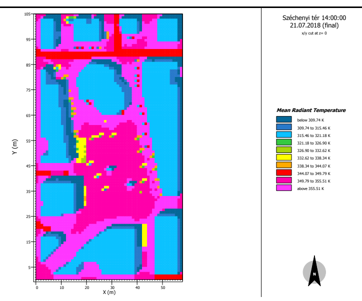
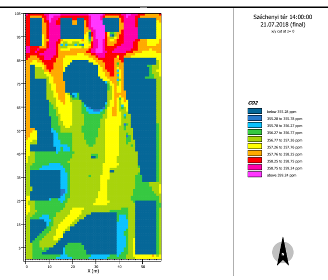
Canyon geometry	Temp	RH	Wind
H/W 0.65 W=14.5 m			
Canyon geometry	PMV	TMRT	CO2
H/W 0.65 W=14.5 m			

Fig.7.6. The mean Ta, RH, WS, PMV, MRT and Co2 in case (9*)*

The following simulation maps of the second scenario (H/W =1) have shown that;

- On average the air temperature is 304.3k (hot);
- The mean relative humidity is 34.4% (within the comfort range);
- The average wind speed is 1.4*m/s (light breeze);*
- The mean PMV value 5 (very hot);
- The average mean radiant temperature is 353K;
- on average Co2 is 358 PPM (normal range);

Canyon geometry	Temp	RH	Wind

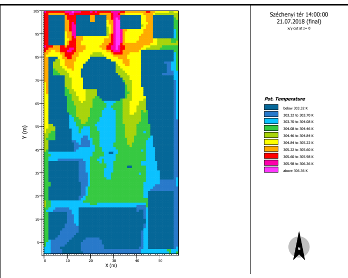
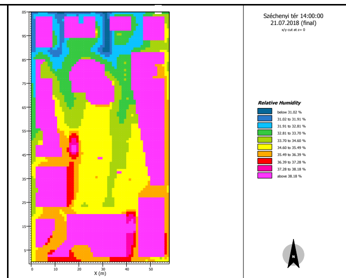
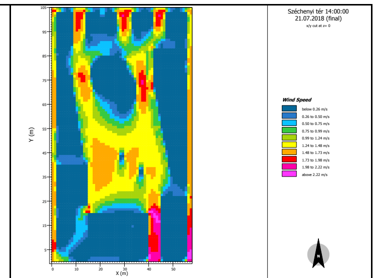
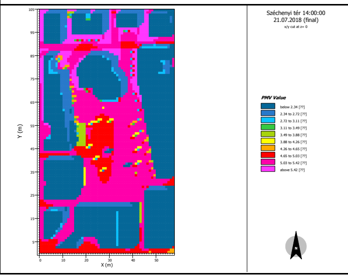
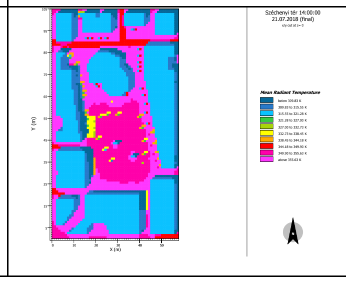
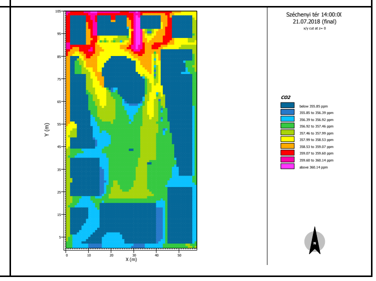
H/W 1 W=10 m			
Canyon geometry	PMV	TMRT	CO2
H/W 1 W=10 m			

Fig.7.7. The mean Ta, RH, WS, PMV, MRT and Co2 in case (10)

The results of the *Table 7.3* for the three scenarios revealed that;

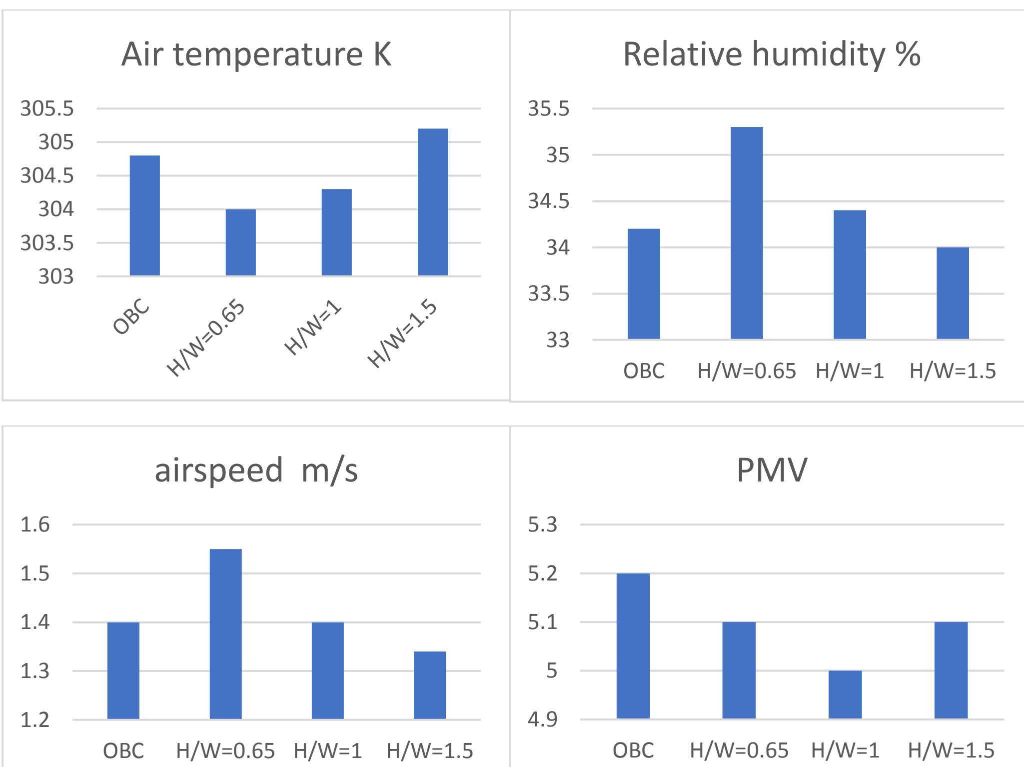
- On average the temperature is 305.2k in the third scenario;
- The mean relative humidity is 34% in the third scenario;
- The average airspeed is 1.34*m/s (light breeze)* in the third scenario*;*
- on average the PMV value 5.1 (very hot) in the third scenario;
- The average the Mean radiant temperature is 353K in the third scenario;
- The mean Co2 is 358 PPM (normal range) in the third scenario;
- The first scenario *Case 9, H/W=0.65* took the lead and achieved the highest total average airspeed at canyons width of *14.5m;*
- The first scenario achieved the lowest mean air temperature among the three scenarios (304k) due to high wind speed and ventilation;
- The first scenario archived the highest relative humidity among the three scenarios 35.3% due to high wind speed;
- The first scenario achieved the highest wind speed on average 1.55 m/s due to wide streets;
- The second scenario achieved the lowest PMV value on average 5;
- MRT is constant in all scenarios;
- Co2 is almost constant in all scenarios;

- The average airspeed over the whole square slightly increases as the distance between buildings increases;

Table 7.4. The mean Ta, RH, WS, PMV, MRT and Co2 in case (9-11)

Street canyon geometry	*Temperature (K)*	*Relative Humidity (%)*	*Wind speed (m/s)*	*PMV value*	*Mean radiant temperature (K)*	*CO2 (PMM)*
OBC	304.8	34.2	1.4	5.2	353	358
H/W=0.65	304	35.3	1.55	5.1	353	358
H/W=1	304.3	34.4	1.4	5	353	358
H/W=1.5	305.2	34	1.34	5.1	353	358

The results of the optimum case 9 were compared to the results of the original base case. By comparing the results of *(OBC)* to their counterparts in case 9, *Fig.7.8,* it can be clearly seen that the optimum case has achieved a slight improvement in most areas of the public space in comparison to the original base case. Nonetheless, case 9 was chosen as the best scenario among the three scenarios.



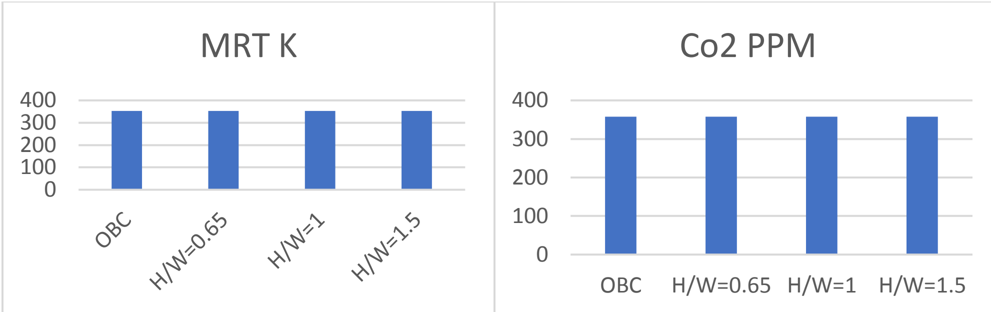
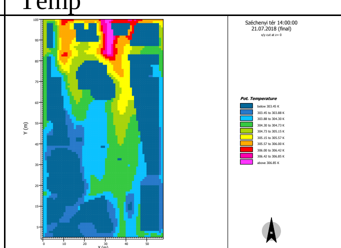
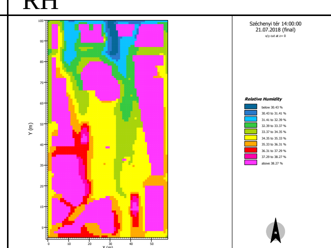
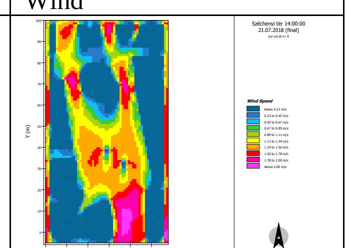


Fig.7.8. The mean Ta, RH, WS, PMV, MRT and Co2 in case (9-11)

7.4.4. The effect of plantation

The vegetation effect on the square's thermal comfort and its measure parameters was investigated in different types and ratios of vegetation, *hedge dense 2m 12% hedge dense 2m 17% hedge dense 2m 25% dense district crown 10m 12% dense district crown 10m 17% dense district crown 10m 25%*, six parameters were applied to the selected case study to extract the best scenario. Plantations were distributed in a way not to block the pedestrian motion in and around the case study, to determine the best possible option among the tested scenarios. In this section, the results of the cases 12-17 of vegetation effects are discussed. Furthermore, it was found that the best method to analyze these cases is to calculate the overall average weather parameters as well as predicted mean vote that are reached in all cases at most areas of the square. This is in order to choose the optimum case. From *Fig.7.9*, *Fig.7.10*, *Table 7.4*, *Fig.7.1* some general conclusions could be drawn as follows:

- There is a minor difference between the tested scenarios, with case 17 being the best scenario;
- Case 17 has shown the best thermal performance among the six cases;
- Co2 is almost constant in all scenarios with case 6 reached the lowest value on average;

Plantation	Temp	RH	Wind
Dense district crown (10m) 17%			
Plantation	PMV	TMRT	CO2

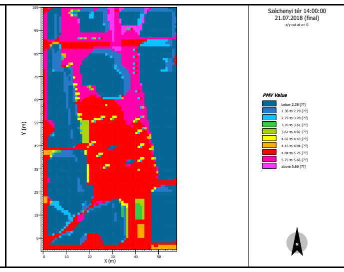
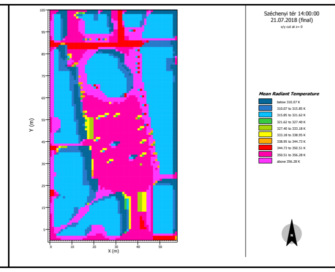
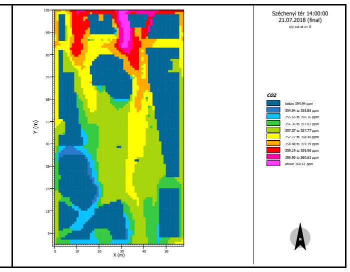
Dense district crown (10m) 17%			

Fig.7.9. The mean Ta, RH, WS, PMV, MRT and Co2 in case (16)

- Case 17 casts a larger area of shadow on the square's areas, so shading is another factor that supports the choice of case 17 as the best-case results showed either a slight; improvement or reduction in the case study;
- It can be seen from *Fig.7.10* that the dense district crown 10m 25% achieved the highest PMV;
- In general, the lowest total average Co2 was found in case 17 due to high vegetation percentage;

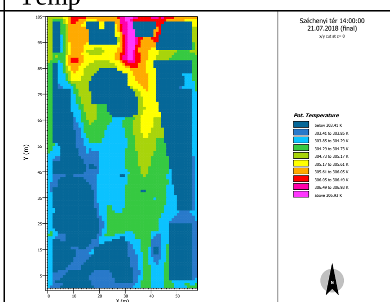
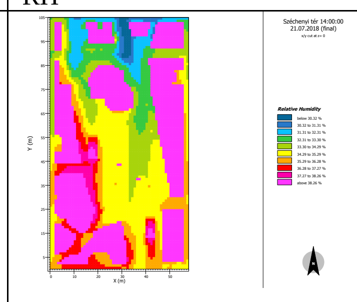
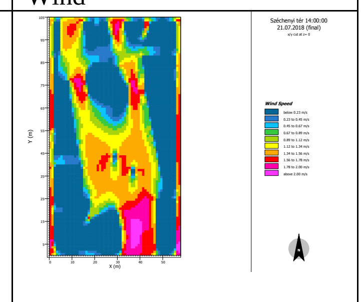
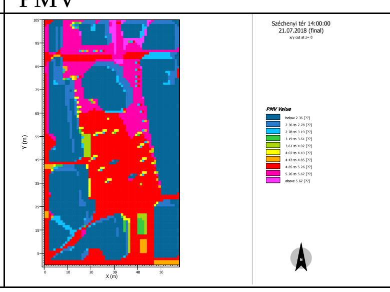
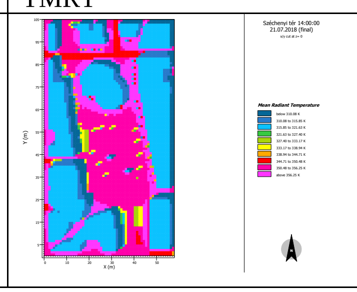
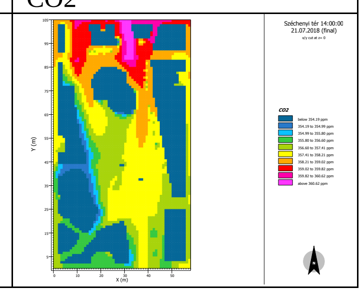
Plantation	Temp	RH	Wind
Dense district crown (10m) 25%			
Plantation	PMV	TMRT	CO2
Dense district crown (10m) 25%			

Fig.7.10. The mean Ta, RH, WS, PMV, MRT and Co2 in case (17)

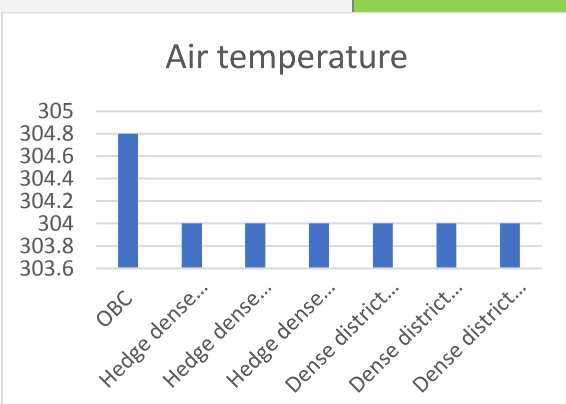
- It can be clearly seen from *Table 7.4* that the mean airflow speed over most spaces is constant in all scenarios with little enhancement +0.5m/s compared to (OBC);
- The mean air temperature over the case study is constant in all scenarios with little enhancement +0.8k compared to OBC;

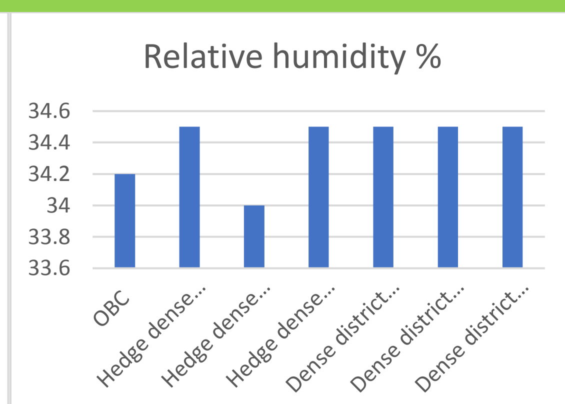
- It can be concluded from *Table 7.4* that the average relative humidity is almost constant within all scenarios with little improvement +0.3% compared to (OBC);

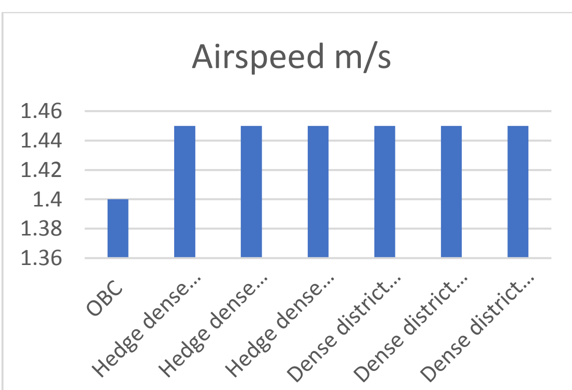
In order to study the enhancement effect of these different parameters, the results of the optimum case 12 were compared to the results of the original base case. By comparing the results of (OBC) to their counterparts in case 12. These improvements introduced a slight increase in the outdoor thermal index and the microclimatic parameters. However, case 12 has been chosen as the best case among these set of cases.

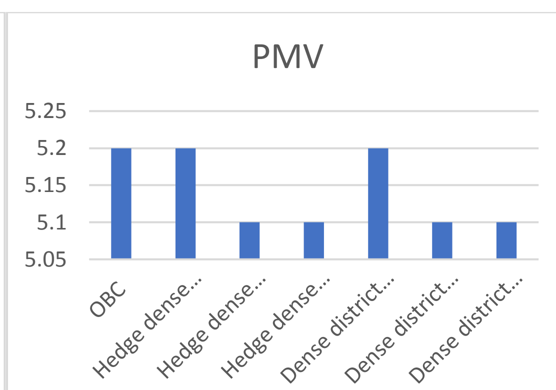
Table 7.5. The mean Ta, RH, WS, PMV, MRT and Co2 in case (12-17)

VEGETATION PERCENTAGE	TA	RH	WIND	PMV	TMRT	CO2
OBC	304.8	34.2	1.4	5.2	353	358
HEDGE DENSE (2M) 12%	304	34.5	1.45	5.2	353	357
HEDGE DENSE (2M) 17%	304	34	1.45	5.1	353	357
HEDGE DENSE (2M) 25%	304	34.5	1.45	5.1	353	356
DENSE DISTRICT CROWN (10M) 12%	304	34.5	1.45	5.2	353	357
DENSE DISTRICT CROWN (10M) 17%	304	34.5	1.45	5.1	353	357
DENSE DISTRICT CROWN (10M) 25%	304	34.5	1.45	5.1	353	354









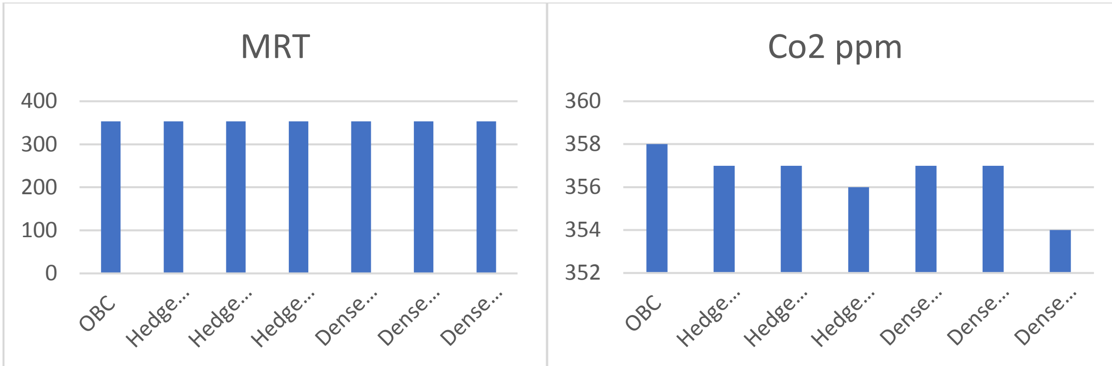


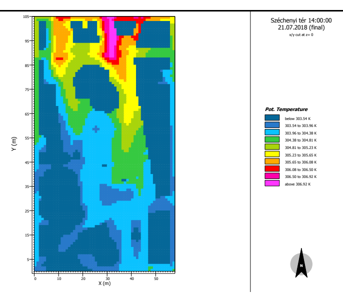
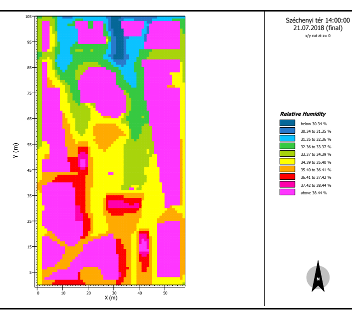
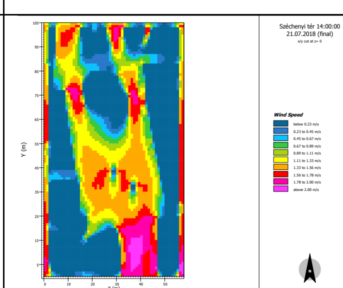
Fig.7.11. The mean Ta, RH, WS, PMV, MRT and Co2 in case (12-17)

7.4.5. The effect of Water body

Two measure parameters of the waterbody were conducted and studied. They are *6% and 9%* in cases*18 and 19* respectively. *Table 7.5* shows the average TA, RH, WS, PMV, MRT, and Co2 in the case study's scenarios after applying the proposed water element on the selected square. In general, it can be seen from the *Fig.7.12* that the waterbody except relative humidity has only a slight effect on increasing or decreasing the predicted mean vote its weather parameters.

Water bodies are known as the best absorbers of radiation, nevertheless show very little thermal response. However, from *Table 7.5*, *Fig.7.13* some general conclusions on waterbody could be drawn as follows:

- The average relative humidity was found to increase with increasing the water element ratio;
- The air temperature over most of the spaces is constant or with little enhancement 0.3k compared to (OBC);

Water body	Temp	RH	Wind
9%			
Water body	PMV	TMRT	CO2

9%

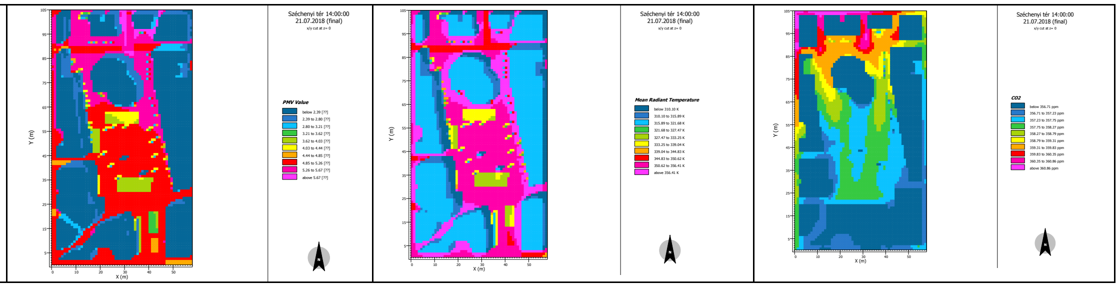
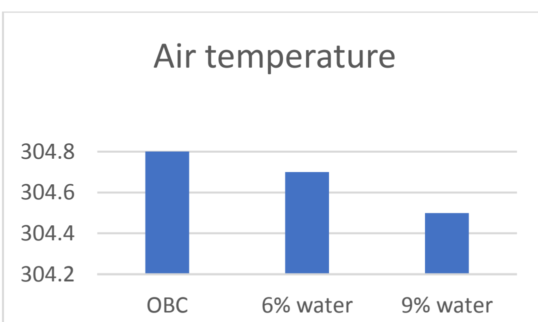


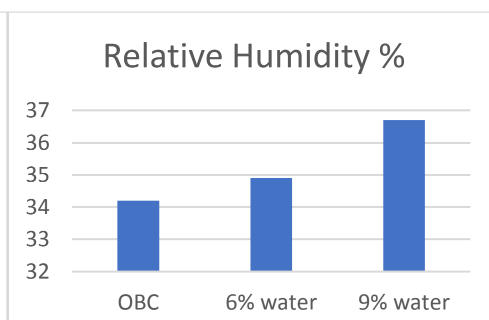
Fig.7.12. The mean Ta, RH, WS, PMV, MRT and Co2 in case (19)

- Water body has a slight effect on PMV, the enhancement of 0.4 compared to OBC was spotted;
- Wind speed and Co2 are more or less constant in all scenarios. So, water element has little or no impact on wind speed as well as Co2;
- Waterbody has a significant impact on MRT, the improvement of 7k compared to OBC was observed, based on these results, it can be argued that case 19, *Fig.7.12* was the best case among these set of cases. Therefore, it was chosen as the Optimum case 19;

Table 7.6. The mean Ta, RH, WS, PMV, MRT and Co2 in case (17-19)

Water body	*Temperature (K)*	*Relative Humidity (%)*	*Wind speed (m/s)*	*PMV value*	*Mean radiant temperature (K)*	*CO2 (PMM)*
OBC	304.8	34.2	1.4	5.2	353	358
6% water	304.7	34.9	1.4	4.9	349	357
9% water	304.5	36.7	1.4	4.8	346	357





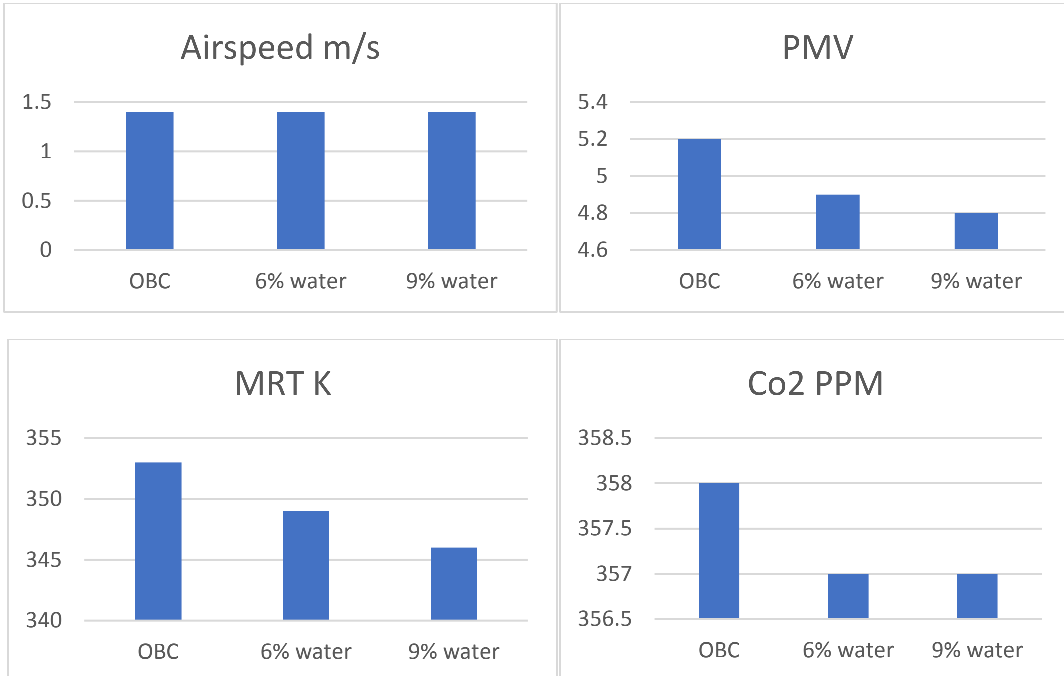


Fig.7.13. The mean Ta, RH, WS, PMV, MRT and Co2 in case (17-19)

7.4.6. The effect of green roofs

Two parameters of the green roofs measure were applied to the selected case. They are *50% and 100% of the total roofs' area* in cases *Case 19 and 20* respectively. *Table 7.6* shows that the average TA, RH, WS, PMV, MRT, and Co2 in the case study's cases after applying the proposed **Green roof ratios**. In general, it can be seen from the *Fig.7.14 and Table 7.6* that the **Green roofs** have only a slight effect on increasing or decreasing the predicted mean vote and weather parameters. However**,** from *Table 7.6*, some general conclusions on green roofs could be drawn as follows:

- Case 21 (100% green roofs) has reached the lowest air temperature 304k, highest relative humidity 35%, lowest Co2 level 357 PMM;
- On average air temperature was found to decrease with increasing the percentage of the green roofs;
- The average relative humidity was found to increase with increasing the percentage of the green roofs;

Green roofs	Temp	RH	Wind

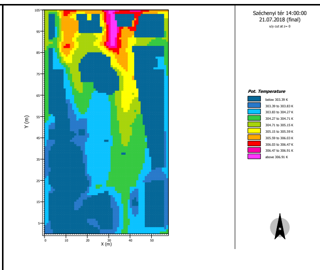
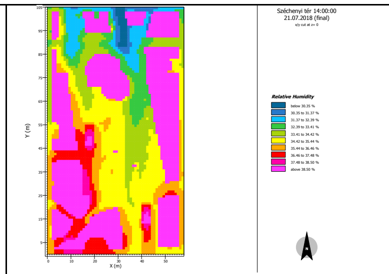
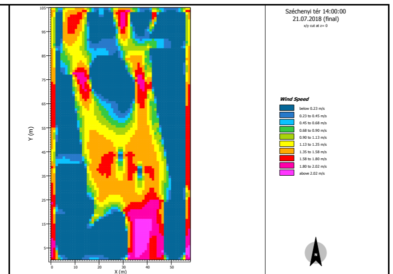
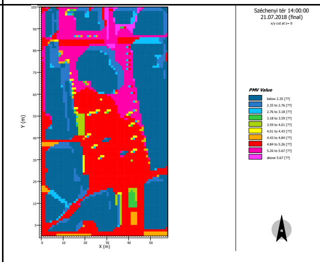
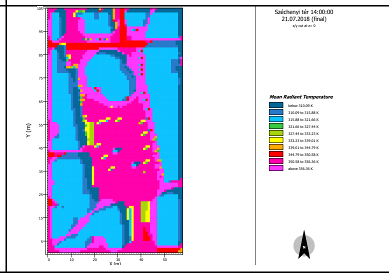
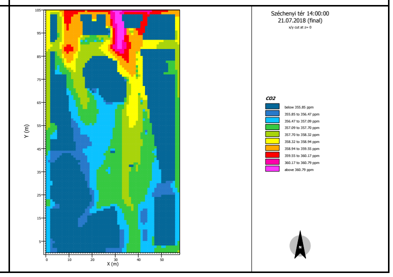
100% of the whole roofs			
Green roofs	PMV	TMRT	CO2
100% of the whole roofs			

Fig.7.14. The mean Ta, RH, WS, PMV, MRT and Co2 in case (21)

- The total average of Co2 level was found to decrease with increasing the percentage of the green roofs, with case 21 reached the lowest Co2 level;
- The Predicted mean vote was found to decrease with increasing the percentage of green roofs, with case 20-21 reached the lowest PMV value compared to (OBC);
- Green roofs have little or no effect on wind speed and MRT (in this case study). Furthermore, wind speed and MRT almost constant in all scenarios as can be seen in *Table 7.6.*, *Fig.7.15;*

In order to quantify the enhancement effect of different green roofs parameters, the results of the optimum case 21 were compared to the results of the original base case. Nonetheless, these improvements introduced an increase in the outdoor thermal index and weather parameters, from *Table 7.6*, it can be seen that the optimum case has achieved a minor enhancement in some areas of the square, in comparison to the original base case. Therefore, case number 21 has been chosen as the best case.

Table 7.7. The mean Ta, RH, WS, PMV, MRT and Co2 in case (20-21)

Green roofs	*Temperature (K)*	*Relative Humidity (%)*	*Wind speed (m/s)*	*PMV value*	*Mean radiant temperature (K)*	*CO2 (PMM)*
OBC	304.8	34.2	1.4	5.2	353	358
50%	304.2	34.7	1.4	5	553	358

100%	304	35	1.4	5	353	357

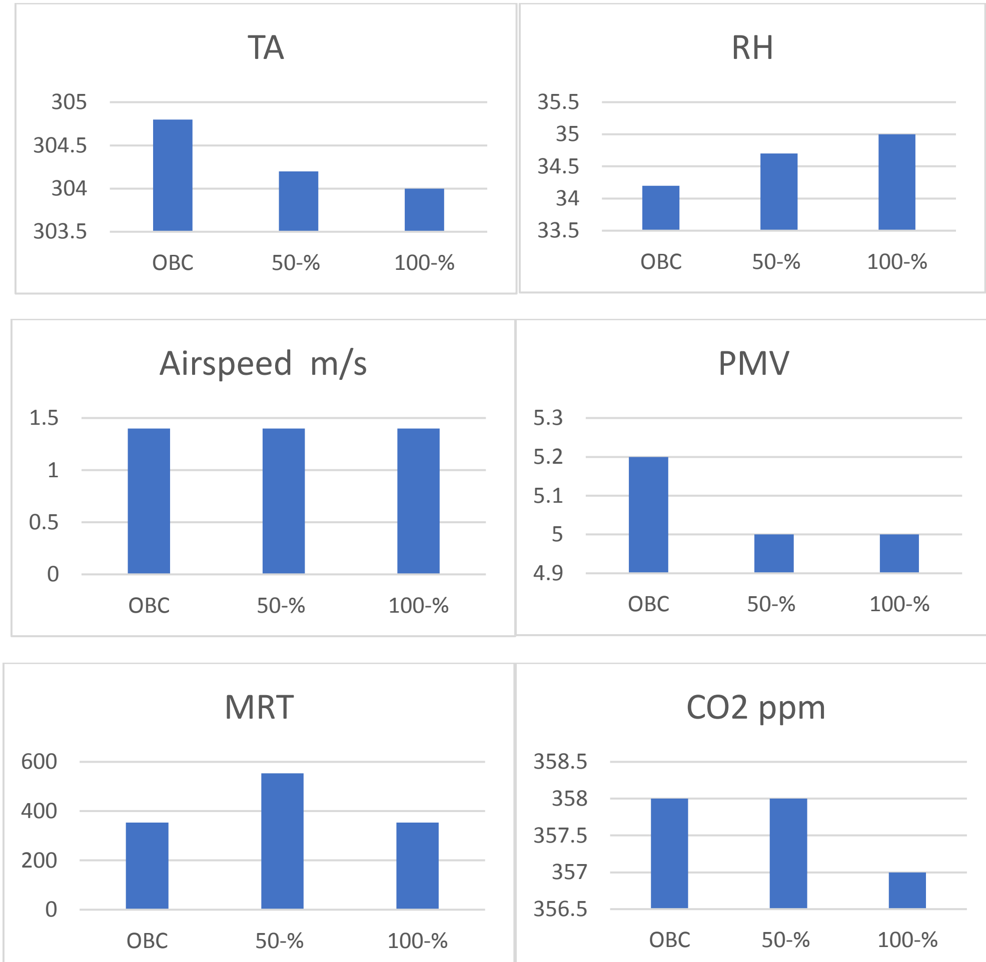


Fig.7.15. The mean Ta, RH, WS, PMV, MRT and Co2 in case (20-21)

7.4.7. The effect of green façade

Green façade is a passive cooling technique in providing a better sustainable living environment, especially in thermal performance. Two scenarios were modeled and investigated first one with 50% green walls (half of the entire facades were covered with green vegetation) and the second with 100% green walls. However, from *Fig.7.16, Table 7.7* some general conclusions could be drawn as follows;

- Case 23 (100% green walls) has achieved the lowest mean air temperature 304k, the highest mean relative humidity 37%, the highest mean wind speed 1.5m/s, lowest MRT 351k, and lowest Co2 level 355 PMM on average;

- The average air temperature was found to decrease with increasing the percentage of the green walls;
- The average relative humidity was found to increase with increasing the percentage of the green walls;
- The average Co2 level was found to decrease with increasing the percentage of the green walls, with case 23 reached the lowest Co2 level;
- On average PMV was found to decrease with increasing the percentage of the green walls, with case 22-23 reached the lowest PMV value;
- Green walls have little or no effect on wind speed. However, wind speed almost constant in all scenarios, with case 23 accomplishing the highest magnitude 1.5 *m/s*;

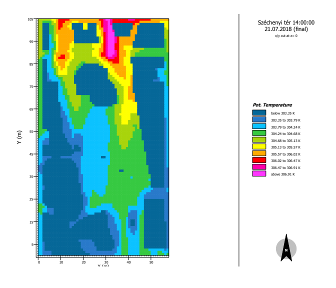
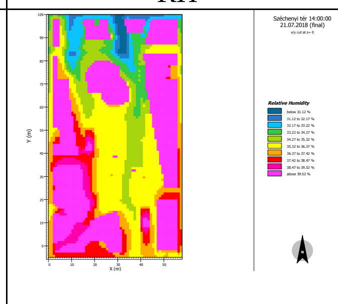
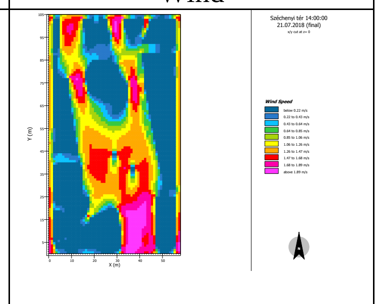
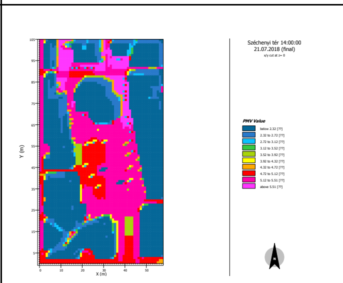
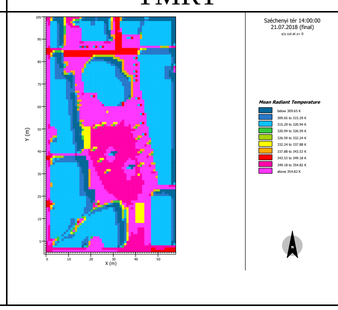
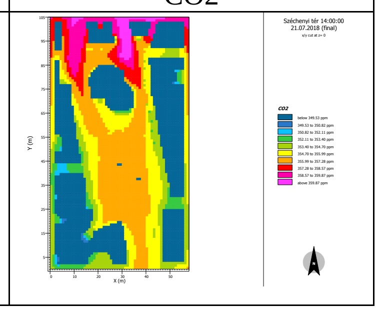
Green walls	Temp	RH	Wind
100%			
Green walls	PMV	TMRT	CO2
100%			

Fig.7.16. The mean Ta, RH, WS, PMV, MRT and Co2 in case (23)

In order to quantify the enhancement effect of different parameters, the results of the optimum case were compared to the results of the original base case. By comparing the results of *(OBC)* to their counterparts in case 23. The improvement introduced an increase in the outdoor thermal index and weather parameters, from *Table 7.7*, *Fig.7.17* it can be clearly seen that optimum case 23 has achieved a minor enhancement in some areas of the square in comparison to the original base case. Nevertheless, case 23 was selected as the best case and will be applied later in this chapter to the final enhanced case.

Table 7.8. The mean Ta, RH, WS, PMV, MRT and Co2 in case (22-23)

Green walls	*Temperature (K)*	*Relative Humidity (%)*	*Wind speed (m/s)*	*PMV value*	*Mean radiant temperature (K)*	*CO2 (PMM)*
OBC	304.8	34.2	1.4	5.2	353	358
50-%	304.2	35	1.4	5.1	352.5	356
100-%	304	37	1.5	5	351	355

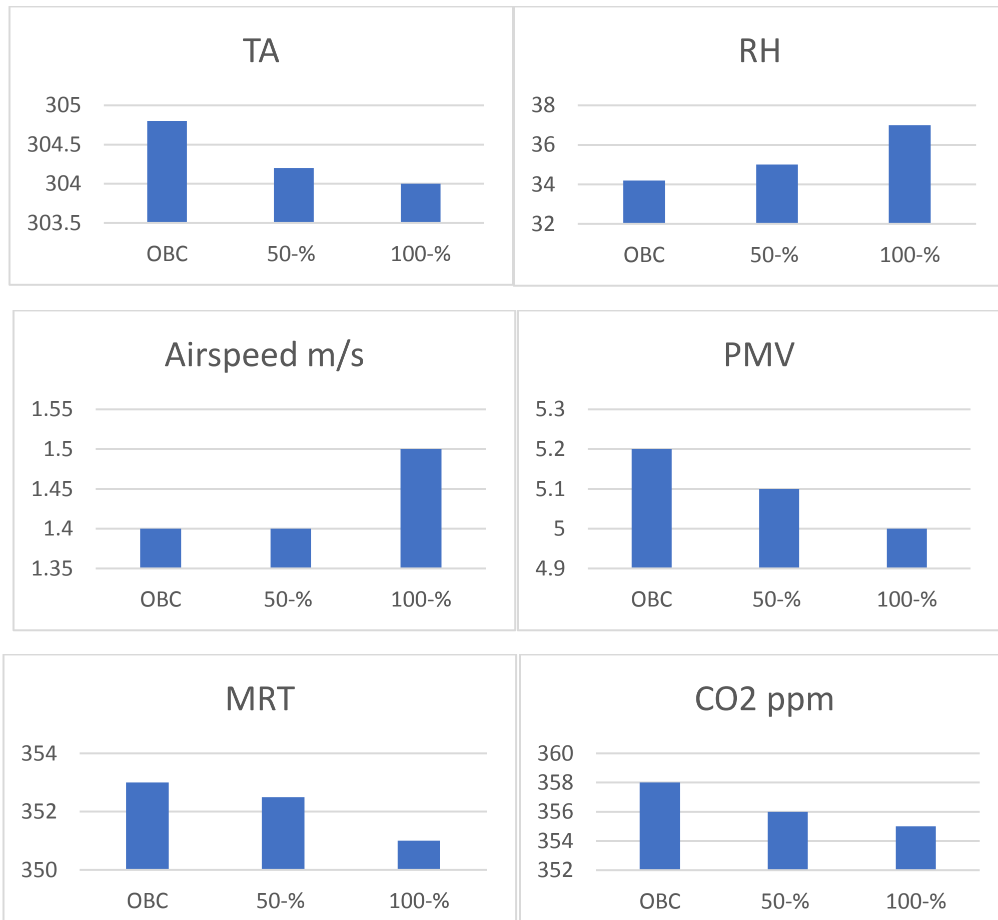


Fig.7.17. The mean Ta, RH, WS, PMV, MRT and Co2 in case (22-23)

7.4.8. The effect of materials and Albedo

In terms of outdoor thermal comfort and its weather parameters, the materials and Albedo showed little or no difference in some cases *Fig.7.18, Fig.7.19, Table 7.8* comparing to the original base case. Moreover, some general conclusions could be drawn as follows:

- Case number 25 showed a slight reduction in MRT and PMV when was compared to the original base case
- Air temperature, relative humidity, wind speed, as well as the Co2 are constant in all scenarios
- In general, case 25 gave better results than case 24.
- Case 25 as achieved the best outdoor thermal performance when was compared to the *(OBC)*

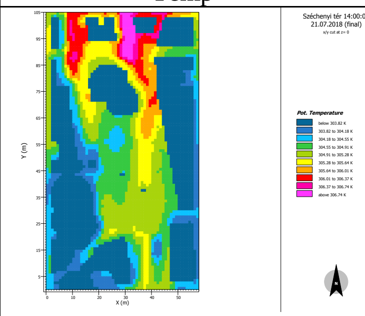
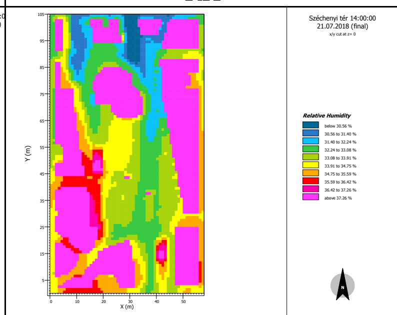
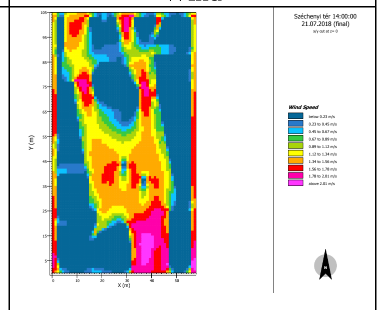
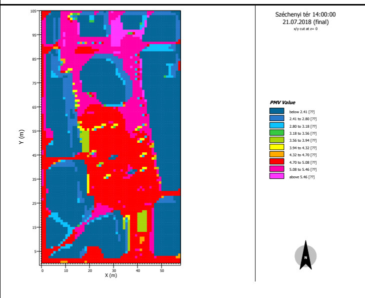
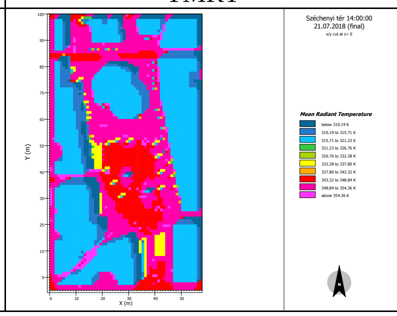
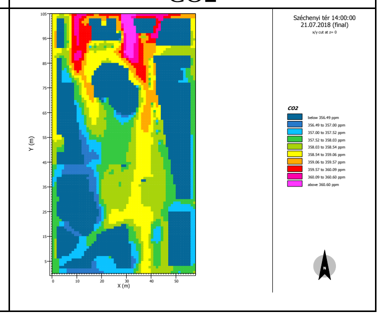
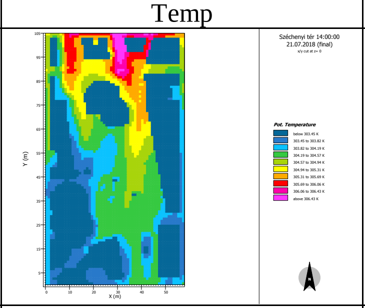
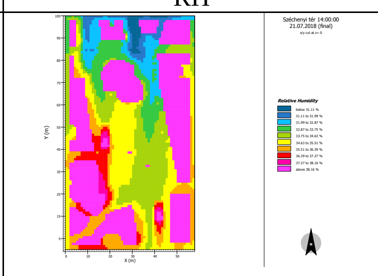
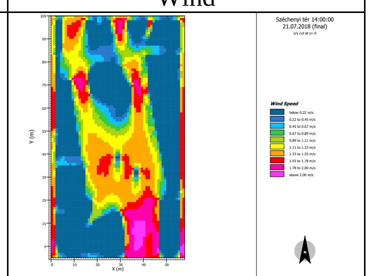
Albedo	Temp	RH	Wind
Red stone			
Albedo	PMV	TMRT	CO2
Red stone			

Fig.7.18. The mean Ta, RH, WS, PMV, MRT and Co2 in case (24)

Albedo	Temp	RH	Wind
Pavement Concrete			
Albedo	PMV	TMRT	CO2

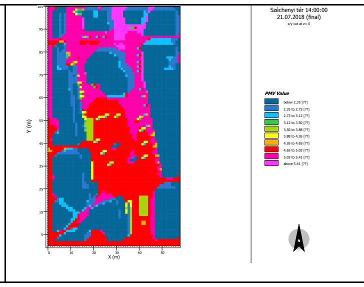
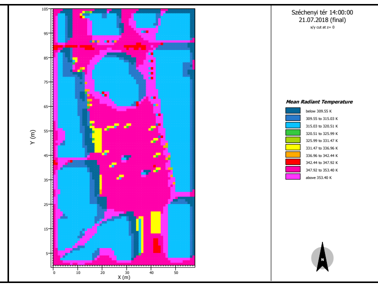
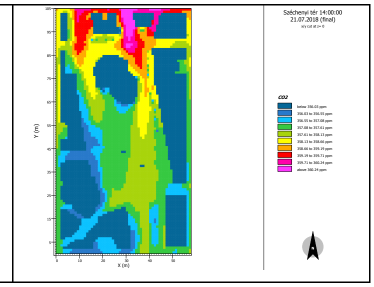
Pavement Concrete			

Fig.7.19. The mean Ta, RH, WS, PMV, MRT and Co2 in case (25)

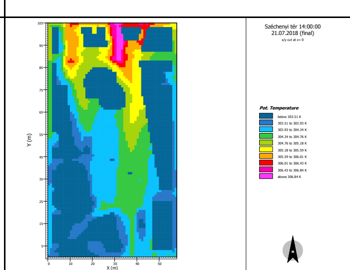
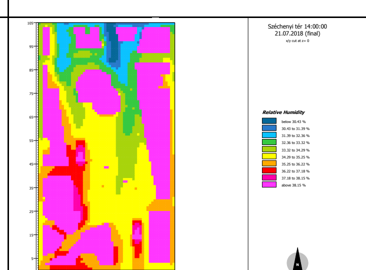
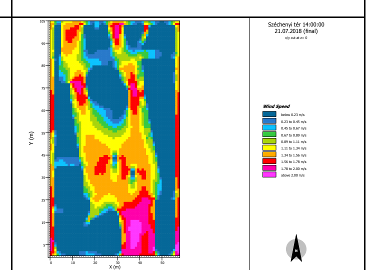
From *Table 7.8*, it can be clearly seen that optimum case 25 has achieved minor enhancement in some areas of the square in comparison to the original base case and case 24. Nonetheless, from the discussion above and after careful consideration case 25 was chosen as the best scenario among the tested cases and will be used later in this chapter in the final enhanced case.

Table 7.9. The mean Ta, RH, WS, PMV, MRT and Co2 in case (24-25)

Paving Albedo	*Temperature (K)*	*Relative Humidity (%)*	*Wind speed (m/s)*	*PMV value*	*Mean radiant temperature (K)*	*CO2 (PMM)*
OBC	304.8	34.2	1.4	5.2	353	358
Red stone	304.8	34.2	1.4	5.1	351	358
Pavement concrete	304.8	34.2	1.4	5.1	347	358

7.4.9. The effect of heat transmission

One parameter of the heat transmission ((With insulation), U-value roof=0.25, U-value wall=0.45) was modeled and analyzed. The heat transmission showed almost no difference when was compared to original bas case *Fig.7.20*, *Table 7.9*. As a result, heat transmission measure was excluded.

Heat Transmission	Temp	RH	Wind
U-value roof=0.25 U-value wall=0.45 (With insulation)			
Heat transmission	PMV	TMRT	CO2

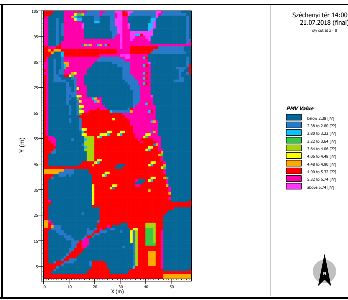
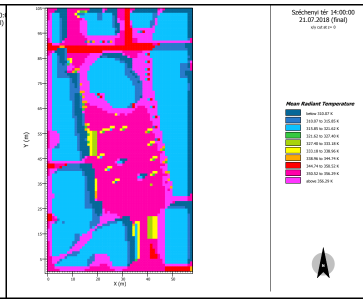
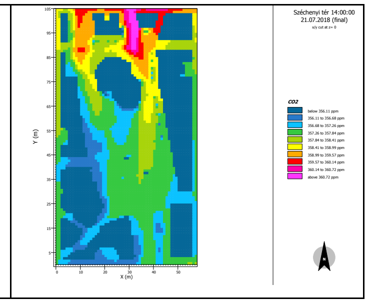
U-value roof=0.25 U-value wall=0.45 (With insulation)			

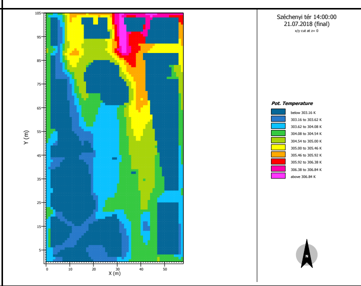
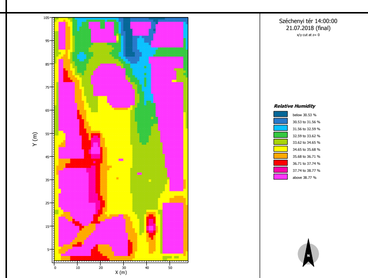
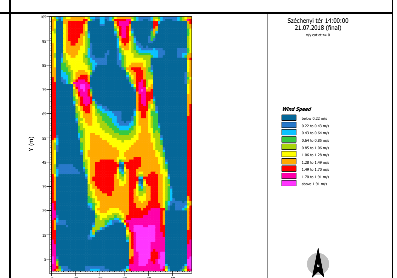
Fig.7.20. The mean Ta, RH, WS, PMV, MRT and Co2

Table 7.10. The mean Ta, RH, WS, PMV, MRT and Co2

Heat Transmission	*Temperature (K)*	*Relative Humidity (%)*	*Wind speed (m/s)*	*PMV value*	*Mean radiant temperature (K)*	*CO2 (PMM)*
OBC	304.8	34.2	1.4	5.2	353	358
With Insulation	304.8	34.2	1.4	5.2	553	358

7.4.10. The effect of roof shape

Roof shape measures are analyzed then discussed in this section. This is in order to extract the optimum case to be added to the final enhanced case. However, roof shape showed almost no difference in all scenarios comparing to the original base case *Fig.7.21*, *Table 7.10*. So, roof shape parameters were excluded.

Roof shape	Temp	RH	Wind
Flat Roof			
Roof shape	PMV	TMRT	CO2

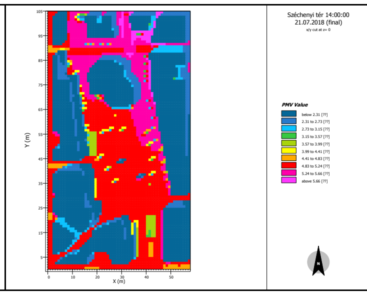
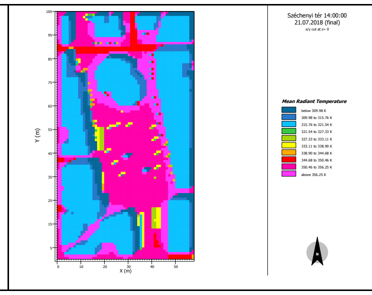
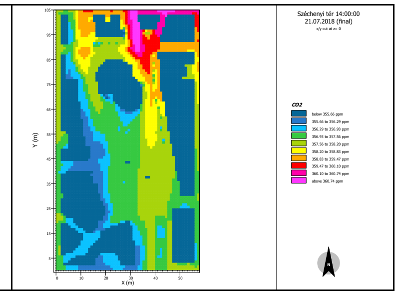
Flat Roof			

Fig.7.21. The mean Ta, RH, WS, PMV, MRT and Co2

Table 7.11. The mean Ta, RH, WS, PMV, MRT and Co2

Roof shape	*Temperature (K)*	*Relative Humidity (%)*	*Wind speed (m/s)*	*PMV value*	*Mean radiant temperature (K)*	*CO2 (PMM)*
OBC	304.8	34.2	1.4	5.2	353	358
Flat	304.8	34.2	1.4	5.2	553	358

7.5. The overall enhanced case in comparison to the original base case

The final overall enhanced case that resulted after applying the best measures and parameters' scenarios as shown in *Table 7.11* of the enhancement process that conducted above was also simulated and compared to the original base case *Fig.7.22*, *Table 7.12.* This in an attempt to quantify the combined effect of the best parameters of the tested design measures on enhancing the outdoor thermal comfort and weather parameters.

Table 7.12. Parameters that were added to the base case to form the enhanced final case

Case name	**TA**	**RH**	**WS**	**PMV**	**MRT**	**CO2**
Original base case (OBC)	304.8	34.2	1.4	5.2	353	358
Street orientation (315)	303	35.5	1.5	4.8	353	357
H/W=0.65	304	35.3	1.55	5.1	353	358
Dense district crown (10m) 25%	304	34.5	1.45	5.1	353	354
9% water	304.5	36.7	1.4	4.8	346	357
Green roofs 100%	304	35	1.4	5	353	357
Green walls 100%	304	37	1.5	5	351	355
Pavement concrete	304.8	34.2	1.4	5.1	347	358

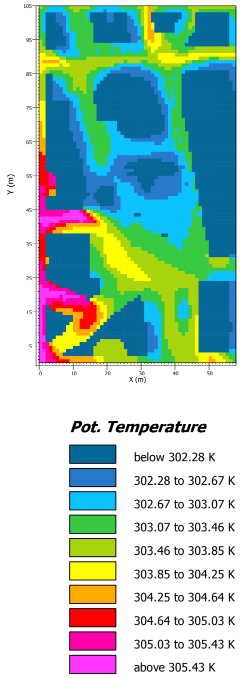
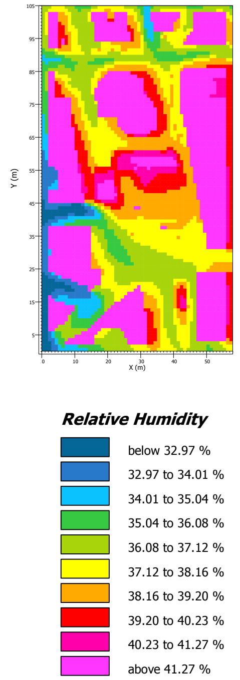
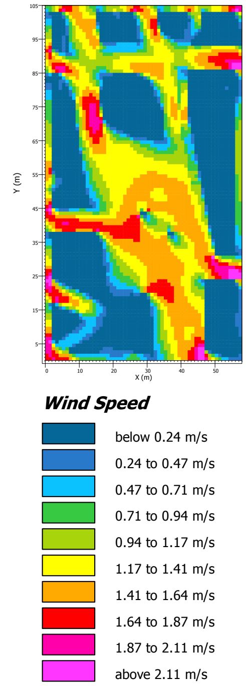
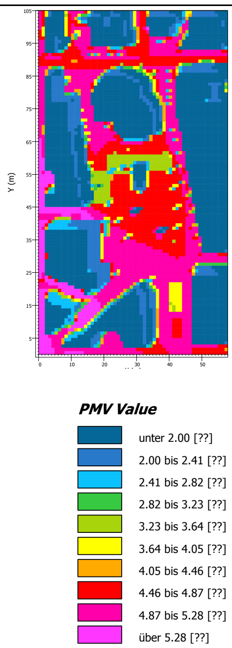
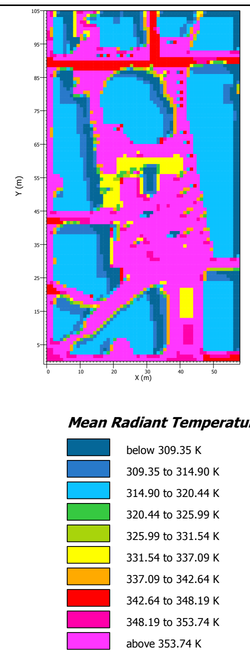
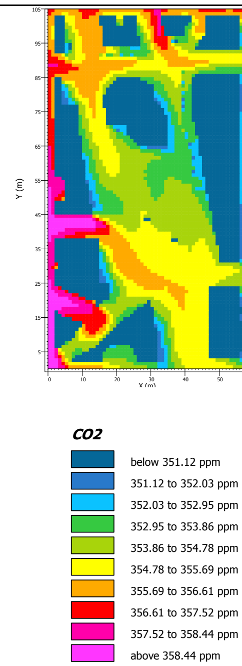
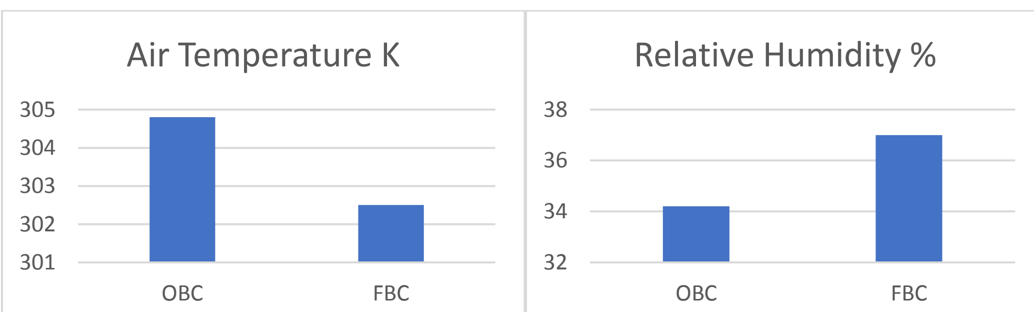
<table>
<tr><td>Final case</td><td>Temp</td><td>RH</td><td>Wind</td></tr>
<tr><td></td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Final case</td><td>PMV</td><td>TMRT</td><td>CO2</td></tr>
<tr><td></td><td>
</td><td>
</td><td>
</td></tr>
</table>

Fig.7.22. The average thermal comfort index and weather parameters in the enhanced final case *(FEC)*

Table 7.13. The results comparison between the final enhanced case and the original base case (all values are average)

Case name	**TA (K)**	**RH (%)**	**WS (m/s)**	**PMV**	**MRT (K)**	**Co2 (PMM)**
Original base case (OBC)	304.8	34.2	1.4	5.2	353	358
Final enhanced case (FEC)	302.5	37	1.6	4.6	345	354
The difference	2.3	-2.8	-0.2	0.6	8	4

Table 7.12 shows the comparison between the air temperature, relative humidity, wind speed, predicated mean vote, mean radiant temperature as well as the Co2 in the original case and the final enhanced case of the Széchenyi square. It can be clearly seen the table, that applying the selected measures to the case study has significantly improved the air temperature, relative humidity, as well as the MRT by *2.3k, -2.8%, and 8k* respectively. Street orientation, canyon geometry, Plantation, water body, and materials and albedo had little impact on wind in this particular case as seen in *Fig.7.23*. However, the most influential measures on the wind speed were street orientation and street geometry where larger building fabric became exposed to the flowing air, which support the use of natural ventilation and maximize its benefit. Green roofs and walls as well have a great impact on the MRT and relative humidity. It can be clearly seen from the all the mentioned figures that the *TA, RH, WS, PMV, MRT, and Co2* within the case study was slightly enhanced after applying the proposed measures.



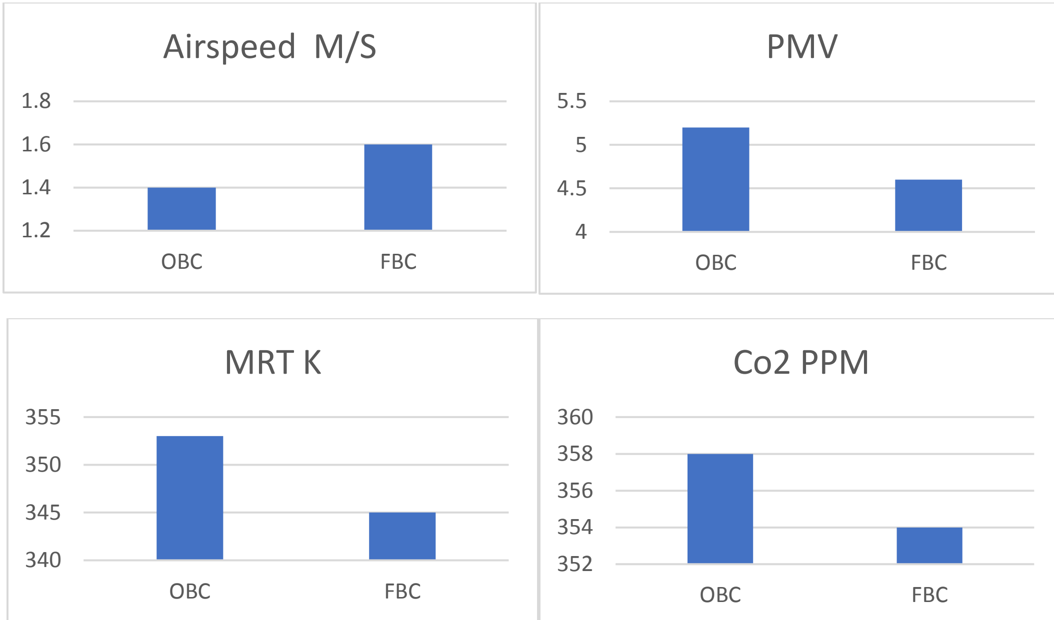


Fig.7.23. The average TA, RH, WS, PMV, MRT, and Co2 over the tested public square in the original base case and the final enhanced case

7.6. Conclusions

- In the enhancement process, the effectiveness of several passive measures in terms of outdoor thermal comfort and its weather parameters were quantified. Although, the quantification of the use of these measures did not achieve satisfactory results when compared against different comfort scales like relative humidity comfort scale, the predicted mean vote scale as well as other scales and standards., it emphasized the importance of using these measures when designing outdoor thermal. ***It can mitigate heat, MRT and CO2 and increase the relative humidity and thermal comfort sensation and emphasized the importance of using these measures when designing outdoor thermal.***

The enhancement process was conducted using the *Envi-met* CFD code. In general, the results showed that the overall average air temperature in the case study was improved by *2.3k* after the enhancement *Table 7.13.*

Table 7.14. The final enhanced case in contrast to different comfort scales acceptable in outdoor

Case name	TA (K)	RH (%)	WS (m/s)	PMV	MRT (K)	Co2 (PMM)
Final enhanced case (FEC)	302.5	37	1.6	4.6	345	354
Different Comfort levels	293.45-299.85	24.4-79.5	+ 2	0	299.85	100-1000

8.1. Conclusions and recommendations

- None of the available literature and studies attempted to test thoroughly all the weather parameters, design measures outdoor thermal index at central European public space of Pecs-city at any of their study sites and the researches since this field of study still very limited in Hungary as well as in central European countries. This gap in the body of knowledge was identified and was bridged in this research. Therefore, the first step of this work was identifying the research problem context, The research main aim and objectives as well as scope and limitations through a literature study
- Discussing the design measures and their parameters affecting the outdoor thermal comfort at different scale levels. which in turn, affects the performance of outdoor thermal. The author comprehensively classified and categorized them. However, this classification expresses these measures in order, starting from the largest scale down to the smallest scale. The measures are grouped under three levels; the macro-level, the intermediate-level as well as the micro-level.

To evaluate the outdoor thermal performance in the study site

- A survey approach of the outdoor thermal sensation has been employed to measure the predicted mean vote, air temperature, humidity, wind speed, as well as solar radiation. In an attempt to understand the voters' thermal sensation. The Author reached the result that the outdoor thermal sensation is uncomfortable. Almost two-thirds of the Participants felt uncomfortable ***(Paper I).***
- A detailed comparison of CFD software serving the scope of research was set out. The author established that among several microclimate simulation tools ENVI-met is capable of predicting and simulating the thermal comfort, meteorological parameters (airspeed, wind direction, air temperature, relative humidity, global solar radiation) as well as most of the design strategies in outdoor spaces. Therefor ENVI-met has been chosen as the most suitable tool ***(Paper II).***
- The complete and comprehensive validation for the model is generally not possible. No model can have an absolute validity it should be valid for the purpose for which it is constructed. The author proved that the results of simulation and questionnaire confirmed Envi-met's great reliability in predicting outdoor thermal sensation.

- A computer-aided tool was used to quantitatively investigate the outdoor thermal comfort and its weather parameters on the study site occupants in order to identify the climatic weather context issues to be addressed later in the next part. The author stated that on average 14:00 PM was recorded the highest very hot *rate 4* value. Furthermore, areas close to buildings and covered in shading and plantation have less temperature than other places of the square, water bodies play a significant role in mitigating the temperature and increasing the relative humidity value. Moreover, street design, shading, water bodies, as well as plantation play a critical role in increasing or decreasing the outdoor thermal comfort level and its parameters ***(Paper I).***
- To formulate the design measures and their parameters that could be used to improve the outdoor thermal comfort performance in the study site. The author has established the design measures and their parameters that are believed to have a positive impact on urban thermal comfort. Nonetheless, a list of possible measures for enhancing outdoor thermal performance was formulated.

To enhance outdoor thermal performance in the study site.

- The author proved that street orientation, canyon geometry, plantation-area ratio, water-area ratio, green roofs, green walls, as well as the pavement materials have a significant impact on the outdoor thermal performance. However, roof shape and heat transmission (U-value of the building) have negligible impact on the urban thermal comfort in this particular study area ***(Paper I).***
- During the study on the microclimate in PECS the author has Found that the proper street design (orientation and canyon geometry) can accelerate the air velocity and mitigate the air temperature in the summertime) which could affect the outdoor thermal satisfaction ***(Paper III)***.
- The author has established that applying the selected measures to the study site has significantly improved the air temperature, relative humidity, as well as the MRT by *2.3k*, -*2.8%*, *and 8k* respectively.
- The author has established that the most influential measures on the wind speed were street orientation and street geometry where larger building fabric became exposed to the flowing air, which support the use of natural ventilation and maximize its benefit ***(Paper III)***. Green roofs and walls as well have a great impact on the MRT and relative humidity. The *TA*,

RH, WS, PMV, MRT, and Co2 within the study site was slightly enhanced after applying the proposed measures.

- The author found that the water body has only a slight effect on increasing or decreasing the predicted mean vote and other weather parameters except on relative humidity and air temperature. Furthermore, the water element has a significant impact on air temperature and relative humidity within *1-2* meters distance from the water body. Moreover, the water body has a great effect on mean radiant temperature, the improvement of *7K*compared to the original base case was observed ***(Paper IV).***
- The author established that. although, the quantification of the use of the design measures and their parameters did not achieve satisfactory results when compared against different comfort scales like relative humidity comfort scale, the predicted mean vote scale as well as other scales and standards, ***it can mitigate heat, MRT and CO2 and increase the relative humidity and thermal comfort sensation and emphasized the importance of using these measures when designing outdoor thermal.***
- The author provides the designers and decision makers with a comprehensive framework for use in evaluating and predicting the effect of different design measures and their parameters in modifying the outdoor microclimate.

8.2. List of contributions

This research project has added many contributions to the body of knowledge in the environmental design of architectural field. These contributions could be listed as follows:

- Introducing a comprehensive classification for the design measures and their parameters that have an impact on outdoor thermal comfort performance to building design system that can help in central European countries;
- Identifying quantitatively and qualitatively the outdoor thermal performance in a moderately warm-wet climate zone and the problems associated with it ***(Paper I)***;
- Quantifying the effectiveness of the design measures on urban thermal performance at a central European public space ***(Paper III)***, ***(Paper IV).***
- Introducing practical environmental treatments for urban thermal design.

8.3. Proposal for further work

- Further research is needed to investigate and enhance the acoustics and lighting comfort levels in outdoor spaces.

- Further study is recommended in different climate zones especially in hot-dry zone
- Further investigation is required to quantify the effectiveness of site landform, heat sinks, building adjacency, as well as urban form
- At the moment, there are no specific outdoor thermal standards for designing environmental public spaces in Hungary. Considering developing a new version is essential for the future.

8.4. List of related papers to the field of study

The following relevant papers to the thesis topics:

I. Numerical evaluation of outdoor thermal comfort and weather parameters in summertime at széchenyi square, Pollack Periodica Journal, University of Pecs, Hungary.

II. An overview of microclimate tools for predicting the thermal comfort, meteorological parameters and design strategies in outdoor spaces, Pollack Periodica Journal, University of Pecs, Hungary.

III. Impact of street canyon geometry on outdoor thermal comfort and weather parameters in pécs, Pollack Periodica Journal, University of Pecs, Hungary.

IV. Water body effects on microclimate in summertime: a case study from PÉCS, Pollack Periodica Journal, University of Pecs, Hungary.

9.1. Appendix (A): The questionnaire's full results

Time	P 1	P2	P3	Metabolic rate	clothing Insulation
12.00	1	3	3	1.9	0.58
13.00	3	3	4	1.9	0.58
14.00	5	3	4	1.9	0.58
15.00	3	4	4	1.9	0.58
16.00	3	3	3	1.9	0.58
Mean	3	3.2	3.6	1.9	0.58

The PMV value at P1, P2, and P3 on
15-9-2018

Time	P 1	P2	P3	Metabolic rate	clothing Insulation
12.00	2	3	3	1.9	0.58
13.00	3	4	5	1.9	0.58
14.00	5	4	4	1.9	0.58
15.00	4	3	3	1.9	0.58
16.00	2	2	3	1.9	0.58
Mean	3.2	3.2	3.6	1.9	0.58

The PMV value at P1, P2, and P3 on
16-9-2018

9.2. Appendix (B): Weather data that used in the validation and modelling settings

Budapest Debrecen Győr Miskolc Pécs Szeged — Locations:

Pécs

2018	Hour	Min/ Max	Temp. [°C]	Precipitation [mm]	Cloudiness [%]	Wind Direction [degree]	Wind Speed [km/h]	Gust Speed [km/h]	Pressure [hPa]
September 13. Thursday	08:00	14	19	0.0	85	East	8	22	1017
	14:00	29	29	0.0	74	Northeast	8	19	1016
	20:00		20	0.0	77	Northeast	8	17	1015

Magyarországi települések - előrejelzés

Budapest Debrecen Győr Miskolc Pécs Szeged — Településválasztó:

Pécs

2018	Óra	Min/ Max	Hőm. [°C]	Csapadék [mm]	Felhőzet [%]	Átlagszél irány [tok]	Átlagszél sebesség [km/h]	Széllökés sebesség [km/h]	Lég-nyomás [hPa]
szeptember 14. péntek	08:00	17	18	0.0	68	keleti	5	18	1015
	14:00	28	28	0.0	78	északi	5	15	1015
	20:00		22	0.0	56	északi	11	23	1016
szeptember 15. szombat	02:00		19	0.7	63	északnyugati	11	24	1017
	08:00	17	18	0.0	26	északnyugati	12	27	1019
	14:00	26	26	0.0	11	északnyugati	7	30	1020
	20:00		20	0.0	8	északnyugati	8	14	1021
szeptember 16. vasárnap	02:00		17	0.0	16	északi	5	14	1023
	08:00	14	14	0.0	15	délkeleti	3	15	1025
	14:00	25	25	0.0	18	északkeleti	9	18	1024
	20:00		21	0.0	3	északkeleti	9	17	1023

9.3. Appendix (C): Subjective-objective comparison and tool validation settings

```
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Filebase name for Output (Text):                     =Széchenyi tér
Output Directory:                                    =[OUTPUT]
Start Simulation at Day (DD.MM.YYYY):                =13.09.2018
Start Simulation at Time (HH:MM:SS):                 =12:00:00
Total Simulation Time in Hours:                      =04.00
Save Model State each ? min                          =60
Wind Speed in 10 m ab. Ground [m/s]                  =3
Wind Direction (0:N..90:E..180:S..270:W..)           =23
Roughness Length z0 at Reference Point               =0.1
Initial Temperature Atmosphere [K]                   =297
Specific Humidity in 2500 m [g Water/kg air]         =7
Relative Humidity in 2m [%]                          =40
Database Plants                                      =[input]\Plants.dat

           ( -- End of Basic Data --)
           ( -- Following: Optional data. The order of sections is free. --
           ( -- Missing Sections will keep default data. --)
           ( Use "Add Section" in ConfigEditor to add more sections )
           ( Only use "=" in front of the final value, not in the descripti
           ( This file is created for ENVI-met V3.0 or better )
[PMV] _______________________________________________Settings for PMV-Calculation
Walking Speed (m/s)                                  =0.3
Energy-Exchange (Col. 2 M/A)                         =116
Mech. Factor                                         =0.0
Heattransfer resistance cloths                       =0.6
[BUILDING]__________________________________________Building properties
Inside Temperature [K]                               = 297
Heat Transmission Walls [W/m²K]                      =0.4
Heat Transmission Roofs [W/m²K]                      =0.2
Albedo Walls                                         =0.5
Albedo Roofs                                         =0.2
[CLOUDS] ____________________________________________
Fraction of LOW clouds (x/8)                        =0
Fraction of MEDIUM clouds (x/8)                     =0
Fraction of HIGH clouds (x/8)                       =0
```

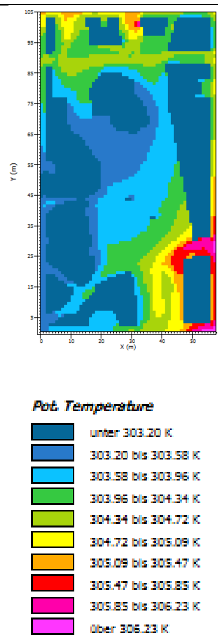
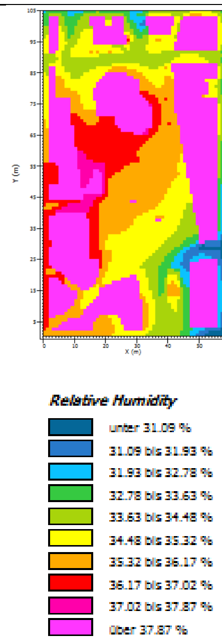
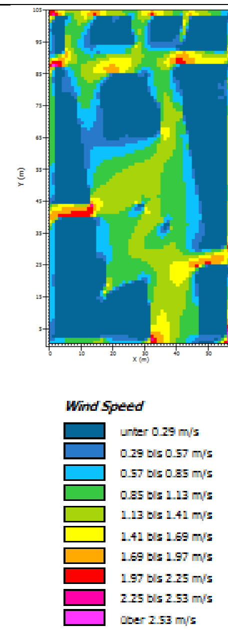
```
% ---- MAIN-DATA Block ---------------------------------------------------
Name for Simulation (Text):                      = Széchenyi tér
Input file Model Area                            =[INPUT]\Albdour.in
Filebase name for Output (Text):                 =Széchenyi tér 14
Output Directory:                                =[OUTPUT]
Start Simulation at Day (DD.MM.YYYY):            =14.09.2018
Start Simulation at Time (HH:MM:SS):             =12:00:00
Total Simulation Time in Hours:                  =04.00
Save Model State each ? min                      =60
Wind Speed in 10 m ab. Ground [m/s]              =3
Wind Direction (0:N..90:E..180:S..270:W..)       =162
Roughness Length z0 at Reference Point           =0.1
Initial Temperature Atmosphere [K]               =301
Specific Humidity in 2500 m [g Water/kg air]     =7
Relative Humidity in 2m [%]                      =42
Database Plants                                  =[input]\Plants.dat

         ( -- End of Basic Data --)
         ( -- Following: Optional data. The order of sections is free. --
         ( -- Missing Sections will keep default data. --)
         ( Use "Add Section" in ConfigEditor to add more sections )
         ( Only use "=" in front of the final value, not in the descript
         ( This file is created for ENVI-met V3.0 or better )
[PMV] _______________________________________Settings for PMV-Calculatio
Walking Speed (m/s)                              =0.3
Energy-Exchange (Col. 2 M/A)                     =116
Mech. Factor                                     =0.0
Heattransfer resistance cloths                   =0.6
[BUILDING]__________________________________Building properties
Inside Temperature [K]                           = 297
Heat Transmission Walls [W/m²K]                  =0.4
Heat Transmission Roofs [W/m²K]                  =0.2
Albedo Walls                                     =0.5
Albedo Roofs                                     =0.2
```

```
% ---- MAIN-DATA Block ---------------------------------------------------
Name for Simulation (Text):                      = Széchenyi tér
Input file Model Area                            =[INPUT]\Albdour.in
Filebase name for Output (Text):                 =Széchenyi tér 16
Output Directory:                                =[OUTPUT]
Start Simulation at Day (DD.MM.YYYY):            =16.09.2018
Start Simulation at Time (HH:MM:SS):             =12:00:00
Total Simulation Time in Hours:                  =04.00
Save Model State each ? min                      =60
Wind Speed in 10 m ab. Ground [m/s]              =3
Wind Direction (0:N..90:E..180:S..270:W..)       =64
Roughness Length z0 at Reference Point           =0.1
Initial Temperature Atmosphere [K]               =301
Specific Humidity in 2500 m [g Water/kg air]     =7
Relative Humidity in 2m [%]                      =42
Database Plants                                  =[input]\Plants.dat

         ( -- End of Basic Data --)
         ( -- Following: Optional data. The order of sections is free. --
         ( -- Missing Sections will keep default data. --)
         ( Use "Add Section" in ConfigEditor to add more sections )
         ( Only use "=" in front of the final value, not in the descripti
         ( This file is created for ENVI-met V3.0 or better )
[PMV] _______________________________________Settings for PMV-Calculation
Walking Speed (m/s)                              =0.3
Energy-Exchange (Col. 2 M/A)                     =116
Mech. Factor                                     =0.0
Heattransfer resistance cloths                   =0.6
[BUILDING]__________________________________Building properties
Inside Temperature [K]                           = 297
Heat Transmission Walls [W/m²K]                  =0.4
Heat Transmission Roofs [W/m²K]                  =0.2
Albedo Walls                                     =0.5
Albedo Roofs                                     =0.2
```

9.4. Appendix (D): Enhancement simulation cases' full results

<table>
<tr><th>Orientation</th><th>Temp</th><th>RH</th><th>Wind</th></tr>
<tr><td>45</td><td>
</td><td>
</td><td>
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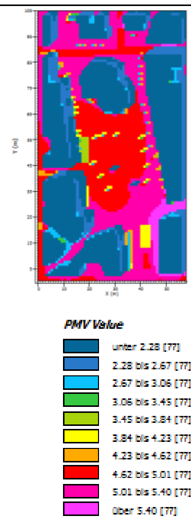
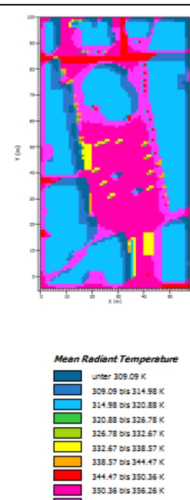
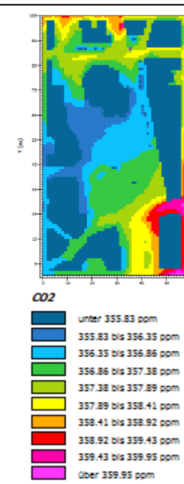
<tr><th>Orientation</th><th>PMV</th><th>TMRT</th><th>CO2</th></tr>
<tr><td>45</td><td>
</td><td>
</td><td>
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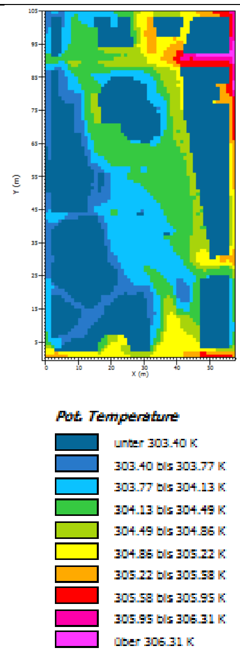
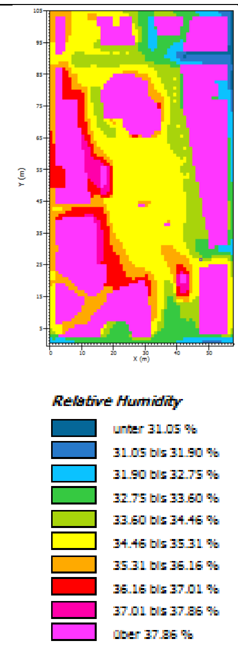
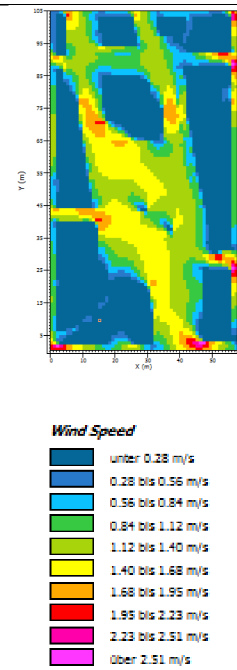
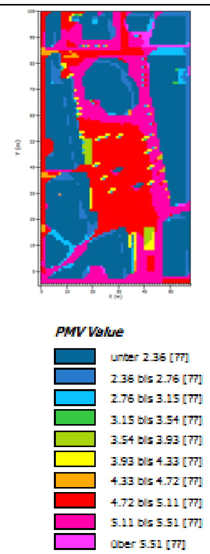
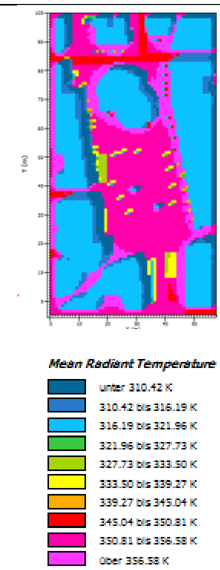
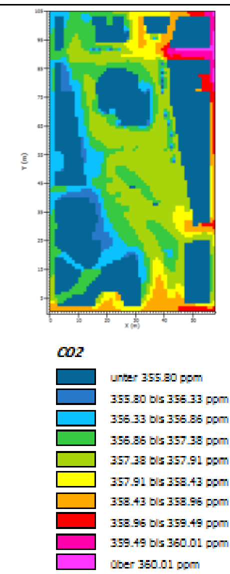
The mean Ta, RH, WS, PMV, MRT and Co2 in case (2)

Orientation	Temp	RH	Wind

<table>
<tr><td>135</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Orientation</td><td>PMV</td><td>TMRT</td><td>CO2</td></tr>
<tr><td>135</td><td>
</td><td>
</td><td>
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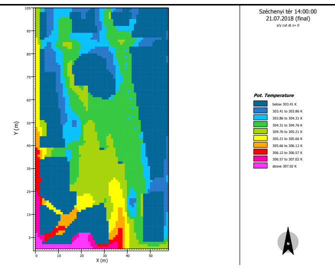
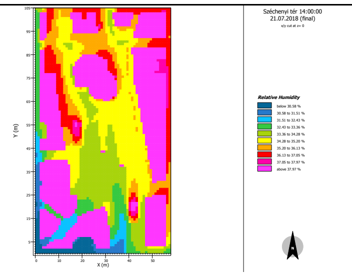
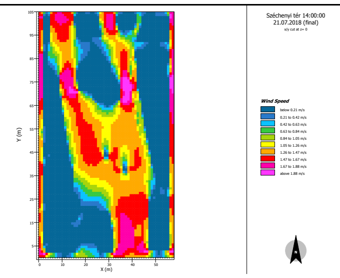
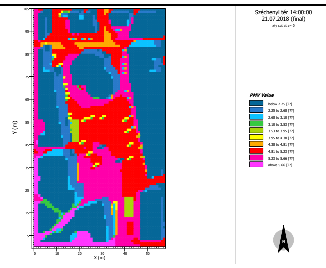
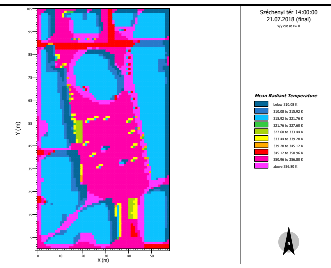
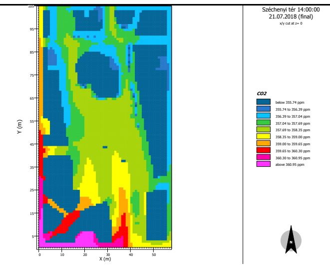
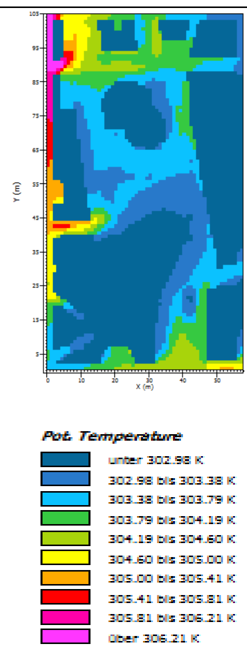
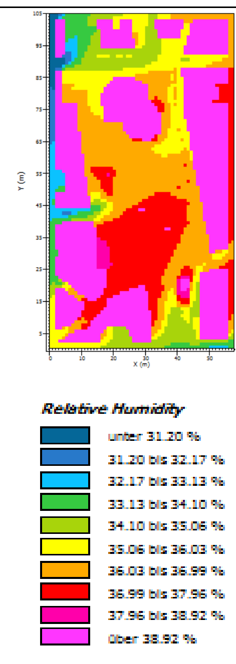
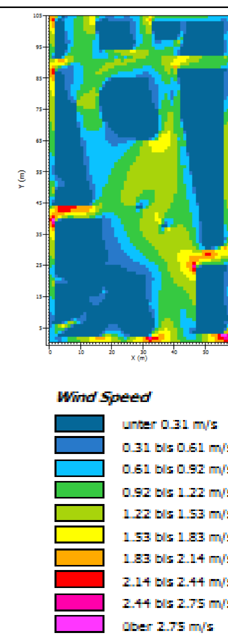
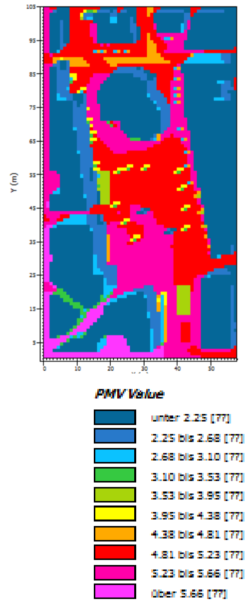
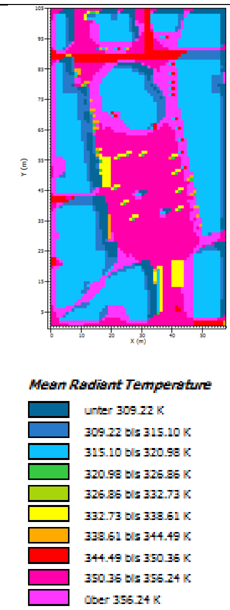
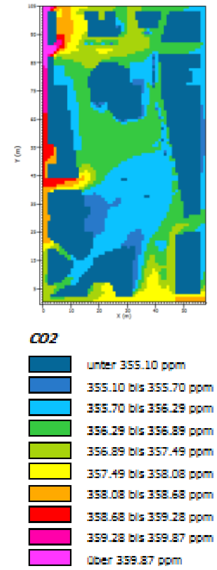
The mean Ta, RH, WS, PMV, MRT and Co2 in case (4)

Orientation	Temp	RH	Wind

180			
Orientation	PMV	TMRT	CO2
180			

The mean Ta, RH, WS, PMV, MRT and Co2 in case (5)

Orientation	Temp	RH	Wind
225			
Orientation	PMV	TMRT	CO2

<table>
<tr><td>225</td><td>
</td><td>
</td><td>
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The mean Ta, RH, WS, PMV, MRT and Co2 in case (6)

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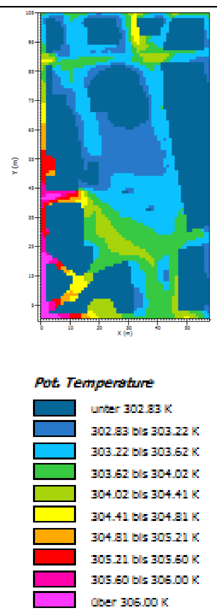
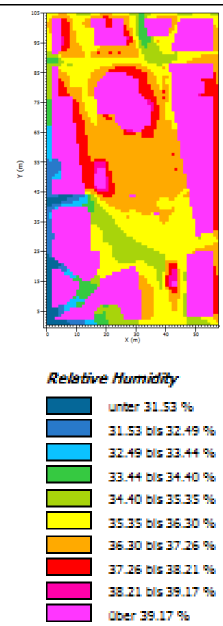
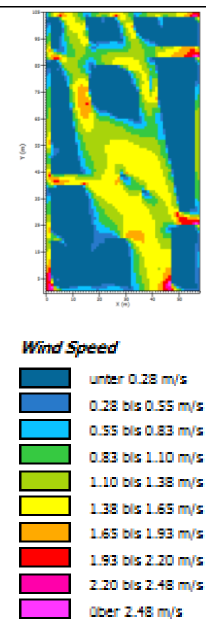
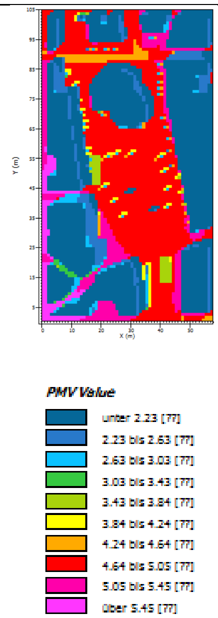
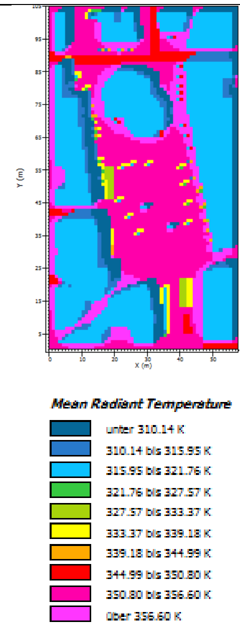
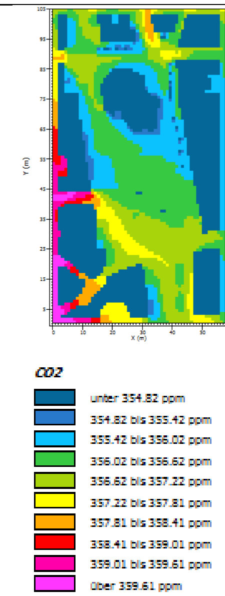
<tr><td>315</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Orientation</td><td>PMV</td><td>TMRT</td><td>CO2</td></tr>
</table>

<table>
<tr><td>315</td><td>
</td><td>
</td><td>
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The mean Ta, RH, WS, PMV, MRT and Co2 in case (8)

<table>
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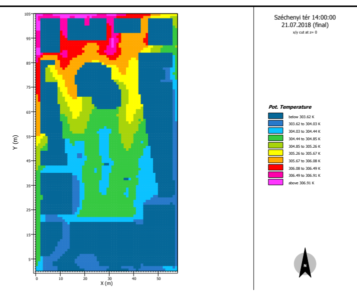
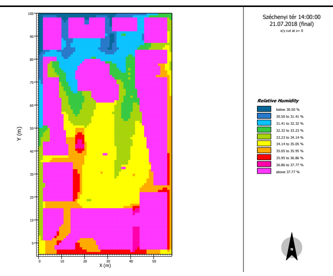
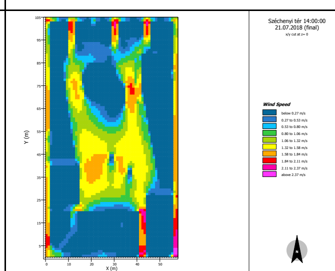
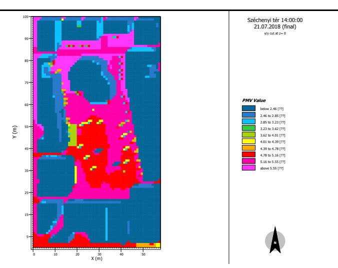
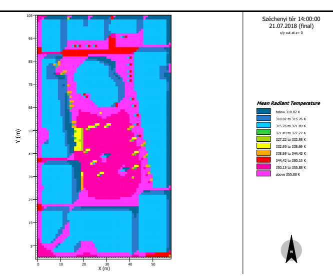
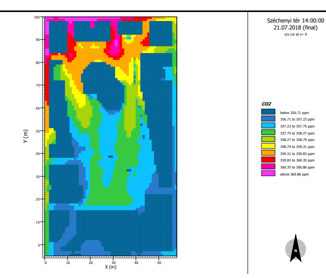
<tr><td>H/W 1.5

W=6.5</td><td></td><td></td><td></td></tr>
<tr><td>Canyon geometry</td><td>PMV</td><td>TMRT</td><td>CO2</td></tr>
<tr><td>H/W 1.5

W=6.5 m</td><td></td><td></td><td></td></tr>
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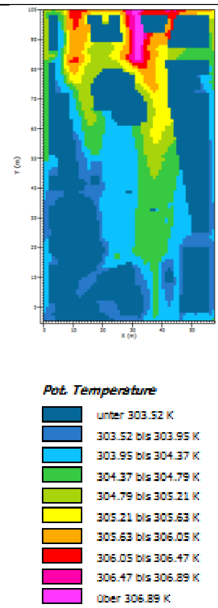
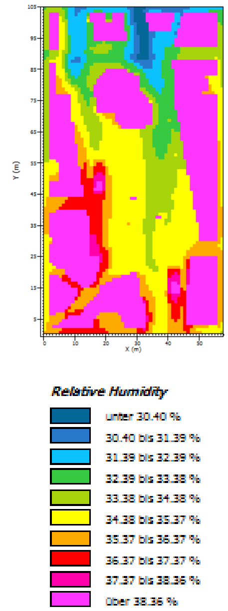
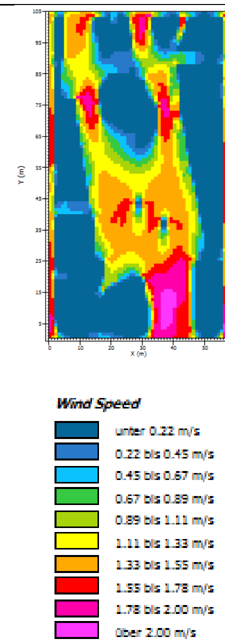
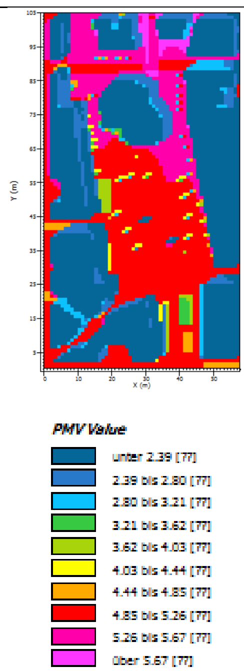
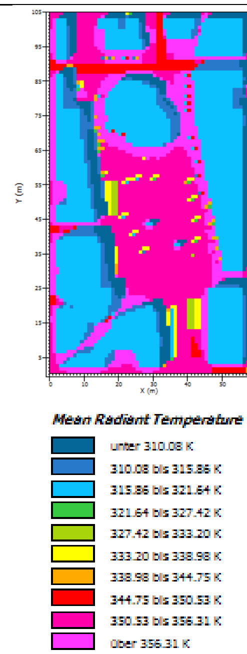
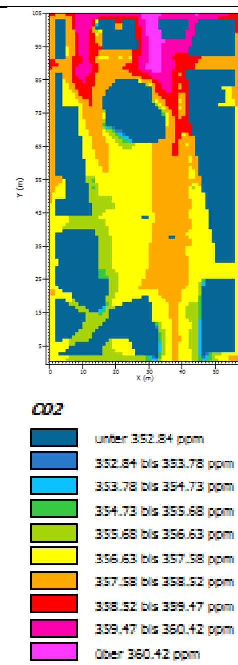
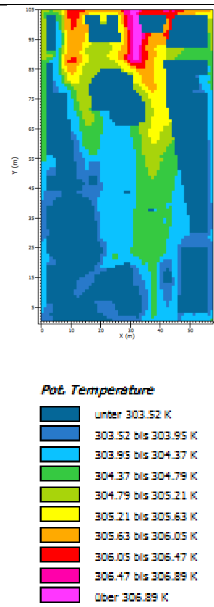
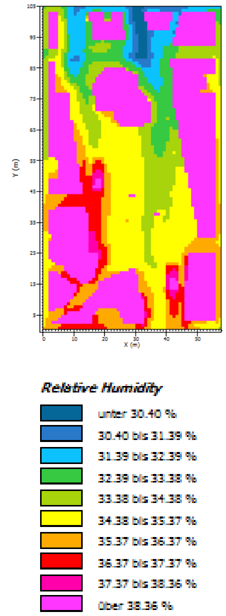
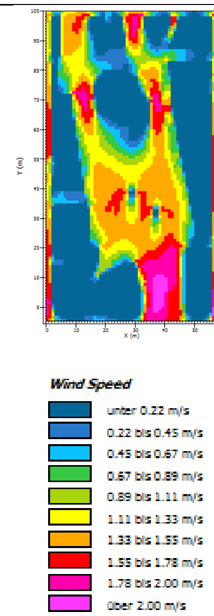
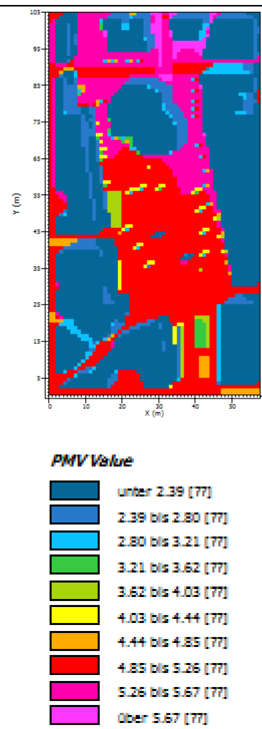
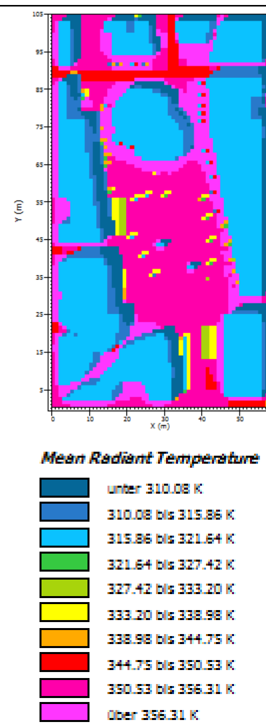
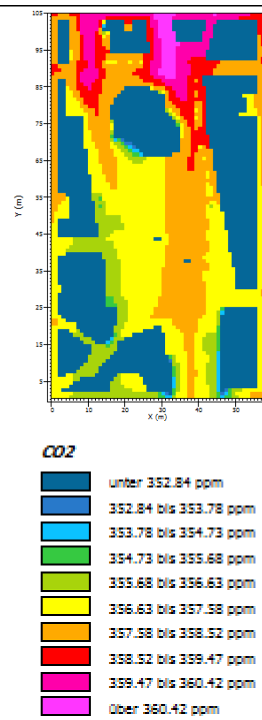
The mean Ta, RH, WS, PMV, MRT and Co2 in case (11)

Plantation (2M) 12%	Temp	RH	Wind
			
Plantation (2M) 12%	PMV	TMRT	CO2
			

Plantation (2M) 12%	Temp	RH	Wind
			
Plantation (2M) 12%	PMV	TMRT	CO2
			
Plantation (2M) 25%	Temp	RH	Wind

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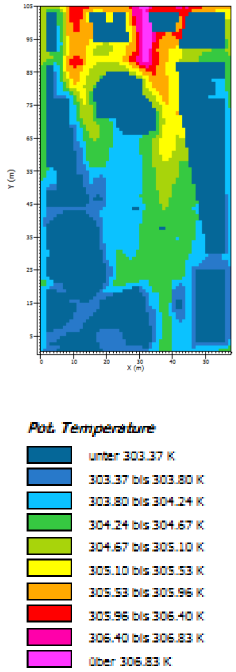
<td>
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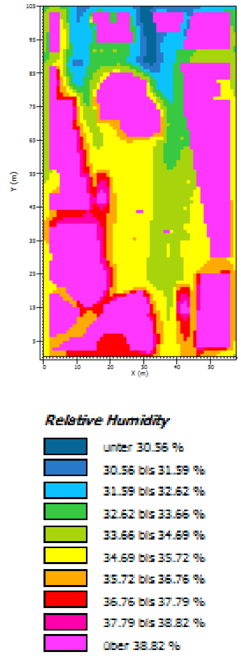
<td>
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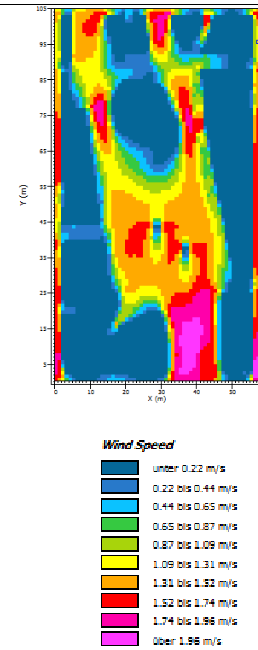
<td>
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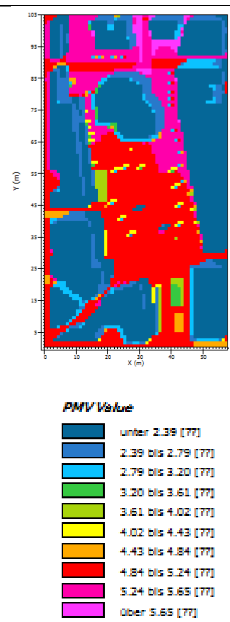
</tr>
<tr>
<td>Plantation (2M)
25%</td>
<td>PMV</td>
<td>TMRT</td>
<td>CO2</td>
</tr>
<tr>
<td></td>
<td>
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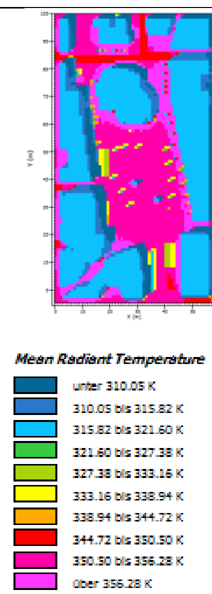
<td>
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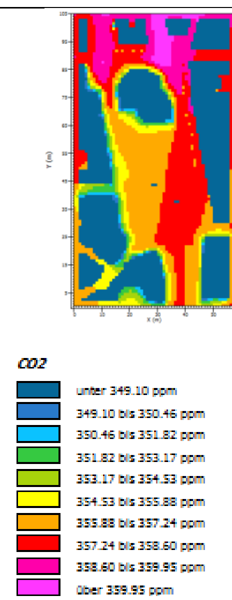
<td>
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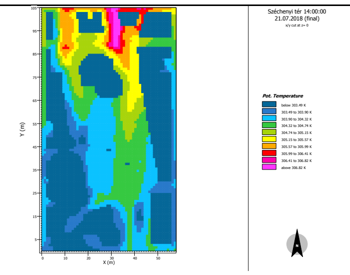
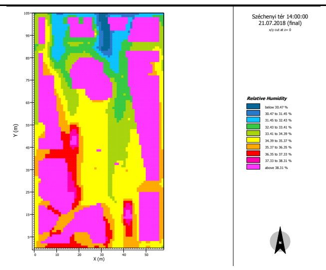
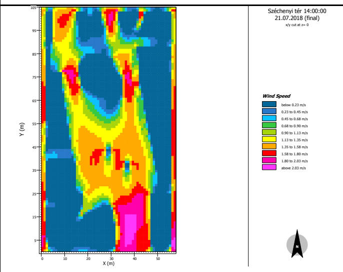
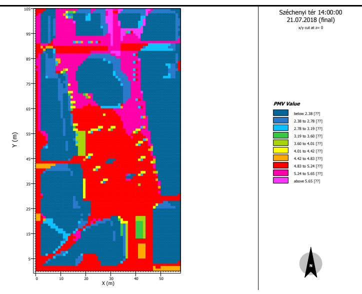
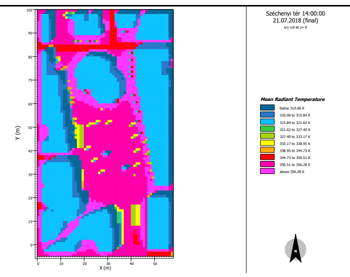
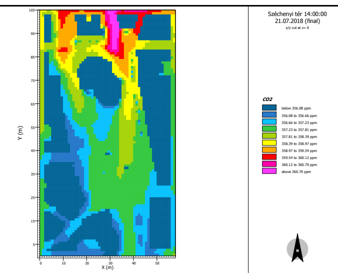
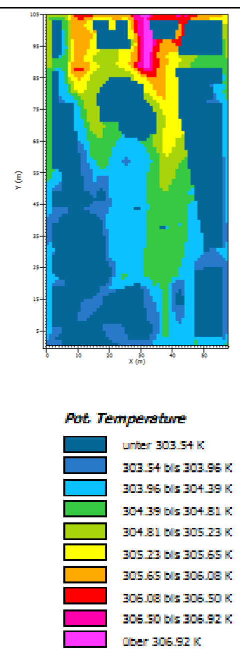
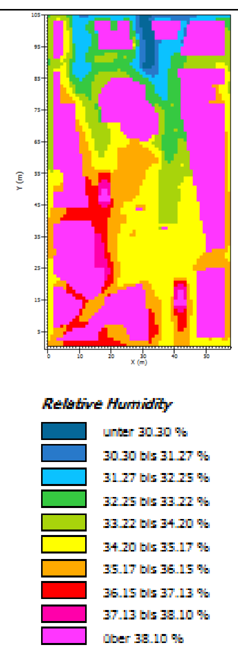
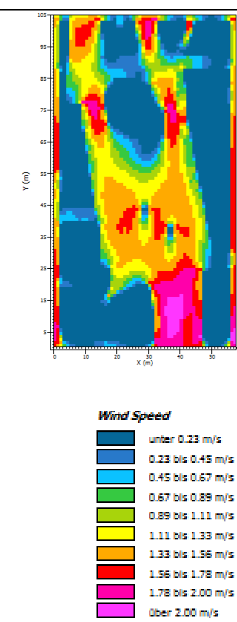
Plantation	Temp	RH	Wind
Dense district crown (10m) 12%			
Plantation	PMV	TMRT	CO2
Dense district crown (10m) 12%			

Water body	Temp	RH	Wind
6%			
Water body	PMV	TMRT	CO2

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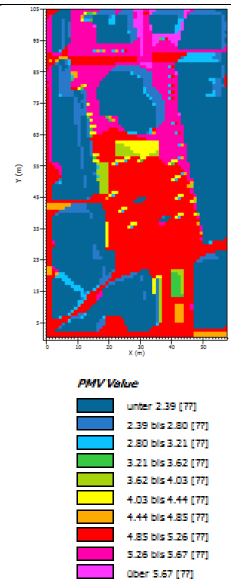
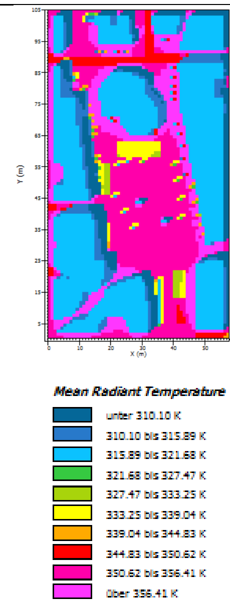
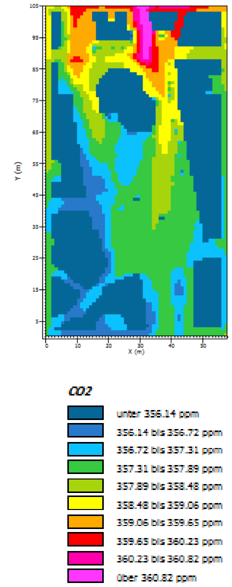
<tr><td>6%</td><td>
</td><td>
</td><td>
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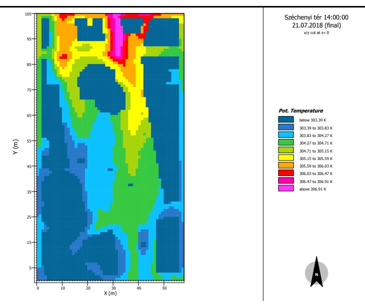
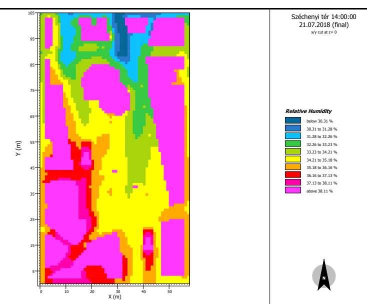
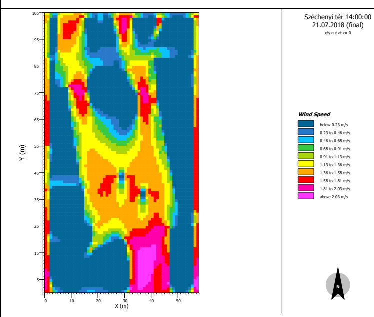
<table>
<tr><td>Green roofs</td><td>Temp</td><td>RH</td><td>Wind</td></tr>
<tr><td>50% of the whole roofs</td><td>
</td><td>
</td><td>
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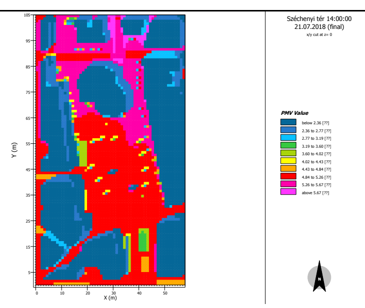
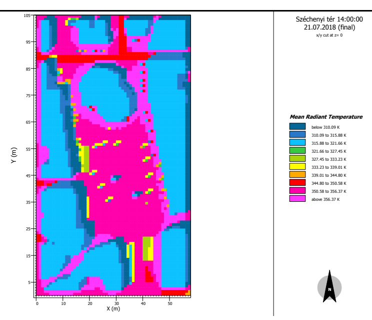
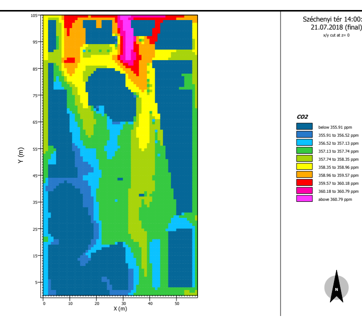
<tr><td>Green roofs</td><td>PMV</td><td>TMRT</td><td>CO2</td></tr>
<tr><td>50% of the whole roofs</td><td>
</td><td>
</td><td>
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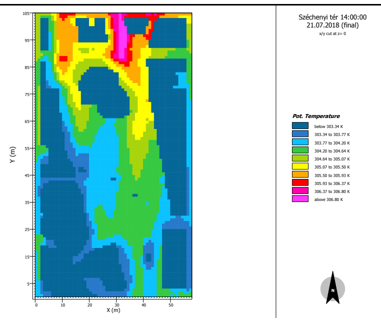
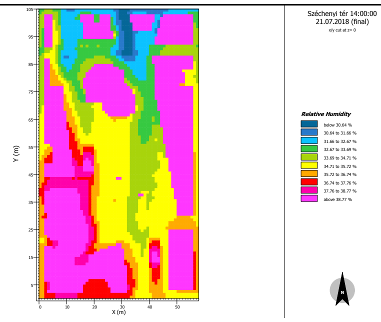
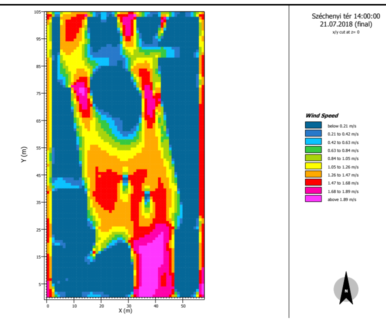
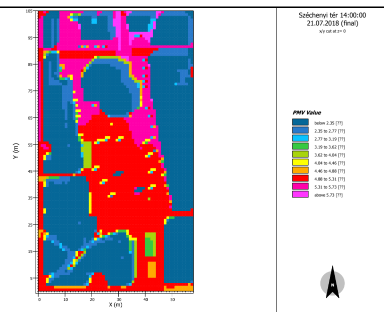
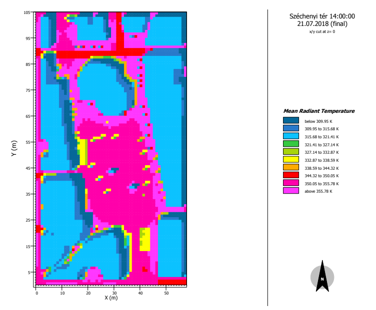
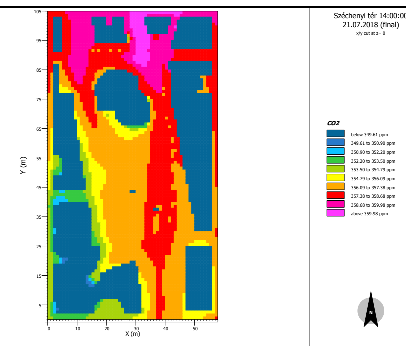
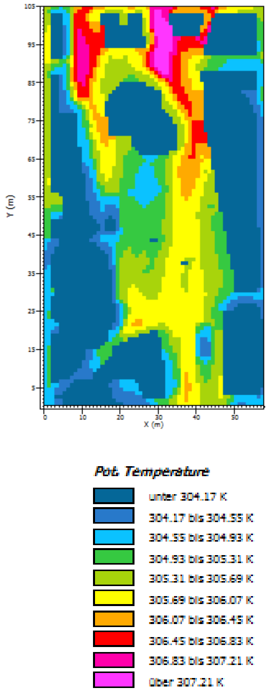
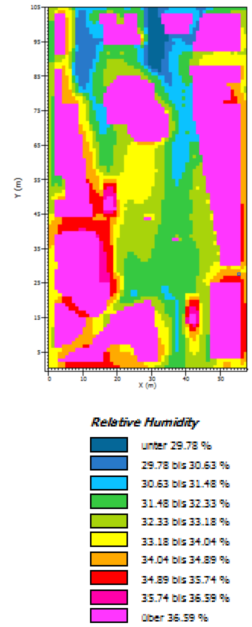
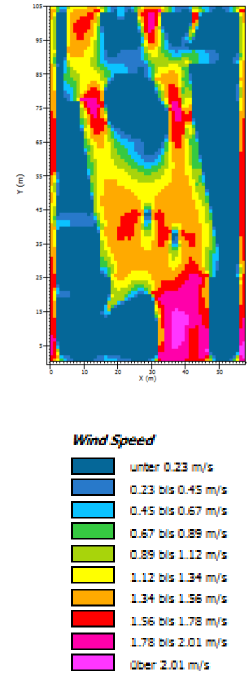
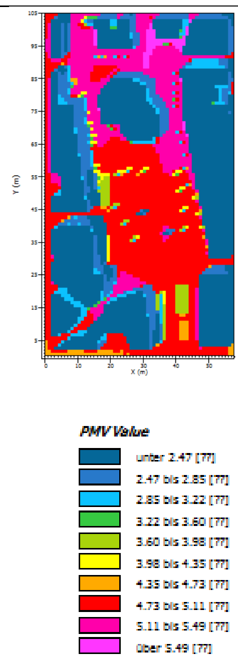
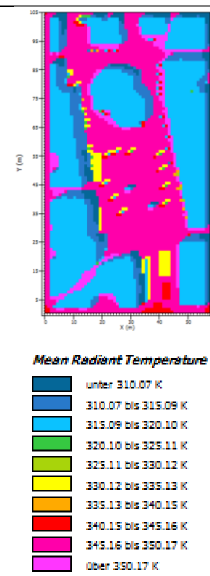
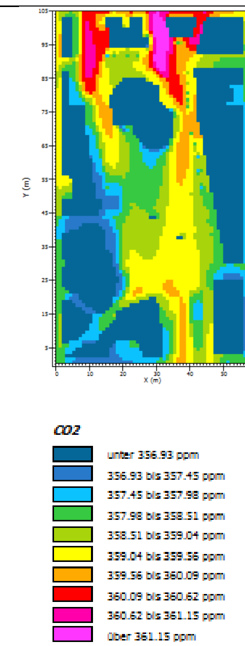
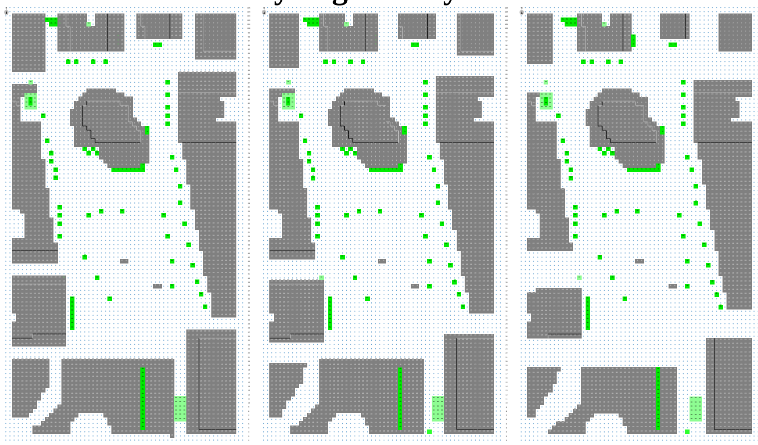
Green walls	Temp	RH	Wind
50%			
Green walls	PMV	TMRT	CO2
50%			

Albedo	Temp	RH	Wind

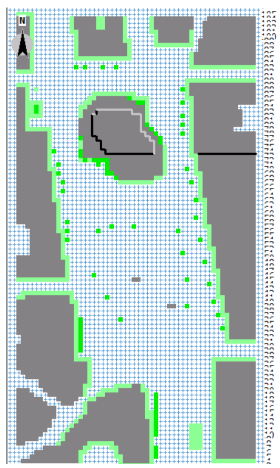
Paving Asphalt			
Albedo	PMV	TMRT	CO2
Paving Asphalt			

9.5. Appendix (E): Enhancement simulation models

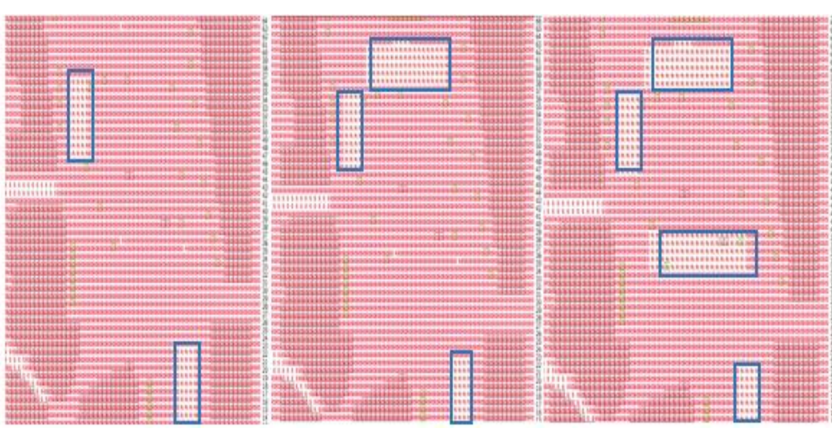
Canyon geometry models



Plantation model

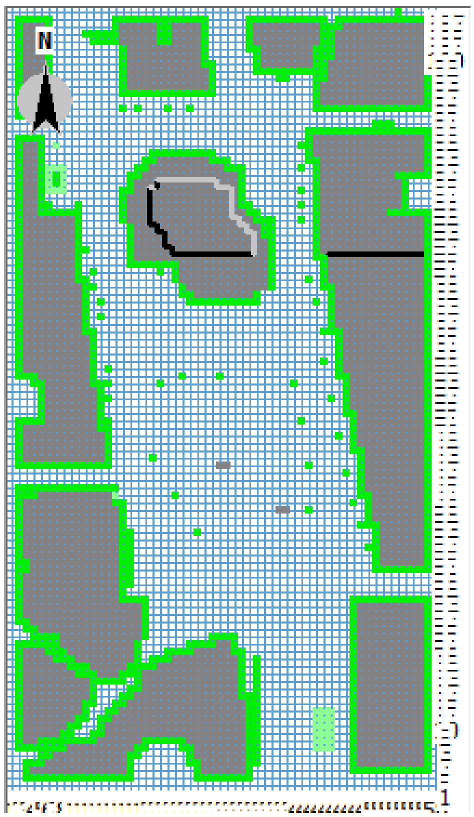


Waterbody models



Green roofs Model

Green walls model



Roof shape model