# The Impact of Bioclimatic Design on Ambient Air Temperature in Dubai Small Outdoor Urban Spaces

## تأثير التصميم الحيوي المناخي على درجة حرارة الهواء المحيط في الأماكن الحضرية الصغيرة في دبي


**By**

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## ABSTRACT

A bioclimatic design approach is based upon incorporating the microclimatic requirements into the design to achieve higher comfort levels and lower energy consumption. The purpose of this study was to investigate the cooling effect of selected bioclimatic parameters on the outdoor air temperature of an open space. Several variables that attested earlier to enhance the outdoor environments were examined mutually to attain the impact that passive design has on the outdoor air temperature.

The computer simulation was found to be the most suitable tool for investigation according to the resources available. Three variables were tested initially, orientation, geometry and vegetation where the coolest parameter of each was incorporated into one scenario named the enhanced scenario. Three scenarios named the existing scenario representing a specific site conditions, the enhanced scenario combining the coolest parameters and a worst case scenario combining the warmest parameters, were compared together and evaluated.

The SW-NE orientation, the highest geometry of a height to width (H:W) ratio of 4, groups of trees and continuous grass revealed to be the coolest parameters incorporated in the enhanced scenario. The enhanced scenario was compared to the worst case scenario based upon an EW orientation, 0.5 H:W ratio and no vegetation which recorded the highest temperature levels. The results revealed a slight improvement in the outdoor air temperature due to the bioclimatic principles applied. The comparative results show cased a slighter improvement between the enhanced scenario and the existing scenario representing the site conditions of Dubai Knowledge Village due to the incorporation of a few principles only. The results of temperature and wind patterns recorded had contributed to understanding several outdoor behaviors which are useful for guiding an ecological design for small outdoor urban spaces.

One main conclusion was the existence of a threshold to the size of bioclimatic applications for them to achieve a significant improvement yet, an improvement was possible. However, the behavior of the outdoor parameters remains quite complex and unpredictable that requires further investigation.

يستند تصميم النهج الحيوي المناخي على دمج متطلبات المناخ المحيط في التصميم لتحقيق أعلى مستويات من الراحة الفردية وانخفاض استهلاك الطاقة. الغرض من هذه الدراسة هي دراسة تأثير التبريد الحيوي المناخي من خلال معلمات المحددة في درجة حرارة الهواء الخارجي في الاماكن المفتوحة. تم فحص العديد من المتغيرات التي شهدت في وقت سابق في تعزيز البيئه الخارجيه على نحو متبادل لتحقيق الأثر الايجابي لهذا التصميم على درجة حرارة الهواء المحيط.

وجد ان برنامج المحاكاة هو الأداة المثلى لتحقيق الهدف وفقا للموارد المتاحة. في البداية تم اختبار ثلاثة متغيرات هم التوجه ، والهندسة, والنباتات حيث تأسست افضل العوامل من كل سيناريو ، في سيناريو واحدة سميه بالسيناريو المحسن. وتمت مقارنة ثلاثة سيناريوهات جنبا إلى جنب وتقييمها وهم السيناريو الحالي يمثل ظروف موقع معين ، والسيناريو المحسن الدي يجمع بين افضل العوامل والسيناريو الأسوأ حالة ويجمع بين اسوأ المعلمات.

وجد أن التوجه شمال شرق- جنوب غرب ، وهو أعلى نسبة هندسية بين العرض واللارتفاع 4 ، بالاضافة الى مجموعة من الأشجار والعشب المستمر ليكونوا افضل العوامل تم ادراجهم في السيناريو المحسن. وبالمقارنة بين السيناريو المحسن و السيناريو الأسوأ الدي بني على أساس التوجه شرق-غرب ، و نسبة عرض لارتفاع 0.5 وايضا بلا غطاء نباتي والتي سجلت أعلى مستويات درجة الحرارة. أظهرت النتائج وجود تحسن طفيف في درجة حرارة الهواء المحيط بسبب مبادئ النظام الحيوي المناخي المطبقة. نتائج المقارنة تظهر تحسنا طفيفا بين السيناريو المحسن والسيناريو القائم الدي يمثل موقع قرية المعرفة في دبي نظرا لإدراج عدد قليل من المبادئ فقط. اسهمت نتائج أنماط درجات الحرارة والرياح التي سجلت في فهم السلوكيات العديدة في الهواء الطلق التي هي مستغلة لتوجيه التصميم البيئي للمساحات الصغيرة في المناطق الحضرية في الهواء المحيط.

واحد من الاستنتاجات الرئيسية هو وجود عتبة لحجم التطبيقات الحيوية المناخية لقدرتها علي تحقيق تحسن ملحوظ حتى الآن ، ولاكنه ممكن. ومع ذلك ، فإن أنماط سلوك العوامل الخارجة في الهواء الطلق لا تزال معقدة جدا ولا يمكن التنبؤ بها بل تتطلب مزيدا من التحقيق.

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## NOMENCLATURE

| | |
|---|---|
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| AIA Florida | American Institute of Architects where its purpose is to highlight the architect's leading role in creating energy efficient environments and in leading the nation to a sustainable future. |
| CO2 | Carbon dioxide |
| Altitude | A solar angle indicates the sun height in the sky |
| Latitude | Location of a place on Earth north or south of the equator |
| Longitude | geographic coordinate of a place for east-west measurements |
| PMV | Physical Mean Vote |
| SVF | Sky View Factor |
| M/S | Meter per Second |
| K | Kelvin |
| Standard Deviation | It shows how much variation or there is from the average value |
| U Value | Coefficient of heat transfer; expressed as [W/m² K] |
| LEED | An internationally recognized green building certification system, providing third-party verification that a building or community was designed and built using strategies intended to improve performance in metrics such as energy savings, water efficiency, CO2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts. |
| Estidama | Abu Dhabi's Plan 2030 establishes a clear vision for sustainability as the foundation of any new development occurring in the Emirate and capital city of Abu Dhabi |
| Ecological foot print | A standard measurement of a unit’s influence on its habitat based on consumption and pollution |
| BREEAM | The world's foremost environmental assessment method and rating system for buildings |
| GLA | Great London’s Authority that aims to continuously improve its environmental performance, as far as resources allow through conserving energy, renewable energy techniques …etc. |

# CHAPTER 1: INTRODUCTION

## 1.2 The Sustainable Ecosystem

The steep economic crisis that struck the world in 2008 is considered to be one of the world's largest breakdowns in its history (Cecchetti, 2008). Supply and demand equilibrium has expectedly been lost in such a way that caused a domino effect throughout the whole system. The demand and supply mechanism depends on local market economic cycle as it is, needless to say that in today's economy all local markets are inter-dependent. It would be pretty naive to think that when a failure in one economic system occurs, it will not spill over across the globe, such is an inherent quality of the current system.

A successful system is a system that has a self sustainable cycle of inputs and outputs and is always able to sustain a balance within itself. Its goal is to never attain the critical levels of its own resources that would lead to its' decline. Not only the world's economy is based upon the concept of the systems cycle but everything in the world has a system within. The whole planet is based upon a natural ecosystem that is quite complex to sustain. The balance of the Earth's ecosystem is based upon an amount of inputs, which is the natural resources (supply) and an output, which is the consumption of these resources (demand) (Wright and Boorse, 2011). Human beings, as the consumers of the ecosystem, are now aware of the bond that links nations together, such a bond being the natural resources available on our planet earth. The depletion of any of the natural ecosystem's resources would corrupt the whole system and lead to an enormous recession within. Thus, a rescue attempt to all of the world's financial resources and especially the 'natural resources' requires more attention and dedication.

The environmental concern now makes headlines and is intertwined with other aspects of life and given such regard.  All businesses are now obliged through environmental laws to incorporate a procedure or two to their manufacturing processes, rendering them sustainable, it is the trend of the decade. Sustainability is no longer coupled with the need to deal responsibly with our immediate environment, the concept is really based upon living our present without compromising the needs of future generations and that should be the humanity's motivator. Living sustainably is the only way out to a better and more secure future albeit after 2008 crisis. A compromise between the use of natural resources and the consumption required for the world's progress needs to be managed properly within a sustainable development plan. To limit our footprints on this world we need to build, evolve and sprawl in a sustainable manner. To be realistic, stewardship –one of the sustainability basics- will never be applied unless fortified with considerable gains on both individual and governmental levels (Wright and Boorse, 2011).

## 1.3 Sustainable Urbanization

Cities were never the case of an empty space that requires planning from scratch. It is a matter of demand and supply. Buildings are found where people settle and people settle where resources are located. This cycle of demand and supply if left naturally usually evolves into what is called ‘urbanization’. The expansion and existence of such forms is always accompanied with errors, such errors can be re-oriented in some cases and in others is a fact that can only be ‘cosmeticized’. Here comes the role of sustainable urban planning which is to set the guidelines for any growth that is to follow. Environmental designs are those that create spaces to satisfy its inhabitants without having to compromise the natural resources available. Building for the future is quite a complex issue because it is based on predicting unknown variables. The higher the number of known parameters of a project definitely raises the possibilities of its success. Tremendous efforts are being made to attempt to predict the future living requirements; however this exercise of expectations has proven to be somewhat inaccurate.

The evolution of urban design through the decades has proved that no specific urban morphology is appropriate for application everywhere. The givens of an urban area have to be arranged in a way to cater to this specific location. The harmony created between solids and voids in an urban design process is extremely essential and liable for the essence of the public realm. Open spaces should merge buildings and structures together, while buildings should accentuate and emphasize these spaces. The interaction between the solid and the void, the building and the space, the indoor and the outdoor has always been a pivotal point for the urban designers. Experiencing successful outdoor spaces and considering how dramatic a space is able to change its surroundings is a dominant aspect that requires great attention. The way people lived ages ago was deduced from the way their cities where organized and built. It emphasized their power, knowledge, and the levels of social interaction of such groups. Through our current cities and the way they are set future generations are to predict such concepts like the need for individual dominance, non-ecological use of materials and deteriorated social relations. We need to convey a better message for the future generations through the vast urbanization processes taking place now. The initiatives towards ‘zero carbon’ cities in several parts of the world are considered to be the first step for achieving a sustainable future such as ‘Masdar City’ in the United Arab Emirates (UAE).

### 1.4 Research Potentials and Limitations

In the twentieth century, Dubai (an emirate/state in the UAE) has become one of the dominant cities, not only in the Middle East but in the world. The city's effort was directed towards booming its financial status to the peak rapidly. Dubai has been trying hard to gain a good reputation rather than being a typical city in this part of the world. The application of ecological principles has become a must in many major projects not only in the city but for the whole country. The UAE is now having its own local rating systems in terms of fulfilling sustainable goals such as ‘Estidama’. These rating systems are there to regulate and direct the massive urbanization move within the UAE.

The urbanization process discussed previously was one of the issues that face a lot of challenges in Dubai. The dilemma between open spaces and built forms in such climate needs further studies to be able to achieve more livable spaces. One of the monument defects in their master plans is that they lack the presence of ‘social spaces’ rather than just being ‘open spaces’. Social spaces are simply inhabited and livable open spaces. There are two dimensions that are interrelated within the existence of an open space; one is the physical place while the other is the human factor. Cities need to create more ecological open spaces that consider the human parameter with all its psychological needs rather than its physiological ones. A successful open space attracts the users to revive the space thus influencing it surrounding. Viewing the city from your car window, which is the typical case in Dubai, is much more pleasant than having a walk around its streets. It is clearly evident that most of the city's design lacked the human factor during early design stages especially when looking at the open spaces. For open spaces to be successful and satisfy its purpose there need to be a set of design guidelines for the designers to follow in order to achieve the users comfort either psychological or physiological. The design of the open spaces needs an 'electrical shock' to be revived and that is the ecological dimension.

There is no doubt that Dubai's climate is very challenging for all designers and urban planners. Dubai has a hot arid climate where it's quite tough to use the outdoors during half the year. It's fairly difficult to provide solutions especially when dealing with the outdoor environment. Yet, dealing with hot arid climate has the advantage of not having to provide solutions for extreme weather conditions. Climates with extreme warm conditions in summer and extreme cold conditions in winter are much more difficult to solve and require innovative solutions. A warm humid environment requires deep solutions in summer rather than having to provide them in winter where the air temperature in similar cities as Dubai is already within the thermal comfort range of an individual. The green design of the outdoor spaces is based on several criteria that need to be prioritized above all other factors.

As the case of any field, the environmental concern is still being considered a new product in the market. The limitations urban designers and architects face when designing ecological are still huge compared with the targets required to fulfill. Tools vary between instruments that measure existing values, social surveys, experiments and last but not least computer simulations. Each tool has its advantages and its disadvantages that make it better than the other in particular cases. The main advantage of computer simulations is that they are suitable for studies that are based on limited time and financial resources which is the case of this study. A computer simulation imitates the real case scenario that allows the researcher to manipulate their controlled environment to achieve their objectives. The idea of controlling the variables of a project is to be able to test them prior to the construction phase assuring the quality of the end product. In this manner the software available is considered to be limited in terms of understanding most of the parameters of an outdoor environment.

Outdoor environments are more challenging than indoor environments due to the uncontrollable findings that may affect accuracy of results. The more accurate the imitation process a simulation can achieve compared to the existing environment the more valid are its outcomes. In this study the Envi-MET software is chosen as the simulation tool to measure the changes of the ambient air temperature according to the applied principles and design recommendations. The main advantage of this specific tool is that it understands most of the parameters of the outdoor environment and their complex behaviour (Kevin, 2002). A comparison matrix will be provided based upon the set of variables available in the outdoor spaces and the concepts of bioclimatic design.

## 1.5 Bioclimatic Design

A bioclimatic approach for design is based upon integrating the microclimatic factors surrounding a building or a space to minimize the energy consumption on various levels and enhance the comfort conditions of an individual within such space (Center for Renewable Energy Sources and Savings, 2010). The word bioclimatic is derived from 'bio' as biological factors of the human parameter and 'climatic' which is the climate of the surrounding building or structure (Wikipedia, 2010). Passive design is considered to be one of the techniques used to achieve a bioclimatic design. A bioclimatic approach encompasses energy conservation, thermal/visual comfort, economic benefits, environmental benefits and social benefits. Following the principles of such approach would facilitate and perhaps guarantee arriving at the previously mentioned benefits leading to a sustainable nourished future.

Achieving a bioclimatic approach for the design of outdoor spaces primarily depends on a deep understanding of all the parameters of the surrounding natural environment. Two factors need to be considered regarding a green design initiative; the natural factor such as the microclimate of the space and the man-made factor which is the urban setting surrounding the space. Both of these two factors are responsible for achieving a passive design (Gaitani et. al., 2005).

## 1.6 Thermal Comfort

Human thermal comfort is defined by ASHRAE as the state of mind that expresses satisfaction with the surrounding environment (ANSI/ASHRAE Standard 55). The surrounding environment represented in the form of structures and spaces are the evolution of the human basic need for shelter to protect him/her from the natural environment. Attempts to create controlled environments to achieve the human comfort sensation have yet to be successful, as they have proven to be a challenge thus far. The current attempt by several studies is to help humans control their natural environment rather than creating rigid structures that create more problems. Such control has created needs that need to be ethically oriented and save our natural resources.

Human thermal comfort level is simply the zone where an individual achieves a comfortable thermal sensation due to several factors set by earlier scientists. The physical parameters that achieve the thermal comfort sensation are the ambient air temperature, the air velocity, the relative humidity and mean radiant temperature. The psychometric chart is a graphical representation to these parameters that can clearly indicate the comfort range depending on the climatic zone. Tools that measure the thermal comfort levels always depend upon the input of the psychometric chart as a baseline to be compared with. There are other external parameters also affecting the thermal comfort levels of an individual which are the activity levels and clothing. Researchers found that a variety of psychological factors as well as physiological factors compliment to achieve the desired comfort zone. Any factor that affects human thermal sensation within any space depends on the type of activity that a person is doing, their clothing, their expectation of the weather conditions prior to their exposure, as well as many other psychological factors. The lifestyle of a person directly affects their comfort sensation as well. In Dubai, all activities are based upon the presence of artificial cooling which makes the expectations of the city's inhabitants for the comfort ranges much higher (Nikolopoulou et. al., 2001). Thus, a balance between all parameters has to be achieved to obtain the optimum results for the thermal comfort levels. The present study's concern is to minimize the ambient air temperature levels that contribute to the enhancement of the overall thermal sensation.

## 1.7 Outdoor Open Spaces

Marylyn (1975) defines an open space in these terms… "An open space is land and/or water area with its surface open to the sky, consciously acquired or publicly regulated to serve conservation and urban shaping function in addition to providing recreational opportunities" (Marlyn, 1975). People abandoned open spaces as part of the modern lifestyle as they became more dependent on cars for daily transport, yet the value of open spaces remains to be self-evident. Open spaces indicate the viability of cities and enhance the need for social interaction which reflects the urban blight of its surrounding.

Throughout history, urban squares played a major role in locating various functions primarily taking place at the intersections of main trading routes. Trading was the main activity that reveals economical, political and cultural coherence and revived ancient societies (Madanipour, 2000). Greek Agora and the Roman Forum are amongst the forms of the ancient marketplace. Spatial closure of the squares was formed by civic, religious and commercial buildings in addition to the landscape features. For more accentuation of the spaces, colonnades, fountains or statues were placed based upon geometrical studies (Morris, 1994). As the modernity took place, this beautiful relationship between a public space and its surroundings started to disappear gradually (Nazl and Ashraf, 2008). Morris (1997) points out that countries had different naming for such spaces, in Europe and specifically Britain the term 'square' was used for enclosed open spaces whereas Italy and France used 'piazza' and 'place' respectively. Cultures have disagreed upon the naming of the open spaces yet they all agreed it to make it a versatile component of the urban fabric (Nazl and Ashraf, 2008).

London is one of the historical leaders in public spaces known as 'squares' (Lawrence, 1991) and remains one of the greenest capitals of the world. The rapid urbanization development and the rural migration to the city indicated the need for public areas people use to have some relief. These public areas were initially private gardens owned by wealthy people and rulers that were later opened to the public (Taylor, 1995). People's lifestyles started evolving all over the world with the presence of public spaces whereas social cohesion was apparent especially in the British society.

In the 1890s and 1900s the American movement “City Beautiful” supported the concept of public open spaces (Roberts, 1970). Segmentation of the open spaces was taking place till the 1990s and a cycle of privatization and transformations similar to that of London’s continued for several years. Modernity has its needs and amongst them the need for public spaces that are developed in forms and functions specifying the purpose of each. Incentive bonuses were offered to developers for including plazas within their designs (for each square foot of open space they would give to the public, they would gain 10 ft2 of extra floor space above the normally permitted) which contributed significantly to the expansion of theses spaces in New York in 1972 (Whyte, 1980).

The awareness of people of the value of quality in urban spaces increased in San Francisco whereas city dwellers were interested in spaces that provided sun sheds and wind protection in the new developments (Bosselmann et al., 1988). Later, cities started exploring the incorporation of open spaces within their planning stages. Some cities with no history for such spaces had an influential role in outdoor urban planning. Today places like Scandinavia have a proliferation of urban open spaces advocating the physical and microclimatic factors within the design process to create livable spaces (Jan, 2007).

The presence of open spaces in a master plan widely depends upon the design and the requirements of each district. Over the past decade, as clients were in search for urban icons it became a trend to create ‘anti-contextual’ buildings that are totally divorced from their surroundings and that makes them unique in their own manner. These icons are located within the existing urban setting without any consideration to their surroundings. The gaps ‘left-over spaces’ created in between these buildings are usually the open spaces within the district and are sometimes called negative spaces. This open space goes into a digestive process to transform it to a livable urban space, depleting a lot of resources in the process. Urban design process has a lot substantive dimensions to focus on. Undoubtedly, yet to create a well designed master plan it has to follow a sequential process that targets the sustainable goals set prior to the design process.

The perception of people of an outdoor space depends on several factors valid within the space. The components of the space such as trees might make people more comfortable to inhabit it. The value of greenery on people’s psychological comfort is self evident;

people usually seek parks and vast spaces with pleasant views on weekends to relax after a tough work load. Air quality and noise is another factor that plays a major role as well on peoples comfort within an outdoor space. The excess of the amount of health hazards in our cities nowadays needs quick treatments especially in outdoor open spaces.

Several attempts have been made to classify outdoor urban spaces. The criteria of these classifications vary depending on several aspects. Some researchers have classified spaces according to their functions or purpose of the space. The purpose of the space vary, some are for health and fitness purposes while others are for social interaction and recreational purposes. Spaces can also be used by people on a daily basis for work purposes such as buying and selling products which also influences these users perception of the spaces. Other researchers have classified spaces based upon their boundaries i.e. enclosed or semi-enclosed spaces, human scale or spaces that are vast to intimacy. The scale of the space boundaries and the surface are of it has a direct impact on users' behavior within. People tend to feel more comfortable in spaces that are proportional to their scale yet open and spacious. Trancik has classified the open spaces into spaces that are legible, complex or coherent spaces. His ideas basically arose from a landscape perspective where he represented the space boundaries as vegetation rather than being buildings but the concept can still apply to all types of spaces. The present study is basically concerned with the bioclimatic design of open spaces generally. The case of Dubai International Academic City (DIAC) has been chosen as the location conducting the analysis. The reason for such location is explained thoroughly in Chapter (3).

## 1.8 Open Spaces in Dubai

Overlooking the city of Dubai is an interesting exploration especially after the city rapidly positioned itself within the world as a vibrant business hub. The city's urbanization has been formed in fifty years going through several crucial stages such as pre-industrial to industrial and post-industrial stages, which is considered to be an excessively short period (Pacione, 2005). The growth of the city mainly focused upon iconic architectural structures such as Burj al Arab and the mega scale projects such as palm Jumeirah and Burj Dubai (Kubat et al., 2009). Recent directions have been against the formation of the city rapidly; nevertheless Dubai has succeeded in fulfilling its goal of domination within the world's business and touristic centers. The city reflects a wide range of cultures and nationalities creating a 'mix cultured city'. Parker (2005) explained that Dubai is frequently described as a city without character, lacking any identity. He argued the rapid urban formation of the city might not be 'real' for a start wondering how it can look like in 50 years time.

Open spaces within the city somehow mediate the relationship between the social and financial needs of its inhabitants creating a life which is full of activity. The government has put a huge effort to attain an eventful city by accommodating periodical shopping festivals, educational activities and international business events that make the city livable and equitable to its dwellers. Several attempts were made to create ecological urban settlements and green buildings. LEED and BREAM, are international environmental systems being used by developers along with ISTIDAMA as the local version fulfilling the sustainable goals. The 'green' concept is now adopted by city governors, developers, designers and city dwellers considerably to place the city on the global environmental trend map.

If you sustain an observing eye upon Dubai's urban master plan it is remarkable that the city has been following the concept of creating 'city within the city' in several parts (El Sheshtawy, 2007). The urban practice of creating smaller urban cities within the main city can be considered as a useful application to urban diversity. Although the application of smaller cities requires a critical layering of sub-services that interconnects smoothly to the main grid, yet if achieved properly would be advantageous. Dubai has a diverse urban configuration that does not necessarily exist in harmony consequently leaving its inhabitants with a sense of not belonging in most cases.

Urban outdoor spaces within Dubai can be considered to go through a cycle of 'life and death' throughout the year. A period where the beautiful outdoor spaces all over the city are heavily occupied is when the climatic conditions are within the average comfort levels. During summer time the outdoor spaces are totally deserted. Through the reduction of the outdoor air temperatures and enhancing the thermal comfort levels, the life span of the outdoor city life can be extended. Bioclimatic design is aimed at reviving the outdoor spaces of the city of Dubai throughout the year through comfort achievement.

Jumeirah Beach Residence known as ‘JBR’ is considered one the most successful examples of Dubai’s public spaces that needs to be applied in several locations. Other open spaces that the users also enjoy are ‘Marina Walk’ and ‘Madinet Jumeirah’ which creates beautiful spots for commercial and social activities with a different theme than JBR's. Shopping malls are a dominant feature of the city that locates various activities within. Through observation, it is apparent that recent malls built in the city have all created outdoor spaces that deserve much attention. Outdoor spaces accommodating restaurants and cafes accentuated by water fountains located on manmade lakes are applicable in ‘Dubai Mall’, ‘Marina Mall’ and ‘Mirdiff City Center’ which were all built after 2003. The way these outdoor spaces are articulated merging different activities and users in sequential pleasant environment is considered a successful practice. The attentiveness of Dubai to the importance of outdoor public spaces recently is growing adjacently with its developments. Open spaces are now seen within the residential, educational and business compounds as well.

Transit spaces are mediating spaces between buildings, activities or structures that people use for a short time when compared to the urban open spaces concerned by this study. The usability of the open spaces in Dubai is pretty high between December and March due to the climatic conditions of the city. Extending the usable duration of the city users to these spaces can be achieved by enhancing the comfort zone within. Offering the guidelines that can improve the air temperature of theses spaces will serve the sustainable development of the UAE. However, not only new designs are to incorporate such guidelines but also existing spaces should be revisited and potential measures taken to improve their ecological footprint of Dubai.

## 1.9 Future Benefits and Purpose of the Study

The aim of this study is to provide the urban designers and architects with a detailed investigation about some of the outdoor parameters that help to improve the microclimate in an arid climate. The paper assumes that the application of bioclimatic design precautions would enhance the outdoor air temperature of small urban spaces but the query was to which extent is that possible. The investigation incorporate several variables such as orientation, geometry and vegetation into various scenarios to check whether a significant cooling effect took place. Based upon the investigated parameters reviewed, a holistic view of the major outdoor parameters was made clarifying the relationship between them and the reasons for their behavior. Environmental guidelines concluded finally were also represented. The idea of presenting such solutions is considered vastly beneficial especially for environmental researchers.

In Dubai, urban planning and urban design authorities will be able to develop their environmental goals of having a sustainable future by implementing the recommendations and guidelines presented while prevention of concepts that contribute to raise the discomfort levels. Awareness of such principles is beneficial not only to the city's authorities but will also aid developers within UAE as well. Projects could achieve higher benefits due to cooling savings that can be implemented. On a wider scale, the study represents a hot arid climate where implementations can be expanded in similar climatic conditions. The gulf region has similar climatic characteristics and is also considered to have a rapid rate of urban configurations evolution. Since the scope of this research is about small open spaces, therefore the bioclimatic principles could even be applied on a community level. Observations and knowledge from the current investigation about the outdoor parameters, their impact and behavior will benefit researchers and ecology seekers vastly.

The outcomes results are based on the comparison of the different scenarios presented, one is of the existing site selected (Dubai Knowledge Village- DKV), the second scenario is based upon the bioclimatic parameters and the third scenario represents the un-ecological design will help fulfill the current goal. The comparison between the results should indicate the level of climatic improvement a bioclimatic design would achieve if applied to outdoor open spaces. A test matrix is discussed thoroughly in the Chapter 3 which represents the examined variables of the space which are space orientation, proportion of the space height to width ratio and the distribution and density of vegetation. Long term and short term interventions of the importance of ecological outdoor spaces will be discussed briefly in the last chapter which encourages developers and landlords to incorporate the ideas presented.

## 1.10 Research Outline

This research is divided into chapters where each elaborates the steps followed to enhance the small outdoor urban spaces. Chapter two is a thorough literature review of all the key concepts involved in the current investigation that overviews all knowledge and findings interpreted earlier in similar fields of study. Such process is considered essential and widely beneficial as the case with any study, since it gives the researchers a good chance to gain knowledge experience done earlier on a particular area. This chapter comprises the hypothesis of the study. Chapter three is the methodology explanation stating every single tool, method and resource used for the completion of this research. This section demonstrates the procedures followed to attain the results presented and discussed in the following two chapters. Chapter four is a presentation of the results and findings attained through the body of investigation based on the methodology set previously. The results will be analyzed systematically and interpretations will be made and discussed thoroughly in Chapter five. Chapter five includes the explanations of the results demonstrated based upon the experience gained in chapter two through the literature review section. A comparison between the temperatures pattern and earlier investigation findings is argued where results are justified. The conclusion of the whole paper will be presented in Chapter six wrapping up the different aspects discussed. The recommendations for future work and the design guidelines will be presented in here verifying the hypothesis mentioned earlier. A holistic view of the study will be attained by reaching this level.

# CHAPTER 2: LITRATURE REVIEW

## 2.1 Introduction

A detailed literature searching of the topic key concepts will be presented in this section thoroughly. Some key words have been utilized for this search such as: bioclimatic design of outdoor spaces, thermal comfort in outdoor urban spaces and the effect of different variables suggested for the study (geometry, orientation and vegetation) on the outdoor climate. Air temperature in hot outdoor urban spaces and passive cooling of outdoor spaces where also used as the key words for the search engines of the current investigation. The key concepts used for research were mainly in hot regions to widen the knowledge gained due to the lack of all the information needed in hot humid climates only. The differentiation between a hot humid and a hot dry climate was also investigated to objectively evaluate the results attained from those papers. A focus upon all parameters of the problem will be presented clearly identifying the potentials and limitations of similar studies. A deep understanding of the relevant attempts made earlier by researchers based upon the problem key concepts was dependant upon electronic scientific resources only.

The articles obtained have gone through a digestive process based upon a specified inclusion and exclusion criteria carried out to select the most relevant ones for deeper review. Precedents who focused upon psychological factors rather than physiological and physical variables were given less importance in the framework of study as well as studies suggested to be with deficiencies in their methodologies or outcomes were excluded. Articles that examined the effect of the ecological and bioclimatic factors on the energy savings were also excluded from the literature review since the focus of this paper is only on the outdoor environment. The articles included were articles that examine the indicators of the problem related to the current study. Articles with suggestions and design objectives were prioritized, specifically those testing the effect of different variables on reducing outdoor temperature levels. The articles included were then reviewed thoroughly, analyzed and classified depending upon their objectives and focus. A spread sheet is then prepared to ease the analytical process extracting the main objectives, the findings and implementation of each study. Figure 2.1 demonstrates the sequence of the process followed in this chapter.

The literature review done in this section discusses the variables to be used for the simulations of the bioclimatic parameters presented in Chapter 4. The set of suggested variables that had undergone the test and lead to successful adaptation had reduced future vulnerability to heat stress which is dependent upon a range of social, environmental and technical factors. This means that the design of spaces and buildings can deliver improved comfort and more sustainable energy solutions (Smith and More, 2002).

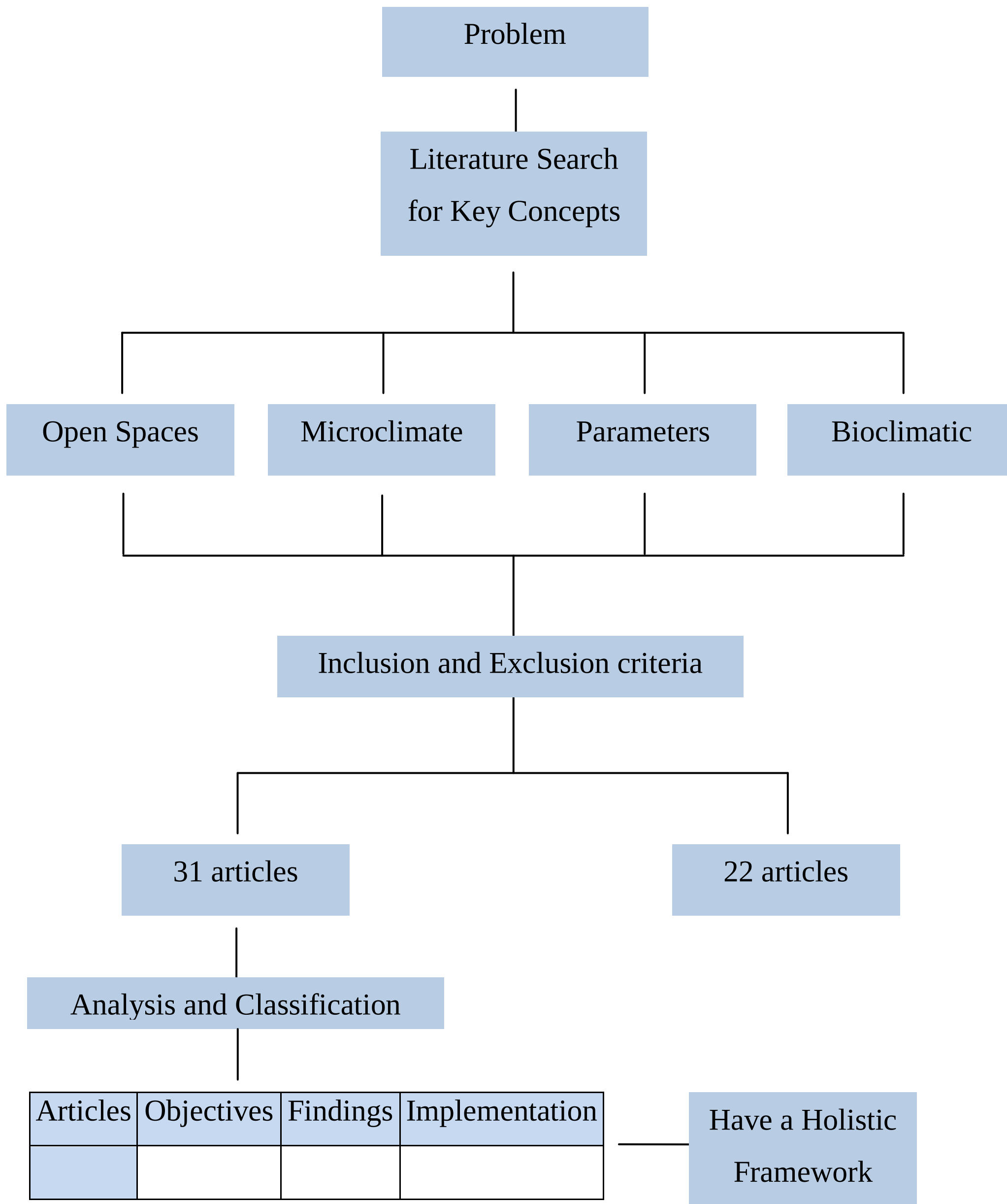



**Figure 2.1. The chronological steps followed for the articles extracted for literature review**

## 2.2 Problem Definition

Achieving ecological design for urban spaces is not a new initiative especially in the last decade during which the environmental concerns along with the side effects of the global warming have been growing rapidly. The general public is now demanding the application of the concepts of 'sustainability' as the need for leading a prosperous life and looking forward to a better future is self-evident. Researchers from different fields have helped people understand more about their environment along with both the controllable and non controllable parameters that would help them improve it. Furthermore, the investigations done previously to enhance our climate thus minimizing our foot print on earth have been growing rapidly, however the available aiding tools are not fully catering to the ambitious goals of sustainability. If the aiding tools were to grow as fast as the environmental knowledge, we would probably be able to achieve more of our objectives. The typical design life of 20–100 years for buildings means that their designers and developers have a responsibility to anticipate future climates and avoid changes prejudicing the structural integrity, external fabric and internal environment of buildings (GLA, 2005).

The motivation for the current study comes from a practical concern facing the inhabitants of extremely hot environments. The need for those inhabitants to enjoy the pleasure of outdoor spaces throughout the year rather than having limited access to the outdoor spaces for a few months only has triggered the need for this investigation. The challenge of controlling the outdoor thermal environment through proper design grew bigger as leisure outdoor activities developed over time. The author being a researcher and an architect sees the concept of enhancing the outdoor atmosphere to suite our future needs and comfort levels as attainable yet challenging. Nowadays, the level of control by the building users to adjust their own indoor atmosphere according to their requirements is immensely encouraging; you can simply adjust your comfortable temperature according to your clothing while your roommate on the other side has a different requirement to their 'comfort zone' yet remains applicable. The lighting levels within a space can also be adjusted automatically depending on the climatic conditions of a cloudy day. Sound insulations compatible with your indoor activities can be incorporated by default within the buildings, reason for that is being in the spaces where you feel comfortable makes you want to visit again and spend more time within.

The concept of comfort is not limited to the indoor environments only but to the outdoor spaces as well, whereas comfortable spaces could simply be indicated as usable spaces thus successful. Achieving outdoor thermal comfort levels still remains a main goal for the designers. The documentation of the outdoor thermal comfort is considered to be much more limited when compared to that of the indoor comfort. Such limitations are rooted in the curtailed relationship between the urban environment and the buildings. Climatologists and urban designers have interpreted the outdoor parameters in many different ways and are still in process of interconnecting this relation to serve the various outdoor investigations (Toudert and Mayer, 2005). It's inequitable to apply the same principles of achieving optimum temperature for an indoor environment when dealing with the outdoor spaces. The outdoor environment has a whole set of uncontrollable variables that are to be handled in a different manner. Wind speed is one of those variables which play a major role in the thermal comfort levels. Sufficient information about all various parameters has to be gathered carefully, particularly when dealing with an outdoor environment. The lack of understanding between the indoor and outdoor environment might be due to the limited examination tools that test this relation. The outdoor and the indoor spaces are considered to be two complementary components of this environment that are interrelated. If we focus on this relation more and try to configure the controlling factors between them, designers will be able to improve the indoor and outdoor microclimate hence achieves an optimum design.

## 2.3 Climate

### 2.3.1 The Microclimate

The environment is composed of the 'climate' which is sometimes called the 'macro climate' and the 'micro climate'. The climate is the average weather over several years divided into main zones with similar characteristics. Within a particular region, deviations in the climate are experienced from place to place within a few kilometers distance, forming a small-scale pattern of climate, called ‘‘microclimate’’ (Santamouris and Asimakopoulos, 1996). Climatologists have worked hard for decades to classify the climate into regions with similar characteristics where in each category people can follow a certain criteria for living. These bioclimatic classifications done where based upon the human requirements for comfort living, clothing, building…etc. The derivative behind all attempts done was the bioclimatic comfort of its inhabitants.

Bioclimatic comfort is simply a state where a person adapts to their surrounding environment using minimum energy. A systematic approach was proposed by Olgyay in the early 1960s of bioclimatic building design and that approach resulted in four main climate types namely; cool, temperate, hot and arid and hot and humid (Mahmoud, 2011). Each category represents its own different needs for shelter from the sun, wind and rain for an environmental responsive design strategy. Olgyay’s method considered the dry-bulb temperature and relative humidity levels for his classifications of the human comfort zone. Various attempts were made in this field leading to different categories, yet they all were followed by the same basic reference for the bioclimatic classifications which were the psychometric charts.

The psychometric charts are standard indicators for the human thermal comfort levels of an individual within different climatic zones. It has been a wonderful aiding tool for designers to clearly identify weather data information regarding the temperature and moisture levels within the climate in relation to one another. The visual presentation of the comfort zone simplifies the bioclimatic classifications for many people. Mahmoud (2011) has attempted to classify Egypt into bioclimatic zones that would later help designers, landscapers, and urban planners achieve environmental responsive designs. As the world's energy consumption keeps growing rapidly and needs reverse strategies for the future energy conservation techniques come into play. It starts with understanding the environment surrounding us to be able to minimize our ecological footprint. Defining bioclimatic zones would benefit a wide range of fields such as landscape and solar energy concepts. The aim of the attempts made to classify bioclimatic zones is mainly to settle on climatic responsive strategies for each specific region that governments would follow and encourage (Mahmoud, 2011). The classification did not include the current climate under investigation yet the information presented was very useful to overview the complexity in dealing with hot climates especially in outdoor environments.

### 2.3.2 Parameters Affecting the Microclimate

The outdoor environment is a wide and complex area of study as explained. The huge number of uncontrolled parameters present in the outdoors outnumbers the ones valid in the indoor (Spagnolo and Dear, 2003). In the indoor environment the average of the surface temperatures can be calculated due to the limited number of surfaces that affect each other. In an outdoor environment the number of surfaces is almost infinite especially with the presence of vegetation and thus the average of the surface temperatures can hardly be calculated (Mahmoud, 2011). Thus calculations done for the outdoor areas are usually closer to reality when based on certain assumptions. The physical parameters of the microclimate are still vast in number and that adds to the complexity of the outdoor studies and necessitates further investigations. Researchers identified the main parameters that influence life within the outdoors and specifically affect the thermal comfort levels, the main four physical parameters that affect the thermal sensation of an individual within an open space are:

-*Ambient air temperature*: it affects the dry and humid exchanges as well as the heat transfer coefficient.

-*Air velocity*: it greatly affects convective and evaporative losses. Near the clothed body, the body motion can increase it. A minimum speed of 0.1 m/s always exists, due to a permanent natural air movement everywhere.

-*Relative humidity*: it presents a small impact when there is not sweating, then, the latent respiratory exchange and the insensible skin perspiration are the only two transfers associated with humidity. Otherwise, the air humidity strongly affects the sweat evaporation, and thus, the skin wetness.

-*Mean radiant temperature*: mean radiant temperature is the uniform surface temperature of a black enclosure with which an individual exchanges the same heat by radiation as the actual environment considered. For outdoors the mean radiant temperature represents the uniform surface temperature of a fictional enclosure for which all surfaces of the fictional enclosure are at the same temperature (Matzarakis and Mayer, 2000). Other external parameters such as the clothing and the activity levels of the space users have to be considered for the calculations of the comfort levels since they play a great role in the thermal comfort levels of an individual.

Mahmoud (2011) considered the air temperature as the most influential parameter within the environment affecting the thermal comfort level. The air temperature factor can easily be indicated and people can rate it with convenience. Other investigations aimed at creating pleasant outdoor environments also voted for the ‘air temperature’ parameter as the most important factor controlling the thermal microclimate. Researchers argued that slight variation in other parameters such as wind speed and humidity could not be recognized readily by the users, especially if the temperature levels were within the comfort range (Nikolopoulou and Lykoudis, 2006). Due to the variations of the climatic characteristics between regions, some factors would be considered more essential than others while in other regions those very same factors would be deemed less important; air temperature is one factor that should always be prioritized in all climatic zones.

Generally the main guideline for environmental design works in reference to the standard levels of comfort and understanding the main climatic characteristics of that particular region. The focus upon the microclimatic parameters of the site under investigation is then to follow. The chronological process of a bioclimatic design approach widens the understanding of the various parameters of the design variables. Setting a bioclimatic approach to the design of outdoor urban spaces in Dubai requires focusing firstly upon the bioclimatic conditions of the selected site under investigation. Second, is to distinguish the circumstances of the existing design that translates to the functional requirements of the site.

### 2.3.3 Climate of Dubai

Dubai lies on the coordinates of 25°N 55°E and classified to be a hyper arid climate with lower precipitation levels than other cities in the subtropical zone. Heat stresses are high from June to September and cool down gradually to the coolest months of the year between December and March with minor precipitation levels (Dubai Metrological Office, 2010). The main challenge of the climate in Dubai is the humidity levels which are markedly high and contribute to reduction of the thermal comfort sensation. Life during most of the year is entrapped inside artificially cooled buildings, while there is a great need for the city's dwellers to enjoy their life outdoors, a need which is mostly fulfilled between November and April when inhabitants release their entrapment sensation. During this time outdoor open spaces are used heavily regardless of some factors that might cause discomfort such as wind and dust.

Fabrous (2009) used a psychological approach that aimed to identify the thermal comfort level in Dubai's outdoor spaces through social surveys along four months of the year (three months of summer and one months of winter). In agreement to previous studies the air temperature has been the most influential factor causing discomfort for users in Dubai outdoor spaces due to the high levels of solar radiation. When shading was provided there was a larger amount of satisfied users willing to use the outdoors for short periods of the day. Therefore, the author suggested increasing the amount of shaded areas vastly especially for the transit spaces that usually cause extreme levels of discomfort. In Dubai humidity is considered to be a crucial factor contributing to users' discomfort. High levels of relative humidity especially between May and September increase the thermal sensation of the users since humidity amplifies the heating effect of air temperature. The study suggested increasing humidity levels during winter especially during January. Wind during January and February has shown high levels that promoted the feeling of discomfort during winter. A balanced design should be achieved to control the wind speed during winter yet enhance it during summer since it minimizes the thermal sensation of the users. The study displayed various weather patterns of Dubai throughout the year and its influence on people's usage of the outdoor spaces in Dubai.

The weather of Dubai remains a challenging environment for creating successful designs however it is still attainable. The deep understanding of the main parameters controlling the environment leads to a bioclimatic design that saves energy and encourages people to use the pleasant outdoor area throughout the year. Thermal stress periods are identified during June, July and maximum values on August which need climatic precautions that do not overcome the extreme coldest levels of that in January (Fabrous, 2009).

### 2.3.4 Design Guidelines for Hot Humid Regions

Dubai, the city under investigation lies within a hot humid region that suffers from high temperature levels during summer. In an attempt to study the impact of planted areas on the urban environmental quality, Givoni (1991) classified the climatic conditions required for each region and suggested the guidelines that should be followed for the design of outdoor spaces. Due to the high humidity and temperature levels wind and shading are the two main factors required to take place vastly. The study mainly accentuated the use of plants in achieving all the objectives required. Moreover, the author suggested dense vegetation placed in groups that provide shade along seating areas and should not create an obstacle for the wind. Perforated layouts usually enhance the wind speed and ventilation within the site which is essential in hot regions. Grass is preferable in most places since it absorbs less solar radiation. Minimal introduction of shrubs is also required since they do not provide shade, yet prevent wind breezes from entering the space. The main idea is to create shaded spots within various parts of the space with high wind breezes that enhances the thermal comfort sensation of the users. The main concern in hot climates generally is the solar exposure which increases the heat absorption within the space. The wind factor is the aspect differentiating the climatic needs of hot humid and hot dry climates in which wind is not preferable in dry climates and highly recommended when designing urban spaces in humid climates.

## 2.4 Urban Open Spaces

### 2.4.1 Background

Outdoor urban spaces are mainly areas designed to accommodate people for social, cultural and economic functions such as parks, piazza, souks…etc. The types of outdoor open spaces vary with shapes and functions depending upon their evolution. Some of those spaces are created during the building compositions as leftover spaces which are usually inhabited in a further stage. Major spaces are usually given more importance during the design phase as part of the urban theme. The current study focuses upon outdoor spaces that are composed between two or more buildings in the form of social, public or transit spaces. There are several physical and nonphysical factors that promote the usage of such spaces and convert them into successful spaces rather than being deserted. The form of the space and its surrounding buildings is usually the first impression taken about a space. Then the components, functions and most of all the environmental factors are also to play an essential role in this subject. The design of outdoor urban spaces is of no less importance than the design of the surrounding buildings which are complementary. Former attempts have tried to regulate the relation between the buildings and its surroundings to create pleasant spaces. Most of the studies done in the past were based upon ergonomic standards and conventional concepts rather than following ecological approaches. It has been proven, through observation that spaces designed upon the basis of functional requirements aesthetic values and psychological feelings of the users are not always successful spaces. Hence, the investigation of optimum design guidelines that fulfills all those needs in respect to the climatic conditions should gain more attention especially for the outdoor environment.

### 2.4.2 Thermal Comfort in Outdoor Spaces

The outdoor environment contains two main parameters that control its use. One is the human parameter and the other is the physical environment or the microclimatic factors. Understanding the human parameter is essential prior to studying the numerous amounts of microclimatic factors present in the outdoor environment, whereas generally the comfort of the users of any space is the baseline that makes it either successful or otherwise. Thermal comfort levels have been identified for the different climatic regions according to the standards of human thermal sensation levels. Studies all over the world were based upon those standards yet evolved them during the understanding of their dimensions. The investigation of the thermal comfort levels served the purpose of focusing on certain outdoor parameters while pushing others to the sidelines. For instance, the effect of wind speed and heat radiation had played a wider role in the effect of relative humidity on the thermal comfort levels and accordingly took a prominent position in the outdoor investigations. Identifying the outdoor parameters affecting the thermal comfort levels according to their effectiveness in the thermal sensation is considered of great benefit to the research field and time saving due to the existing wide number of parameters in the outdoor environment.

The RUROS project in Europe (rediscovering the urban realm and open spaces) is a huge example for the awareness of governments for the need of usable outdoor spaces that fulfill the cultural; climatic and urban needs of the users and the environment. Nikolopoulou and Lykoudis (2006) presented the findings of the RUROS focusing on the environmental and comfort conditions in the open spaces of five different European countries. A database of 10,000 questionnaires was developed in 14 different case study sites to identify the thermal comfort conditions with existing open spaces physiologically and psychologically to set the guidelines for such spaces with a suitable microclimate. Nikolopoulou and Lykoudis surveyed two different case studies in each of the cities participating in the RUROS project. A huge database was built over a whole year covering the different seasons with weekly readings. Correlations between the microclimate and comfort levels were compared upon the ASHREA standards. The project confirmed the dependence of the users' thermal comfort within the outdoor spaces upon the microclimatic conditions such as air temperature, humidity and solar radiation.

Based upon the evidence that air temperature is the most influential factor on the thermal comfort of the users, the current study will consider the air temperature parameter as the main factor under investigation. Wind speed and relative humidity has proved to be less recognized by the users unless the change is dramatic. Furthermore, higher wind speed level or humidity levels could be tolerated by the users under a lower air temperature. Air temperature was compared with physical activities using grouped metabolic rates which gave interesting results. There is a tendency for low metabolic rate activities to be accompanied with higher air temperatures for each season separately (Nikolopoulou and Lykoudis, 2006).  Zambrano et al. (2006) mentioned that it is quite relevant to understand the activities within any outdoor space before the investigation of the comfort levels. For the designer to achieve an optimum design that really promotes the users comfort, activity levels have to go under deep observations.

People had proved also to tolerate higher temperature levels based upon their expectations which are part of their psychological adaptation. Inhabitants of warmer cities usually have higher levels of thermal comfort than those living in moderate climates due to the psychological parameters such as personal choice, memory and expectation. Yet, people’s adaptation has varied within the same day and location which explains the idea that human response to physical stimulus varies according to the information they have about the situation. The climatic consideration needs to be prioritized in the outdoor space design process which has grown rapidly over the last couple of years (Nikolopoulou and Lykoudis, 2006).

Zambrano et al. (2006) concluded the factors affecting an individual’s thermal comfort into solar incidence and radiation exchanges, local characteristics of winds, topography, vegetation and the presence of water. Beyond these factors, the urban design, the morphology of the buildings, the characteristics of the surfaces and the behavior of the individuals are also factors that affect the thermal levels in the outdoor spaces. The study assured the concept of disagreement of all users for a comfort situation and defined that percentage between 5-10%. A comparison between the results obtained by this study has been compared to the previous study RUROS project based upon the actual sensation vote for the validation purpose.

A study conducted in the city of Rio de Janeiro, Brazil, a city of humid tropical climate with mid-rise buildings surrounding the spaces. All the permanence points happened to be mainly located in shaded or half-shaded areas, provided by small and medium trees with a large area of low vegetation. The concept of shading either by buildings or trees has influenced the users’ satisfaction immensely. It is understandable that shaded areas have reduced the air temperature and accordingly enhanced the air temperature. Another factor showed a positive effect on the thermal levels which is the materials. Stone pavement, granite benches and painted wooden benches have increased the temperature while on the other hand the planted areas have created a more pleasant environment. Therefore, vegetation has proved to have several benefits on the surrounding environment that made it an essential component in most current sustainable designs (Zambrano et al., 2006).

Pleasant outdoor urban spaces have in turn major implications on the development of the cities. Activities such as walking, cycling, the use of public transport and social cohesion are dependent mainly on the use of such spaces (Baker et al., 2001). Sustainable cities are usually based upon the concept of compact layouts which creates walkable distances and human scale streets in addition to bioclimatic advantages. Baker et al. (2001) argued that interpretations of the outdoor thermal comfort have to be based upon physiological and psychological parameters. It's fundamental that the 'adaptation opportunity' has to be taken not only by space users but also by the physical components of such space such as buildings, trees…etc. The study was done in resting spaces where people choose to sit in order to avoid discomfort, four sites where chosen with different typology, geometry, orientation and intended use to undergo the investigation.

It was quite interesting to know that the physical parameters had proved to be of less importance than other parameters. Creating aesthetically attractive spaces and getting people to use them is of much more importance than creating shaded areas that reduce the air temperature. The study accentuates the concept of expectation as a main psychological parameter. The authors argue that since people came out of the buildings to use the space then they can tolerate unpleasant climatic conditions. Creating a wide variety of spaces should be the urban designer's main goal to suite different needs all over the year (Baker et al., 2001).

The previous surveys present the idea of people's psychological preparation before using the spaces. The concept of expectation of the users comforts the designers and serves the easiness of the achieving an optimum design method in extreme climatic conditions. In extremely hot humid countries a balance could be achieved between the highest thermal stress requirements on shorter periods of the year and the average climatic conditions. Overcoming some recommendations that serve the extreme thermal period is sometimes a right decision especially when substituted by psychological alternatives. For example, spaces that suffer two month of high thermal stress can accommodate activities that attract people and help them tolerate that stress, such as ice cream stations and companies advertising types of coolers.

### 2.4.3 Urban Space Design

The urban design process is composed of a set of consecutive stages layered one over the other. First, is setting the main theme of the city which defines the silhouette of the city and is usually represented by street design. The second process is more of defining the silhouette set previously in the form of plot and street division. These two stages are then followed by the insertion of a solid layer represented in building forms and accordingly a layer of voids is created which represents the outdoor spatial compositions. The guidelines to be presented later are the designers aiding tools in the solid and void stage of the urban design process. The set of bioclimatic design principles are to guarantee the achievement of ecological urban spaces and accordingly ecological master plans. Yet all stages of the urban design process are to follow an ecological approach to achieve a sustainable development plan.

The detailing stage of urban design is then to take place dealing with the direct relation between the solid and void compositions. The inspiration of an outdoor urban space theme could start inversely from the internal core of the building till we reach the outdoor spaces. The composition of the outdoor spaces is sometimes composed initially in turn inspiring its surroundings. This design process can be done either way where interior designers are usually emphasized by the exterior of the building theme and function while; the building composition is an outcome of the urban spatial composition of its context. Thus, it is an ordinary outcome that those internal spaces reflect back its context and accordingly its adjacent spaces. The set of consecutive interactions continues to happen in a way that reflects a successful design of a usable outdoor space which is capable of reviving the public realm. The dialogue between the buildings and the surrounding outdoor spaces also happens on a thermal level where spaces sometimes gain heat and release it to the adjacent buildings; on the other hand spaces that are ecologically designed usually act as shelters for their surroundings.

The responsive attitude of the users to open spaces depends mainly upon the microclimatic factors. During the occupation phase, alterations for the circulation and usage of public spaces usually occur and are considered to be spontaneous. The designers' role is to cater to the needs and patterns of different users within a consolidated program of spatial requirements. The design process should abide by the climatic constraints and suggestion to have efficient spaces and prevent future amendments. The main goal for the design of the outdoor spaces should be the users' thermal comfort where all the other dimensions of the design are to follow.

The intrinsic potentiality of these spaces calls for more effort to be done to transform them into usable spaces. The recent urban transformations, by inducing a generalized mineralization of urban external spaces, often synonymous with summer overheating, make necessary the recourse to thermal regulation techniques (Masmoudi and Mazouz, 2004). It is quite necessary to understand the relation between the thermal environment and an urban space that is capable of transmitting its excess heat to the surrounding premises. Building cooling loads are much affected by the microclimate surrounding them, which makes it necessary to study the environmental factors affecting such spaces not only for their usability but also as part of the energy conservation goals. We need to understand the way theses spaces gain heat during thermal stresses identifying the influential factors such as space height to width ratio, space geometry and size (Masmoudi and Mazouz, 2004).

Smith and Levermore (2006) discussed the concept of 'urban heat island' UHI effect and its impacts on urban and rural areas. The UHI is a well documented phenomenon that is especially valid in warmer cities. The heat effect is considered an outcome of the urban design process which either augmented the problem or limited it depending on the climatic considerations. Spaces surrounding the buildings gain heat during daytime depending on the sun exposure percentage, releasing this amount of heat during night time. The buildings arrangement enclosing each space play a major role during day heat gain and night heat loss. The time interval of the nighttime heat radiation increases during winter and is reduced during summer which results in higher temperatures. Rural areas usually have less compact layouts than urban ones which promote the night time release process. One of the biggest disadvantages for the UHI effect is that it increases the consumption of the surrounding buildings of artificial cooling emitting more heat to the outdoor environment and which in turn intensifies the UHI effect.

The balance to be achieved within the compactness of an urban composition was indicated by the ‘sky view factor’ SVF. The study indicated the SVF as a more robust indicator of the heat island intensity than the aspect ratio since it indicates the clear vision angle of the sky by 180 degrees field of view. It has been agreed that cities with denser layout have a higher UHI effect than those with less dense compositions that essentially allow the infiltration of air in between the buildings resulting in shorter periods of night flush. Several studies argued that by the presence of larger water bodies and vegetation, the UHI effect decreases substantially (Graves et al., 2001; Spronken-Smith and Oke, 1991). Vegetation with its enormous benefits should be promoted on green roofs and bio-shaders as well. Nevertheless, the adaptation of the urban design strategies for summer should not impinge on the potential of reducing the thermal comfort during winter. Therefore, a balanced set of guidelines should be identified, reducing the cooling demands in summer as well as in winter (Smith and Levermore, 2006).

Orientation is another important factor of design that requires prior knowledge. Smith and Levermore (2006) demonstrated that East-West oriented streets have a higher solar exposure than North-South street canyons. It has been settled that the shading factor is one of the main controllers of the microclimatic conditions which is composed mainly of the factors mentioned previously; urban morphology and orientation. The solar exposure is minimized by the increase of the shading factor coefficient that needs to be controlled carefully to prevent the increase in the lighting consumption. Orienting the layout composition to enhance the cooling effect obtained by the wind is one of the strategies that should be considered in an urban design process.

The study highlighted the importance of a policy framework set by governments which is more likely to encourage the use of ecological design principles. Decisions regarding the urban built environment should be based upon long term savings and is to follow a sustainable development plan. There should be a holistic approach for decision making. The authors assured the validity of such guidelines and policies that needs to be applied more strictly to ensure future reduction to the UHI. Growth of usable outdoor open spaces can deliver improved comfort conditions by placing crucial guidelines to the master plans (Smith and Levermore, 2006).

The set of bioclimatic design principles to be suggested later should aim to eliminate common designs that cause high temperatures or induce the wind flow excessively which results in the users' discomfort. The users comfort should be one of prioritized regard for the design of any space rather than the aesthetic values. These principles will enhance the physical and the built environment and positively influence the social fabric. Moreover, understanding the varied functions of urban open spaces and its microclimate is an important part of helping to improve their effectiveness, both by enabling better management of existing urban spaces as well as improving the design of new ones.

## 2.5 Bioclimatic Design

### 2.5.1 Background

The American Institute of Architects (AIA) Florida (2008) prepared a 'sustainability design quick reference manual' as a resource intended to assist architects in moving towards the AIA's 2030 Goal of achieving a minimum 50% reduction of fossil fuel consumption in all new buildings by 2010 and carbon neutrality by 2030. The manual had defined the bioclimatic design as a sustainable one that conserves resources and maximizes comfort through design adaptations to site-specific and regional climate conditions. Basically the bioclimatic approach is a process of extracting the maximum benefits of the inputs available to come out with the maximum amount of long term and short term savings. The first step requires an understanding of all the climatic conditions of the site under investigation. Establishing a thorough site analysis with all the topographic, functional and weather conditions identifies the constraints and potentials of each project is then to follow. Moreover, areas with high thermal stress and excess loads versus those with lower stresses would require a sense of balance to be achieved. The next process is to match the right resources together and shape the building plan, section and mass based upon the ecological strategies that reduce or eliminate the need for non-renewable energy resources. The way these strategies specifically affected placement, orientation, and shading of the building is to be considered the bioclimatic design principles set for the project and could sometimes be used for similar projects as well.

The reference manual has provided a very useful set of bioclimatic guidelines to be considered in each phase of the project design. The guidelines of the different project phases included the proper orientation, earth sheltering, passive solar collection opportunities, vegetation, water conservation and providing sun shading in the project definition and schematic phases. Having a checklist of the bioclimatic principles within the design of an open space guarantees the energy saving levels to more than 40% and would definitely increase the thermal sensation levels (AIA Florida, 2008).

Another study presented some of the bioclimatic architectural principles to improve the thermal comfort conditions in outdoor spaces using two different thermal indices. The goal of the study was to test the effect of applying passive cooling and energy conservation techniques to enhance the outdoor thermal sensation which showed pleasing results. Seeking to reduce the 'urban heat island' effect through various architectural improvements has been found to be constructed in a conventional existing space in great Athens. A comparative analysis was made between the two scenarios to validate the level of improvement that bioclimatic architectural principles potentially posses. The two methods used for the surveys were the 'TS-Givoni' method and the 'Comfa' methods utilizing social surveys based upon the thermal comfort sensations. The goals and objectives were set clearly and then where processed in a synthesized form to the stage of testing. The objectives were summarized as follows;

- Providing natural passive design elements that enhance the microclimate and minimize the heat gain through shading, natural ventilation and other factors
- Minimizing pollution and CO2 absorption

The implications of such objectives revolved around three main concepts; vegetation, water features and materials. Manipulation of such concepts where as follows:

- Yielding a dense green buffer zone along the periphery of the site to act as a wind shelter and enhance the microclimate

- Locating deciduous plants along streets to enhance the cooling effect through shading
- Providing greenery in all open spaces in and around the site with various densities
- Applying a central water source in the park the increase the cooling sensation on hot summer days
- Choosing carefully site materials to match the microclimate such as porous reflective materials

Values of the comparative analysis have been documented carefully indicating a great improvement in the thermal comfort levels within the site. Both methods have validated the conclusion that bioclimatic architectural principles could possibly enhance the outdoor microclimate. The energy savings have been observed to reach an average of 40% and the hot sensation levels have been enhanced by an average of 6% (Gaitani et al., 2005).

Generally the multiple benefits of incorporating ecological design principles within the space design have confirmed their value through various research methodologies. Studies that used simulation models, field measurements or even numerical methods have guaranteed the enhancement of the microclimate through bioclimatic design thus increase the demand for such spaces. Yet a deep knowledge of the microclimatic conditions that are to be considered within the design remains the first step towards a bioclimatic design. The characteristics of each region lead to a set of guidelines that is to be incorporated within the construction of such spaces.

## 2.6 Parameters of the Study

### 2.6.1 Background

Empirical research studies have been piling recently trying to understand the relationship between buildings and the urban climate. Building settings create urban patterns that control the wind direction and solar gain; hence the thermal comfort levels of the outdoor spaces and energy consumption of the indoor ones. The urban planning process is required to place buildings where adjacent spaces are overlooked and considered in the master plan.

The space composition, its materials and components are the main factors controlling the microclimate of an open space. Passive cooling of the outdoor spaces is usually governed by the space orientation and its morphology as measured by the height to width ratio. Adding greenery to an open space has significant results in cooling the microclimate as well. The consequences of the ecological open space contribute to the surrounding environment positively. Thus investigation of these factors is considered to have a great role in leading a sustainable future. The environmental recommendations and guidelines that should be provided for urban designers and architects needs further exploration.

The current research is more of a synthesizing the bioclimatic improvements type, rather than an examination of each parameter individually. Through earlier studies, parameters that demonstrated to have a positive effect on the outdoor microclimate would be considered more than others. The concept of combination of these parameters assesses the capability of bioclimatic design approach to improve the thermal comfort of outdoor open spaces in Dubai. The following parameters illustrated will be tested in an organized manner at a later stage.

### 2.6.2 Geometry

The urban configuration is one of the main factors affecting the urban climate (Oke, 1987, Watson et al., 1991, Arnfeild, 2003). The cycle of heat gain during the day as a result of high temperatures and the nocturnal heat losses have to be managed through a critical height to width H/W space ratio of the surrounding buildings within a space. The distance between buildings defining an open space, their settings and heights play a major role in the incoming and outgoing heat radiation and the wind speed (Johansson, 2006). The negative effect of improper space geometry would increase the solar gain and prevent wind circulation within the site. Several studies have tried to achieve the best H/W ratio, according to the space form, that reduces the thermal sensation.

Providing more shade within outdoor spaces located in hot regions contributes to higher thermal comfort levels since shading has proved to be an overarching factor that has a pleasant cooling effect. Shading is provided naturally by the buildings and objects enclosing a space. The amount of shelter provided from the solar radiation depends upon the coverage factor of the shade whereas the shaded areas are emphasized by the building height and density enclosing the space. Furthermore, a semi enclosed space with short buildings would have less shading coefficient than an enclosed space with taller buildings surrounding it. It is obvious that the more the space is penetrated by the sun the more heat is gained during day time. Studies done previously on urban canyons H/W ratios have been very beneficial to the current study as they have revealed the proper ratio for an outdoor space.

Tight urban canyons with lower H/W ratio amplified the cooling effect during peak hours of the day more than wider canyons with bigger H/W ratio which is mainly due to the increase of the shading coefficient (Toudert and Mayer, 2006). Several studies confirmed that shading revealed an effective means to mitigate heat stress in outdoor spaces. Four different street ratios were simulated to validate the effect of H/W ratio in relevance with the sky view factor 'SVF' shown in Figure 2.2 which is basically the openness of the cluster to the sky. An inverse relation has been approved between the H/W ratio and the air temperature. Whereas the lower H/W ratio (0.5 and a SVF of 0.87) contributes to higher air temperature levels than that H/W of 4 and SVF of 0.37 with maximum difference of 3 degrees Kelvin. Yet the H/W ratio of 2 achieved the most appropriate balance in relation to the SVF of 0.54. Furthermore, the more shade is provided within the spaces the dimmer they become, and hence the more energy is needed for lighting especially for the surrounding structures. Therefore, Toudert and Mayer (2006) accompanied the SVF with the analysis of the H/W ratio.

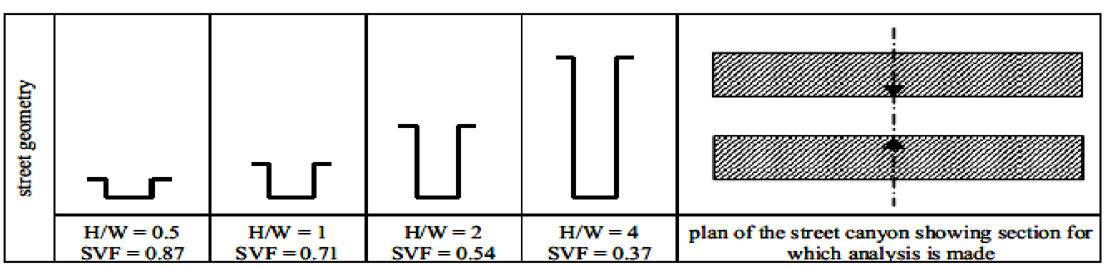



**Figure 2.2. Schemes of simulated street canyons.**

**Source: Toudert and Mayer, 2006**

Oke (1988) in his study suggested that a ratio between 0.4< H/W >6.0 is considered a good compromise between the thermal needs (high ratios) and the pollution needs (low ratios). This ratio was considered to be acceptable by Arnfeild (1990) if applied in cities with heavy cloud coverage only. Ahmed’s study in the hot humid environment of Dhaka, found that on average the daily maximum temperatures decreased, by 4.5K when the H/W ratio increased from 0.3 to 2.8 which was considered to be fair for achieving the thermal comfort levels (Etzion et al., 2004). Hoffman and Bar (2003) linked the effect of the space geometry to the surrounding buildings geometry which had proved to play an important role on the microclimate. They investigated the cooling effect of colonnades in the building base using the cluster thermal time constant CTTC model. In the Mediterranean Coastal region for example, the maximum cooling effect of colonnades was found to be 3–5 K for H/W ¼ 0:5 and 2–3 K in narrower streets (H/W ¼ 3) at noon in summer.

A recent study focused upon the SVF as the main indicator of the thermal comfort level. Field measurements have been done simultaneously in 18 different points; Figure 2.3 shows the images of the monitored points. The study revealed the relation between the pollution consequences and the desired air temperature standards. Since denser spaces contribute to higher levels of air pollution and lower levels of air temperature while less dense layouts minimize the pollution entrapment and lead to higher temperature levels. The study accentuated the need for a balance between the two factors (Minella et al., 2010).

**Figure 2.3. Fisheye images to calculate the SVF using Rayman software**

**Source: Minella et al., 2010**

Finally, summer design precautions of the H/W ratios are not sufficient for setting environmental guidelines for the outdoor urban areas. A very low ratio in an outdoor urban space would contribute to the prevention of solar access during winter that abandons the use of these spaces due to the cold sensation. Buildings surrounding the space are permanent structures that cannot be modified according to the sun path yet can be used as design potential that needs to be utilized cautiously in early design stages. Sun path varies according to the location of the city dictating the problematic spots within the site during the day that should be sheltered by shading strategies.

The current study aims at achieving a balanced ratio that minimizes the sun penetration during daytime hence minimizing heat gain and enhancing the heat loss during the night taking into consideration all seasons of the year. Following a proper urban design ratio is promising to improve the thermal comfort levels within the urban spaces hence the surrounding buildings.

### 2.6.3 Orientation

Urban spaces can be oriented to enhance the air flow within the space hence giving a cooling sensation during hot summer days. On the other hand they can also be oriented in such a way that accelerates the wind excessively and contribute to a discomfort sensation. The wind flow is a crucial factor affecting the air temperature within the outdoor urban spaces that needs thorough studies in the future along with the temperature studies. Solar exposure is another essential factor that is affected by the space orientation. Shading coefficient is responsible for the thermal comfort levels and is inversely related to the solar exposure levels. Researchers attempted to achieve the most suitable orientation for each region through the process of enhancing the outdoor thermal levels.

The space orientation is more effective on the distribution of the temperatures of surfaces and net absorbed solar energy in time and space than on the absorbed quantities. Toudert and Mayer (2006) argued that the heat stress of an East-West oriented canyon was of high levels when compared to the North-South orientation providing a better thermal environment. For the Northeast-Southwest or Northwest-Southeast orientations, these canyons have proved to achieve better comfort levels as the shading coefficient increased, with a slight difference nonetheless. In some cases a compromise has to be achieved for the best orientation for summer and winter to suit the comfort levels of both periods. The orientation factor appears to be less sensitive to the air temperature variations when compared to the W/H ratio of the space. The consequences of N-S and E-W orientations could be compromised by the H/W ratio. Furthermore, orientations with higher solar exposure requires deeper spaces (larger H/W ratio), while orientations with less periods of solar exposure can tolerate wider spaces with smaller H/W ratios. Figure 2.4 shows various orientations tested according to the same H/W ratio.

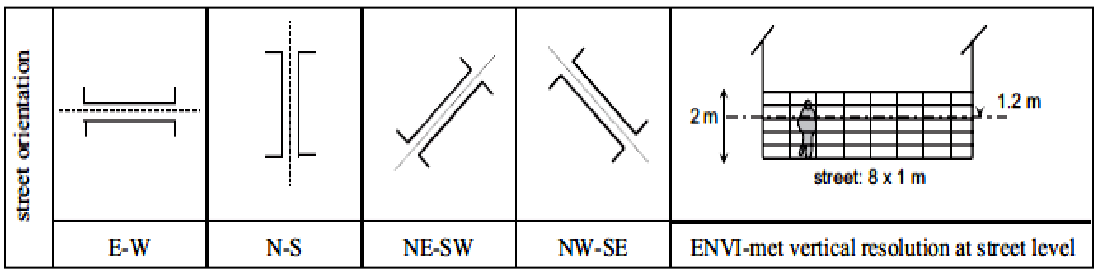



**Figure 2.4. Various orientations tested through simulation by standardizing the H/W ratio.**

**Source: Toudert and Mayer, 2006**

Bar and Hoffman reconciled the geometry orientation and greenery factors in the CTTC model to enhance the thermal comfort levels. According to the CTTC model results, space orientation variations between N-S and E-W orientations have proved to be of slight differences. N-S orientation had provided 83% of shaded areas while E-W orientation had provided less amount of shade 74%. Figure 2.5 shows the slight variations between the two orientations according to the mean solar radiation intensity on the ground (Bar and Hoffman, 2003).

A recent study demonstrated the effect of orientation not on the shading percentages but on the wind flow and air quality. Studies validated the relation between the wind flow and air quality since air movement prevents air stagnation and thus pollution blockage. Pollution has proved to contribute to lower air quality levels thus higher temperature levels. The study recommended orienting urban canyons to be parallel to the wind direction which would increase the air inflow within the outdoor spaces. Prevention of site orientations that cause wind blockage has been highly suggested (Minella et al, 2010).

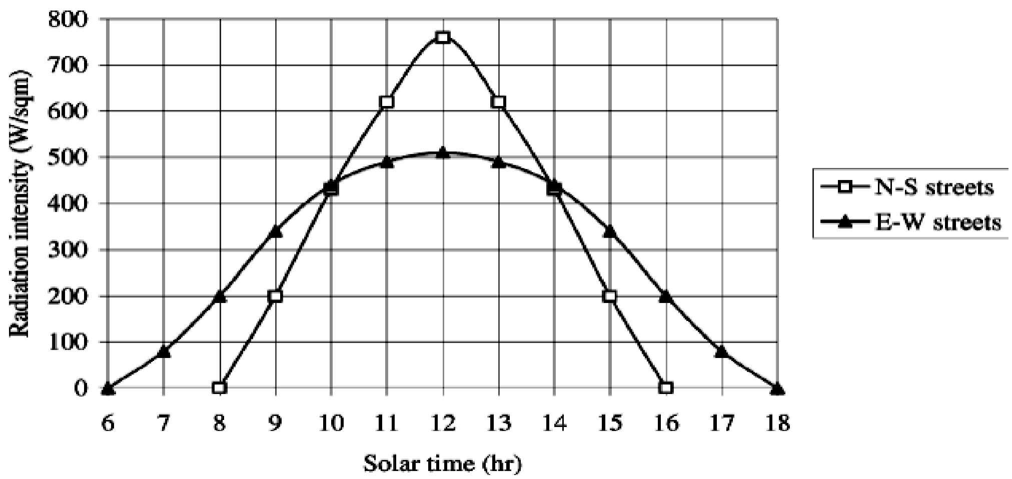



**Figure 2.5. Daily variation of the mean solar radiation intensity on the ground in Jerusalem streets on the 21 September.**

**Source: Bar and Hoffman, 2003**

The orientation of the outdoor spaces formed within a master plan has to follow an ecological method considering the wind factor and the shading co-coefficient. The criteria to be followed are to be based upon the contradiction of the seasonal needs and the variations of the day and night requirements. Previous studies agree that orientation effect on the air temperature has proved to be of a slight effect (average 1 - 2$^{o}$ C). The current paper aims to synthesize minor effects by several parameters that would contribute to a noticeable improvement of the outdoor air temperature.

### 2.6.4 Vegetation

Greenery has proven to be the most crucial parameter in improving the microclimate due to its multiple benefits. Testing the concept of improving the thermal environment by having more greenery has been over killed. Wilmers (1988) has mentioned that vegetation can reduce the air temperature up to 20K and its effect is extended to its surrounding built environment called the 'background effect' (Hoffman and Bar, 2000).

The background effect can reach the 1.3 degrees Celsius (Win et al., 2007). The microclimate of a site adjacent to an urban park is much cooler than that adjacent to an urban area since the effect of the surrounding sites extends beyond its limits. The background effect varies between 100m from small green areas to 2km from bigger green areas such as parks. Therefore the advantages of vegetation are considered to be various not only on a local scale but on a wider level.

Vegetation incorporates several characteristics that aid in reducing the air temperature. Trees provide shading that has a statistically significant effect on the heat absorption levels of the shaded surfaces. A cooling effect of the site can be obtained by providing trees, manmade or shading elements. Hoffman and Bar (2003) proved that 80% of the cooling effect provided within 11 sites in Tel-Aviv urban complex was due to the shading effect obtained by trees. During daytime, trees reduce the penetration of solar radiation due to shade and attenuation of the thermal gains due to its thermal mass. A CTTC model has been used for testing such effects which omitted a serious passive cooling effect on its surroundings. Oke (1989) explained the process of air exchange of the long and short wave radiations between the trees and its surroundings contributing to the cooling effect explained in Figure 2.6. The dissipation of the heat load is due to the evapo-transpiration and convective heat exchange with the air. The authors argued that the cooling effect due to vegetation extends its impact on its surroundings.

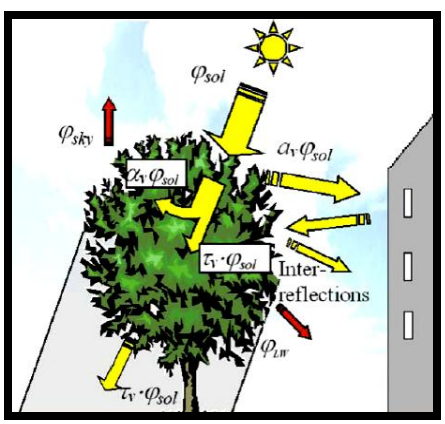



**Figure 2.6. Schematic representations of radiative exchanges of a tree.**

**Source: Hoffman and Bar, 2003**

The influence of vegetation had been adjunct to the water pond effect on the microclimate. A both cooling and moistening effect was tested that proved to have a great enhancement to the thermal comfort level. The geometry of such parameters has been simplified during the tests. The consideration of the layout orientation had revealed to be essential for enhancing the cooling effect. The wind factor would spread the cooled air within the layout as shown in Figure 2.7 (Robitu et al., 2005).

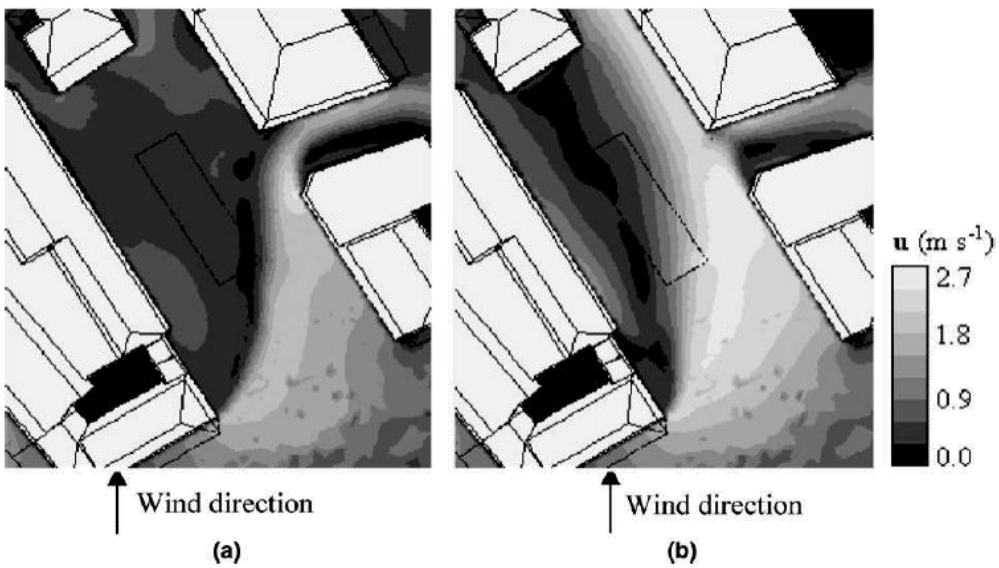



**Figure 2.7. Wind speed in an open space in Fleuriot Square where case (a) shows an empty situation and case (b) is with the application of vegetation and water pond.**

**Source: Robitu et al., 2005**

The soil characteristics of a site is one the main factors affecting the microclimate. The cooling effect obtained by a green site is due to the poor ability of its soil to absorb heat whilst, the vegetation surfaces have proved to absorb much less heat due to many factors. The biological composition of plants reduces their ability to store heat within due to the evaporative evapo-transpiration process (Robitu et al., 2006). Plants' color and surface characteristic act as a neutralizer to the thermal environment.

An old study done by Givoni (1991) demonstrated various studies that were carried out on the thermal effect of plants in urban areas. The studies revealed the use of greenery as an energy saving method due to the reduction of cooling loads on the surrounding buildings. Studies done by Parker (1989) mentioned that the effect of landscaping (consisted of trees and shrubs) on the cooling loads of the surrounding buildings was marked by around 50% savings where the loads dropped from 5.56kw to 2.28kw and was even more marked during peak load periods (8.65kw to 3.67kw). The author's study concluded that applying vegetation has a number of benefits such as pollution reduction, noise attenuation and social cohesion.

In contrast to the ‘heat island effect’ a localized cooling effect due to vegetation in parks and open spaces had been known as ‘park cooling island’. Drops in the air temperature up to 4 degree Kelvin have been observed during hot summer days in areas with greenery (Bernatzky, 1982; Oke, 1989; Shashua-Bar and Hoffman, 2000; Dimoudi and Nikolopoulou, 2003; Chen and Wong, 2006). This phenomenon has proved to be of great significance depending upon the types and distribution of the vegetation, microclimate and the topographic characteristics of the site. Bar et el. (2009) assured the need to study the effect of vegetation on the microclimate in relevance to the site conditions, component, site characteristics and the materials used. Vegetation as a passive cooling element has a set of interactive relations with its surroundings depending on numerous amounts of controlled and uncontrolled variables. Whereas, the cooling effect of a bunch of trees depends on the materials used within the space (grass, albedo or stone tiles), geometry of the space, its orientation and the compositions of the adjacent buildings. The reactions between those variables are considered to have a complex role on the heat gained and released.

In a similar climatic region Bar et el. (2009) focused on the water consumption factor of several combinations of shade and vegetation in relation to the cooling effect they produce in an urban context. The study used six different combinations of trees, grass and shade as summarized in Table 2.1 which is quite beneficial for a bioclimatic design guideline. The study introduced a set of limitations that needs to be considered in future semi enclosed space design based upon its empirical findings.

- Providing shade through a canopy mesh (used in many of the hot arid climates) had proved to be inadequate when compared to that provided by trees and moreover had caused a slight heating effect up to 0.9 Kelvin
- Grass has proved to reduce air temperature yet consumed more water unless shaded (preferably by trees)
- Providing grass under shading trees or shading canopy had enhanced the cooling effect more than shaded areas with no grass
- Trees are considered the most effective in reducing cooling loads and water consumption

**Table 2.1. Six landscape strategies followed.**

**Source: Bar et el. 2009**

| Overhead treatment | Ground surface | |
|---|---|---|
| | Bare soil and concrete pavers | Irrigated Durban grass |
| Exposed | "Exposed-Bare" | "Exposed-Grass" |
| Trees | "Trees-Bare" | "Trees-Grass" |
| Shade mesh | "Mesh-Bare" | "Mesh-Grass" |

A balance between grass and trees has proved to be the most effective in terms of enhancing the microclimate through shading and respiration. Figure 2.8 shows the cooling efficiency levels according to the landscape techniques used (Bar et el., 2009).

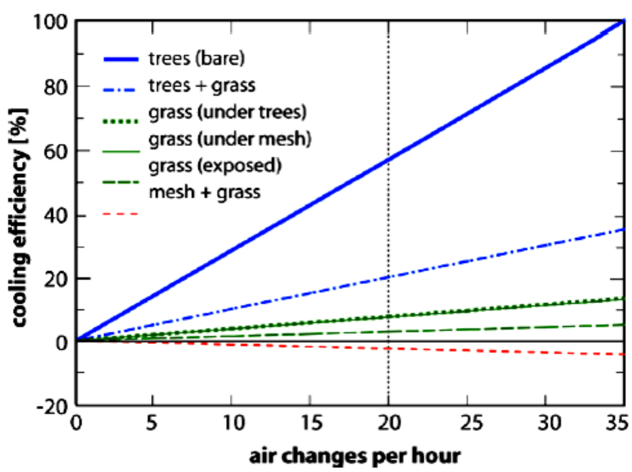



**Figure 2.8. The effect of calculated cooling efficiency of different assumed air change rates in the courtyards.**

**Source: Bar et el. 2009**

In search of the relation between vegetation and the microclimate Masmoudi and Mazouz (2004) assured the presence of such premise. The reduction of air temperature on the ground level was found to be about 5$^{o}$ C for the different plan forms tested (square and rectangular form). The examination of the results showed that the effect of the presence of vegetation is more effective than its quantity. The increase in the quantity of vegetable masses had no great significance when compared to the influence of applying trees in highly thermal stressed locations. The study guided the best orientation of trees line as north-east/south-west due to the reduction of the solar energy absorbed on the ground surfaces.

Several factors need to be addressed in the vegetation parameter investigation along with the orientation factor discussed by Masmoudi and Mazouz Mazouz (2004). The scale of the green areas needs to be fixed since this study is not just revealing the cooling effect of plants thus addressing several bioclimatic principles together. Large vegetated areas might work on enhancing the air temperature during peak heat hours rather than smaller parts but that might not be economically or practically applicable in many cases and also has disadvantages during night since it reduces the heat radiation. Densely vegetated areas find difficulties to dissipate heat during the night due to large concentrations of vegetable masses (Wong et el., 2007). The next factor to be investigated is the spacing between the green parts, the researchers argued that it would be effective in the cooling process if distributed with enough intervals (Hoffman and Bar, 2000). Goergi and Dimitriou (2010) had examined an area of a 100m2 and recommended that 8 trees can be planted with 5m from each other to achieve desirable thermal comfort balance throughout the year. The design of the vegetated area would to be undertaken from a holistic view regardless the types of trees.

Vegetation has proved to enhance the microclimate mainly through shading, reduction of surface temperatures and evaporative cooling (Mc Pherson et al., 1994). Accordingly several parameters of such component will be investigated. The urban canopy factor depending on the amount of trees within the site is significant and hence would be considered in the investigation process. Although high shading levels increase thermal comfort during the day in summer, they can decrease long-wave radiation loss on the surface, contributing to high temperatures at night. A balance between minimizing the sun radiation during hot summer days and allowing it during winter to maximize the heat gain has to be achieved when designing shelters for outdoor spaces (Hwang et al., 2010). Grass surfaces are considered to be of great cooling effect yet a proposed design ratio between the amounts of trees to the grass ratio will be suggested. The set of design guidelines proposed later will be indicative to an ecological design of an open space including the measurements of the vegetation parameter.

## 2.7 Summary of the Variables

The previous parameters reviewed have proved to enhance the ambient air temperature on various levels. Other factors have also revealed a positive effect on the thermal environments yet will not be covered within this study due to the lack of resources. Precedents have shown that vegetation has the most relevant differences on the air temperature followed by the space geometry and orientation respectively. Briefly, trees proved to have a higher cooling effect than grass due to the characteristics of plants along with the shade provided. The NS-EW and SW-NE orientation revealed to reduce the air temperature more than other orientations tested due to the shade provided. Higher geometry ratios have better effect on reducing the outdoor temperature while low ratios cannot tolerate heat stress. The ratio of 2 provided a balance between the day heat gain and night heat loss process. Very few studies have revealed the synthesized effect of the three variables; geometry, orientation and vegetation on the outdoor air temperature. More studies have tested each factor separately where all the parameters proved to promote the thermal comfort levels outdoors.

Applying passive design strategies needs further levels of details and specifications. Furthermore, very tight spaces proved to maximize the thermal comfort during summer while minimizing it during winter. The H/W ratio proved to be inversely proportional to the SVF which contributes to the dependent variable of energy consumption due to artificial lighting. Dense vegetation provides more shade and improves the cooling effect yet acts as wind breakers. Briefly, bioclimatic design is mainly about applying the passive cooling parameters but with critical design that suits both solar gains and diurnal radiation. Bioclimatic designs have to suit both warm summer conditions and cold winter needs. Thus automated principles that change their characteristics between seasonal variations have spread widely as of recent. If not applicable then compromises between seasonal requirements have to be achieved depending on each region.

## 2.8 Topic Limitations

### 2.8.1 Limitation of Materials

Within an open space, the penetration of the sunlight into the space is desirable yet crucial. The direct contact between the surface materials of the ground, seating and buildings is expected to absorb the heat and release it to the physical environment depending on the characteristics of each material. Ignoring the role of materials on the microclimate would be considered immature. The urban surface materials are responsible immensely for the urban heat island effect (Oke et al., 1991). Nowadays, a wide selection of materials is available for each part of an urban space with different characteristics where the choice between them should be based on several factors such as their emissivity and the heat capacity. The ability of a material to store heat and release it to its surrounding is better known as the heat capacity of the material. Some materials have high heat capacity which contributes to warmer surroundings and is more desirable in cold regions. Low heat capacity materials or reflective materials are more suitable for hot regions. Moreover, the tools available for testing the material's ecological suitability and its efficiency within an existing setting currently remain limited which is the reason of exclusion of materials effect on air temperature.

### 2.8.2 An Optimum Design Method

Achieving optimum design standards for the outdoor thermal environment is a challenging matter that has not been covered thoroughly. The reason for that lies behind the complexity of the outdoor parameters along with the limitation of the available tools and their easiness. Researchers attempt to be realistic about what should be tested and what can be tested due to the infinite parameters of the outdoor environment. Testing the huge number of the outdoor parameters within a couple of studies remains impossible yet essential for the design field (Chen et al., 2006). Designers seek optimum standards that are usually done empirically to develop their concepts and take them out to the real world. Furthermore, studies that focus on the benefits of vegetation, shading, geometry…etc and its impact on the outdoor environment basically seek an ideal outdoor thermal comfort. An optimum design method that achieves the comfort sensation levels sums up the different studies that achieve the same goal. This research aims to emphasize the earlier investigations of the positive effect of various ecological design aspects for an outdoor environment. Figure 2.9 explains the concept followed for achieving an optimum design.

According to Chen et al. (2006) investigation, achieving an optimum design method for a pleasant outdoor environment was possible. The lack of such investigations within the current research field signified their study vastly. The study used a numerical method to meet the objectives presenting the sequential process that was used to achieve an optimum design criterion which widens the research applications for different climatic zones as well including the current study. The research was generally based upon three consecutive stages; the first stage sets the problem focusing on all its parameters, objectives and the methods to be used for solving and evaluation. The second stage was basically about observing the outdoor thermal environment including the spatial distribution of wind velocity; air temperature, humidity and mean radiant temperature were obtained. The third stage congests the previous stages to be able to evaluate a controlled optimum design method that has been identified in the first stage. Several methodologies were used throughout this process such as the Monte Carlo method, CFD and Genetic Algorithms consecutively.

The optimum design method has been identified through the Genetic Algorithm method following two inquiries for the candidate of the highest fitness to be considered as the optimum design. Furthermore, the optimum arrangement of trees and building has gone through a Genetic Algorithm method for achieving a pleasant outdoor thermal environment. The organized demonstration of process used for the study clearly fulfills

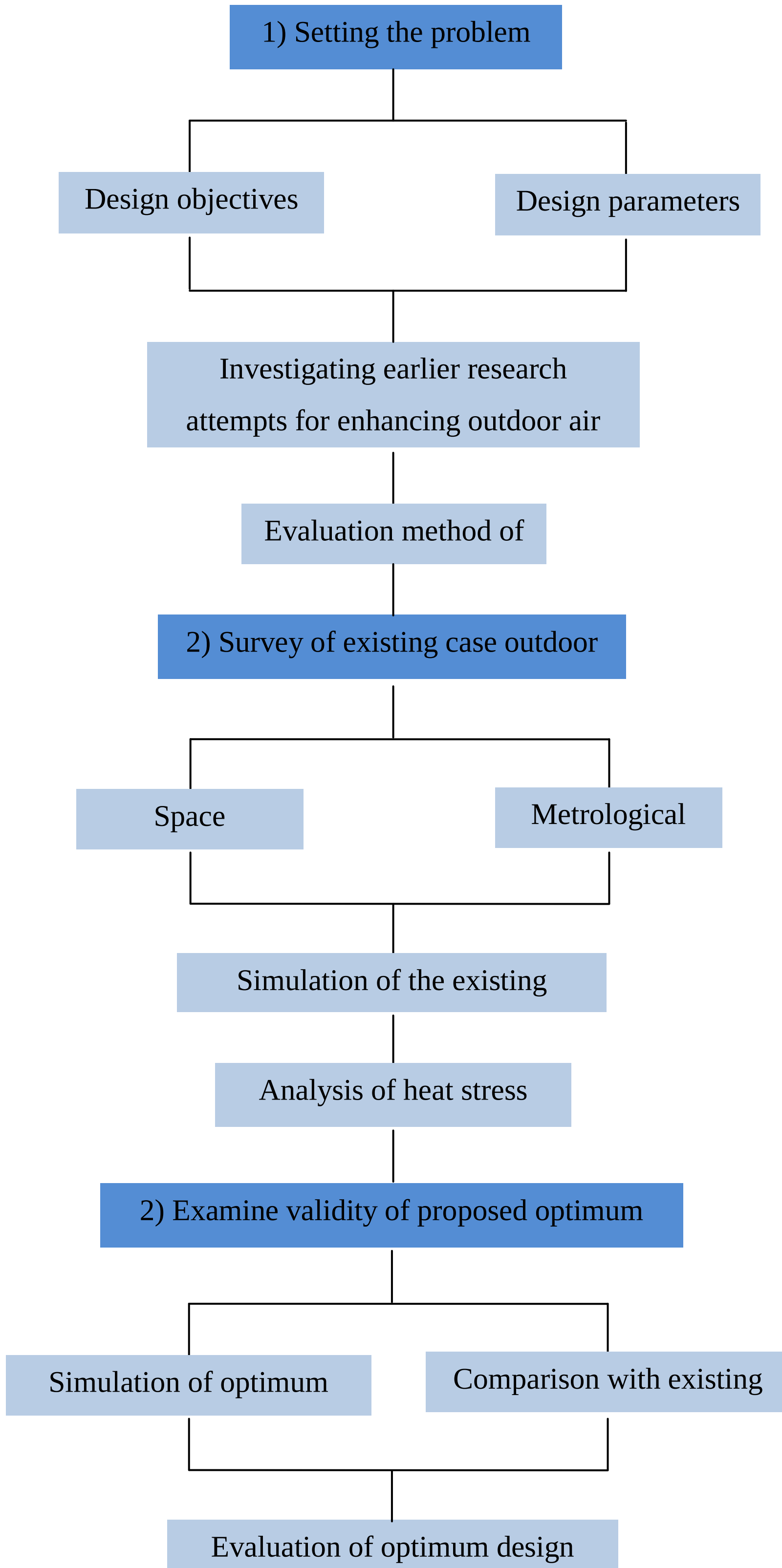



**Figure 2.9. Process followed to achieve an optimum design method for outdoor space design through bioclimatic design principles based on the previous study.**

the main goal. Buildings where standardized as (20x20x30m (LxWxH)) where July 23rd at 15:00h is defined as the date and time for analysis. The number, size and distribution of the trees and buildings where defined clearly. Their results prove the effect of building heights, orientation and geometry on the outdoor thermal environment surrounding them identifying the orientation factor. With the rotation of the fixed buildings and trees arrangements through the stages of the test matrix, the wind speed has enhanced the outdoor spaces when allowed to penetrate them. Figure 2.10 shows that different building geometry within the site orientation has proved to be more effective, whereas, in cases 2-1 and 2-3 a more pleasant outdoor space has been achieved due to the influence of the wind direction. To showcase a justified method for achieving a goal is more valuable to the research field than simply fulfilling the hypothesis under investigation. The methodology used makes the study more beneficial for a wider range of researchers with different hypotheses which is very similar to the goal of the current study (Chen et al. 2006).

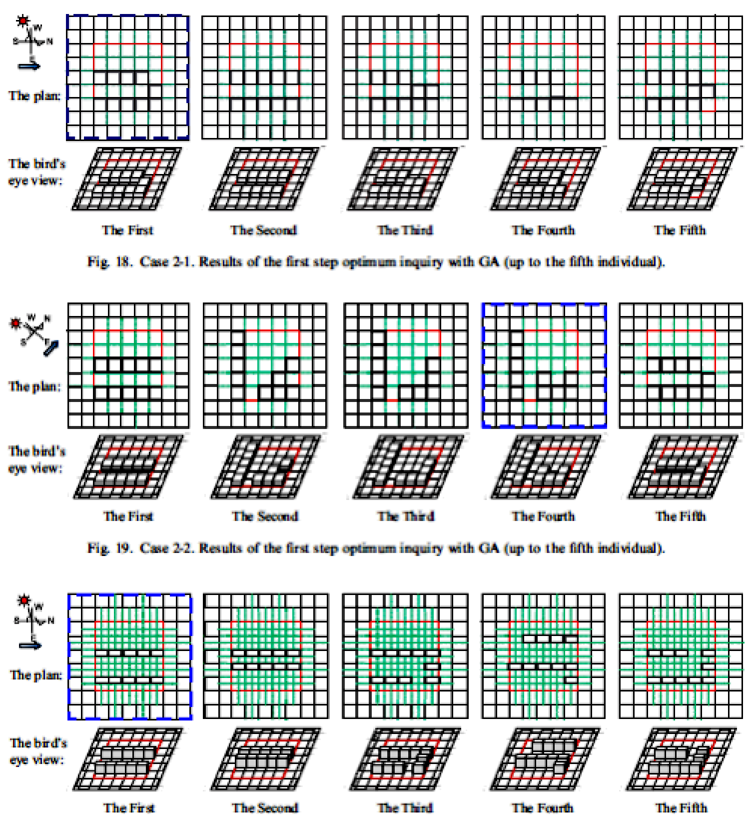



**Figure 2.10. Three case scenarios whereas cases 2-1 and 2-3 has proved to have more pleasant outdoor environment.**

**Source: Chen et al. 2006**

## 2.9 Research Niche

The current research investigated several parameters affecting the outdoor microclimate in search for a deeper understanding to the environmental behavior in which needs to be enhanced. Through the reviewed articles presented above it was clear that several studies examined various factors affecting the outdoor microclimate but on solitary basis rather than testing their combined impact. Furthermore, the parameters presented such as geometry, orientation and vegetation proved to contribute positively to the air temperature with different values yet its undefined weather the improvement achieved in case all these parameters were incorporated in one space would even be more significant.

In real case, the complexity of the outdoor environments lies behind the behavior of the different parameters together leading to a set of reactions influencing the microclimate. The composition of an open space includes all the mentioned parameters such as geometry, orientation and vegetation whether designed passively or spontaneously present. However, the promise given that those parameters would enhance the thermal sensation if designed passively in one space is unclear and requires further investigation. The criteria used for the current investigation was based upon combining the cooling outdoor parameters together where the total result of improvement of a passive space design would be demonstrated understanding the patterns and phenomena leading to it. Understanding our microclimate and its parameters behaviors is a further step towards achieving a sustainable future.

## 2.10 Research Framework

### 2.10.1 Hypotheses

i. Use of bioclimatic approach in the design of outdoor urban spaces enhances the ambient air temperature in the climate of Dubai.
ii. Application of the bioclimatic principles such as proper space geometry, orientation and vegetation increases the cooling effect significantly within the spaces.

### 2.10.2 Objectives

- Examine the impact of the microclimatic variables such as orientation, geometry and vegetation on the outdoor air temperature individually and in a combined manner that incorporates the coolest parameter within each variable.
- To understand the vital parameters influencing an outdoor thermal behavior such as air temperature and wind speed to observe carefully during the investigation.
- To create different scenarios based on a defined criterion conducting a comparative analysis that would help to;
  - Evaluate the level of improvement achieved by each variable and by all together
  - Understand the behaviors of the variables tested thus predicting patterns of other untested variables.
- To provide a set of climatic design guidelines for an ecological outdoor urban space based on the previous understandings.

## 2.11 Summary of Findings

The literature review exhibited in this section presented a clear definition of the problem and all its dimensions. Recognizing the importance of urban open spaces and their influential significance over decades triggered the need for the current research. The ability of urban open spaces to revive the public realm recalled the need to focus upon the parameters that makes it successful. The current study aims at achieving a set of bioclimatic design guidelines that are to be followed for enhancing the air temperature of the outdoor urban spaces. This study attempts to synthesize all parameters of enhancing ambient air temperature of outdoor spaces rather than being concerned with the effect of each separately. Due to the infinite set of possibilities that can be tested, a selective process has been made to the design parameters based upon the thorough literature review. Most effective parameters on the microclimate have been prioritized for research examination such as vegetation. Other parameters that revealed to enhance the microclimate will be tested along with vegetation such as space geometry and orientation.

The growth of Dubai's outdoor urban spaces and their importance to serve the governments goals has been reviewed. To achieve the current goal in this particular location is quite challenging especially after reviewing the climatic conditions of the region. The extreme conditions of the summer require much of attention to the techniques used. Jeopardizing the thermal comfort levels of the winter will definitely be done to a certain extent due to high thermal stresses during a longer summer period. The upcoming chapters will show an application of the various ideas and knowledge gained above. A digestive process of the bioclimatic parameters examination will be presented based on the verified or falsified hypothesis and leading to a set of environmental design guidelines in the last section.

# CHAPTER THREE: METHEDOLOGY

## 3.1 Background

In practical life, the need for research usually arises along with an incident that triggers a few queries in need for an answer. In this case a slight research process starts spontaneously and deepens gradually until it reaches the stage where planning is required. A general goal, known as the research aim, is set at the onset of the process and identified by what is called the objectives which are the means to achieving the goal. The steps followed to achieve the aims and objectives of a research would be considered as the research methodology. Each and every part of a research has its own methodology where all contribute to one goal. The scientific research methods used need to be based upon earlier attempts with similar investigations.

In this section a detailed explanation of the steps and procedures followed to carry out the current study will be reviewed. The tools and techniques used in each stage of research will be identified and justified critically. A description of the tools and methods used for the collective and analytical stages tackles the accuracy and validation of the results reviewed in Chapter 4. Methods addressed for each stage will be based upon the research limitations that will also be identified.

Through earlier investigations done to enhance the outdoor air temperature and achieve a better microclimate it has been found that several methodologies where used depending on each research resources. It is essential to get an overview of methods used by other researchers to attain similar goals and guarantee the quality of knowledge added to the research arena. According to the literature review done in Chapter 2, trying to understand the various parameters of a bioclimatic approach, three research methods were mainly used. Social surveys, field measurements, and computer simulation were mainly followed for outdoor parameters investigations. Each of the mentioned methodologies will be clarified separately justifying the selected method for the current investigation.

## 3.2 Methodologies Used for Similar Topics

### 3.2.1 Social Surveys

The cooling effect attained by any of the outdoor parameters has shown that the human parameter has played an effective role in analyzing the qualitative or quantitative data obtained. The terminology ‘thermal comfort’ defined in the first section was one of the main concerns driving a lot of studies. Topics related to the thermal comfort levels based on the human parameter involved social surveys. The purpose of using such method is to gather information about peoples’ response to the outdoor parameters. Questionnaires were used extensively to cover the subject of outdoor thermal comfort levels. This method is highly flexible in terms of time, duration and location. However might sometimes lack scientific reliability due to levels of bias obtained. To avoid the down side of the preceding method, a fixed sampling criterion should be set and be very critical and accurate towards the digested analytical process to the data obtained. Age, gender, clothing and other factors affect the accuracy of the information gathered. Social surveys can sometimes render subjective rather than objective results and that is where it lacks scientific reliability. Recording the psychological levels was considered more complex than the physical measurements due to the huge number of unstable dependent variables.

Baker et el. (2001) focused on understanding the human parameter through their investigations about thermal comfort in outdoor spaces. They used a purely physiological model which was found to be inadequate in characterizing thermal comfort levels in outdoor urban spaces. The samples proved to have different purposes for using the outdoor spaces which controlled their level of acceptance for the microclimate. Nikolopoulou and Spyros (2005), on the other hand, used a huge database consisting of 10,000 questionnaires in several cities and confirmed that using one parameter as a determinant for comfort is inadequate for the assessment of thermal comfort levels. Whereas Nikolopoulou and Lykoudis (2006) used social surveys along with field measurements that proved to have a correlation between the physical and the psychological parameters for investigating the use of outdoor spaces.

To regulate the interrelation between the qualitative data obtained from social surveys and quantitative data measured, some softwares were developed to define the results in scientific units. Physical Equivalent Temperature PET, Physical Mean Vote PMV, Actual Sensation Vote ASV, Predicted Percentage of Dissatisfied PPD were thermal indices developed to standardize thermal comfort levels. Bastos et al. (2006) used PMV as a prediction of comfort through the software developed by De Dear (2005) to insert the social survey data gathered. Gaitani et al. (2005) used the ‘Comfa’ and ‘thermal sensation’ as bioclimatic indices to indicate the levels of satisfaction and dissatisfaction. The outcomes were used to improve the outdoor microclimate by applying passive cooling techniques through a simulation method. All studies approved that using social surveys is not enough to indicate the thermal comfort levels of an outdoor environment.

### 3.2.2 Experimental Method

Experiments have high scientific reliability and high validity of results due to the high levels of experimental control achieved. Experiments are one of the oldest methodologies used throughout history. The concept of repeatability gives the chance of trial and error which taught humanity tremendous discoveries. The controlled environments obtained in a lab usually guarantee the level of accuracy of the results if accuracy has been attained through the testing process. On the other hand this high level of accuracy required along with the time and money needed for using such method, leads to its inconvenience in many situations.

Experimental research method can be considered one of the methods for proving the hypothesis of this research. Outdoor urban spaces can be used as in situ labs, and accordingly a lot of preparations can be done to compare the existing unsuccessful situation with a modified one. Such outdoor experiments have the advantage of existence of the numerous outdoor complex parameters in the testing model which minimizes the levels of errors to a wide extent. Yet, it is considered to be more effective in the investigation of several parameters together since it is impossible to separate one or more variable and test it on its own. The results obtained in this case would be more associated with the specific experiment location rather than extracting a generalized concept.

Very few studies used such method to investigate the effect of outdoor variables that enhance the microclimate. It is mainly old studies that had used experiments heavily due to the limitations faced. Givoni (1991) revealed six experiments done to investigate the thermal effect of plants in urban areas. Experiments done had tested one or two variables maximum in each study such as spacing between trees, or effect of landscape on cooling energy consumption, or the air infiltration rates from the outdoor environment to the indoor surrounding structure…etc. The climatic guidelines recommended were based upon the earlier investigations rather than Givoni's investigation due to the limited resources available.

Bar et al. (2009) configured an outdoor open space in a hot arid climate to investigate six different landscape strategies. A controlled experiment in two adjacent semi enclosed spaces such as courtyards with similar geometry, orientation, exposure to the environment and material attributes but with different landscape treatments has been used. The measurements have been taken simultaneously in the two courtyards providing each with three landscape configurations. The concept of combining several configurations undermines the reliability of the results. The cooling efficiency has not been measured directly since it requires an estimate of the air change rate which is quite difficult to measure in an outdoor space. The experimental method is considered to be a very critical one since it requires quite challenging experimental conditions. The results of such experiments can lead to uncertain results unless the test environment is controlled and the hypothesis set only concerns a single parameter.

### 3.2.3 Field Measurements

In situ, data gathering revealed to be an essential method for most of the scientific studies. It is simply an interpretation of the existing situation into data that can be further utilized in another study. Hence, this method is usually a complementing, yet essential one to the main method used. It can be used separately to state certain existing phenomena or theories. The accuracy of this particular method is based upon the preciseness of the measurement tools. The field measurements method has a scientific reliability due to its simplicity. When such method is used for the investigation of a case, thus it follows that thermal comfort records are expected to cover all various climatic conditions (all seasons of the year). The time interval required to study certain phenomena are rather long.

When testing thermal comfort in outdoor urban spaces, climatic records have to be measured with precision. Therefore the in situ survey becomes essential and requires high levels of accuracy. The time interval of data recorded in the case of study needs to be long enough to obtain valid measurements. The presence of a lot of dependent and independent variables in the field requires the great awareness of the researcher to how they can affect the readings. Field measurements investigating the outdoor complex parameters have always been combined with social surveys or simulation methods.

Bastos et el. (2006) used the actual sensation vote ASV, predicted mean vote PMV and the predicted percentage of dissatisfied PPD as the guide to the thermal comfort levels of the outdoor spaces. Field measurements have been accompanied by the conducted questionnaires to monitor the local environment physical condition. Using a combination of scientific methods such as field measurement or simulations in addition to social surveys has minimized the usually biased results obtained from questionnaires if solely used. Gaitani et el. (2007) used simulation along with the 'Comfa' method in an attempt to improve the outdoor thermal conditions. The study accommodated some bioclimatic principles that solved the discomfort sensation surveyed in the first stage of the research which validated the study's results.

The findings of the RUROS project Nikolopoulou and Lykoudis (2007) concentrated on the effect of the microclimatic factors and the usage of the outdoor spaces. Their findings exhibited the great dependence of the usage of space upon the microclimatic factors. Field measurements have been done along with the social surveys in several locations. The importance of the psychological and physiological factors for the thermal comfort sensation remains valid, yet it is quite important to enhance the physical outdoor microclimatic parameters to be able to attract people to use the space in the first place. Providing a variety of microclimatic solutions to help suit various users' needs has been recommended and thus needs further investigation.

Several studies used the field measurement as an aiding tool to their main methodology which is the computer simulation. Field measurements were the source of the input data required for simulations. The idea of measurements done to be input in computer software makes the results more realistic than having to insert absolute measurements. Studies done by Wong et al.and by Hoffman and Bar based their computer simulations upon experimental observations done in the site of study.

### 3.2.4 Computer Simulations

This research methodology is based upon transferring all the parameters of the environment accurately into the language that the computer understands to test it under certain variables. During this translation a critical choice of which of the contextual variables are to be imitated and which will be dismissed while making sure those dismissed do not affect your results. This method allows the researcher to make some assumptions that need to be dealt with carefully. Simulations have the ability to rapidly run complicated tests with complex parameters with more efficiency than experimental methods which is why it has been vastly used recently. Simulations can predict situations that have not occurred yet and predict factors that are threatening to the environment.

Computations are now taking place in all fields of study. People find it much simpler and economical to run tests and studies in a virtual medium rather than reality. Advancements taking place within the available softwares is helping this merely to happen. Recognition by authorized organizations towards those programs achieves the validation of the results obtained. The high level of accuracy of the performance is another reason for this validation. Repetition and flexibility of the simulation process makes it a scientifically reliable research method if the tools/softwares used are authorized. Computer simulation can be used to test complex parameters that are in some cases impossible to test, which is the case of outdoor environment. On the other hand, the experimental method, the virtual form of data and parameters can sometimes be tricky to the researcher and might lead to invalid results.

Wong et el. (2007) used ENVI-Met, a three dimensional microclimate model designed to simulate the surface-plant-air interactions in an urban environment. The input data was based upon the electronic map and information provided by the office of Estate and Development. The simulation conducted, included four different scenarios including the existing case. Three variations were simulated, other than the existing situations according to the data gathered by satellite images indicating hot spots. A worse case and a better case scenario were tested in locations identified to show high thermal stresses during day and night time. Field measurements on a specific day were done to validate the simulation readings and results. The software used was limited in terms of simulating the vegetated roof tops which was the case in some buildings and would have showed much potential.

Another study by Robitu et el. (2005) coupled the airflow and thermal radiation models to test the influence of vegetation and a water pond on the microclimate, and that proved to be of a positive effect. A complex geometry of urban spaces has been modeled through the SOLENE software for the thermal radiation and the computational fluid dynamics CFD model for airflow implemented in FLUENT environmental software. Two variations have been done to the existing situation, one of which enhances it and adds trees and a water pond while the other has no tree or water pond. The study revealed the need for one week to be able to simulate one scenario only. Despite the shortcomings of the computing method it can provide useful quantitative information for outdoor design decisions.

The effect of aspect ratio and orientation of an outdoor space has been tested through ENVI-Met and SOLENE softwares in a couple of studies. Outdoor urban configurations have been generalized by several studies rather than investigating specific site maps. Validating the concepts was more of a concern than testing other parameters valid in the existing location. Some of the researchers constructed controlled environments with realistic locations to test a number of variables, their results have been generalized and used in similar climatic conditions rather than being improvements of existing sites (ex: Toudert and Mayer, 2005, Masmoudi and Mazouz, 2004, Chen et al., 2008).

The cluster thermal time constant CTTC model is another simulation tool used and has been carried out by Bar and Hoffman (2003) to investigate the passive cooling effect of geometry, orientation and vegetation in an outdoor environment. The software predicts the air temperature through the calculation of the heat received from external sources, mainly net solar radiation and anthropogenic heat release. The researchers' choice of the simulation software used to validate or falsify the hypothesis was based on the capabilities of the tool in question. All softwares available for simulating the outdoor urban environment require different types of data and accordingly provide different outputs. Through papers reviewed, the choice of the suitable method is based upon the resources available for each study.

## 3.3 Selected Methodology

Considering the complexity of the parameters in an outdoor urban environment, the limited resources and the research goals, several methodologies were excluded from the current study. Using social surveys is not suitable for measuring the physical parameters of the environment such as air temperature, however the comfort levels approved by earlier surveys would be considered as the base line of the heat sensation. Experimental method requires huge financial and time resources that are unavailable and unpractical in the current situation. Another method used earlier for similar studies was field measurements which have also been excluded due to the limitation of time and the outdoor measuring tools. Measurements during various seasons of the year are considered to be essential since the ecological enhancement has to fit the summer and winter conditions. Therefore, the substantial information needed regarding the local outdoor environment throughout the year has been gathered through official weather data stations provided by the UAE government. Such measurements have been used as the foundation for the results of the research.

Computer simulation has been commonly used in similar investigations and was selected for the current study due to the distinct advantages over other methods. The research hypothesis set earlier to investigate the cooling effect of the bioclimatic design principles to an outdoor urban space requires a large number of tests to be performed. To identify the bioclimatic principles that would enhance the outdoor air temperature of a space, each of these principles has to be tested separately and validated. Furthermore, determining the best orientation for an outdoor space requires testing all possibilities prior to the selection, thus testing each of the parameters of the bioclimatic principles independently requires the elimination of other variables during testing to prevent misinterpretation. The need for a controlled environment for such tests has encouraged the use of computer simulation for the topic under investigation. The simulation process also has the advantage of testing the wide number of variables of the hypothesis in a very short time yet accurate enough to generalize the results to similar climatic conditions.

## 3.4 Selected Software

ENVI-Met, SOLENE, CITY SHADOWS, CityCAD and Eco-tect software are computer softwares used for the outdoor environment investigations. Eco-tect analysis and CITY SHADOWS are considered to be quite limited in terms of calculating wind and accurate temperature variations in the outdoor environments. These softwares consider general information about the climate of study with no variations within each climatic region. Yet, Eco-tect has been used for the extraction of general data about the climatic conditions of the current study. Compared to the available tools for measuring outdoor parameters ENVI-met software was found to be the most suitable for the parameters identified due to various reasons. ENVI-met is regularly updated free software dedicated for outdoor investigations which focuses upon all the dimensions of the environment such as the atmosphere, the soil and all of the surfaces in a space. The software incorporates all the imperative parameters valid in an outdoor environment which attains validated results. The software is a three dimensional microclimatic model designed to simulate the surface–plant–air interactions in urban environment. The ground surface, vegetation, buildings surfaces and elements within the space are all incorporated in the calculations of the heat sources of an outdoor space. It also has the advantage of incorporating different types of vegetation deeming the foliage temperature, the heat and vapor exchange within the air canopy which is one of the crucial variables of the study. Considering the wind effect in the statistical analysis of the results is essential and provided by such tool where the wind flow field is treated as a normal prognostic variable and calculated each step. Moreover, the software is designed for micro-scale 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 10 sec at maximum. This resolution allows analyzing small-scale interactions between individual buildings, surfaces and plants that is appropriate for this research (Bruse, 1999).

### 3.5 Software Validation

ENVI-met software has been used several times in scientific researches that happened to make it as scientific publications. Toudert and Mayer (2006) used the software for testing the thermal comfort in an outdoor environment. The software was able to simulate the impact of the aspect ratio and orientation of a street canyon where the results provided were in accordance with the results obtained by Masdoumi and Mazouz (2004) using the SOLENE software to investigate the same parameters. The investigation of the same parameters by Johansson (2006) using field measurements in assessing the thermal comfort levels discussed were also in compliance with the above mentioned studies. The building materials in ENVI-met have compared to be in good approximation for their average properties (Fahmy and Sharples, 2009).

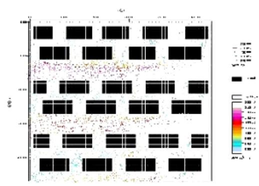
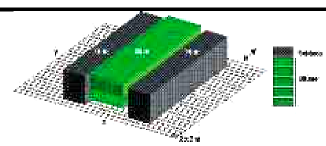
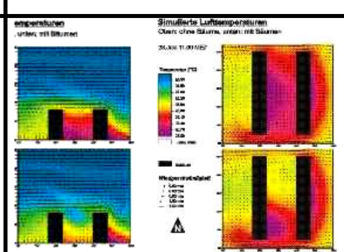
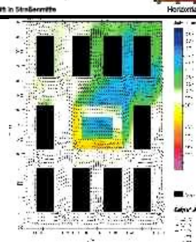
Bruse and Fleer (1998) simulated surface-plant-air interactions inside urban environment using ENVI-met using a grid of 5m focusing on the horizontal and vertical wind flow and temperature distribution. The study showed that all inputs are being considered in the simulations such as building a small green area adjacent to the site of study. Another study using the same software compared the current results of the existing conditions in National University of Singapore to the enhanced scenario which proved to give a higher value by $1^0$C (Hein and Jusuf, 2007).

Results attained by the software have proved to be in compliance with studies done using other methodologies or other softwares. The only shortcoming of the software, ENVI-met, is exhibited in the values of some of the outdoor parameters where some studies argued to be exceeding or below the existing situations. Thanpar and Yannas (2008) investigating the urban form of Dubai where the simulated results were almost similar to those measured in-situ but with a slight reduction. Toudert and Mayer (2006) summarized that the PET values obtained by the software might be overestimated compared with real situations. Several researches recommended the need for adjustments of the results attained by ENVI-met (as the case with all computer simulations) with field measurements. The reason for such drawback might be due to excluding the heat storage of the buildings that would contribute to more heat radiation in the outdoor environment.

Several online validation attempts done in 2002 using ENVI-Met tested the capabilities of the software to consider various variables into the results. The examples available online demonstrate the behavior of the software towards some outdoor parameters such as wind, temperature, vegetation, height etc. The demonstrations presented below in Table 3.1 are easy to access, brief yet expressive enough to validate software.

**Table 3.1. Summary of the online ENVI-met validation projects related to the topic.**

**Source: www.envi-met.com**

| Model | Variable | Image | Outcomes |
|---|---|---|---|
| Street layout in SE Australia | Wind direction, speed and behavior around buildings |  | The software updates the initial wind direction according to the layout orientation.<br>Wind direction and speed changes with the presence of any obstacles. |
| Street canyon | Vegetation impact on the space |  | Trees are being considered as 3D objects incorporating the vegetation characteristics. |
| Street canyon | Horizontal and vertical air temperature distribution with and without trees |  | Trees provide a 3D cooling effect rather than affecting the ground surface temperature. |
| Park | The expanded cooling effect of vegetation |  | The software simulates the environment as a whole taking into account the presence of an object or a neighbor park. |

### 3.6 Research Procedure

The large variety of the bioclimatic techniques that proved to enhance the outdoor air temperature through earlier studies and the difficulty to investigate them all caused the selection of a few parameters for investigation. The selection criterion of the parameters to be investigated will be mentioned below. Such parameters will be tested first separately to nominate the optimum condition of each parameter which then will be assembled together in an 'environmentally enhanced scenario'. For instance, during the investigation of the height to width factor, a H:W ratio of 1:2, 2:1 and 1:3 will be tested each to know which ratio has contributed to the lowest temperature values. That ratio will be incorporated in the 'enhanced scenario' in addition to the other factors that proved to record the lowest temperature in the other parameters. The enhanced scenario will be compared to an existing site in Dubai that has also been simulated using the same tools and climatic conditions to establish an impartial comparison. The outcomes of the comparison are expected show the real effect of the bioclimatic techniques applied.

Each and every procedure of the current study has gone through a thorough investigation that will be demonstrated below. The research procedures have been divided into three consecutive stages; data collection, simulation and the results analysis. The data collection section will demonstrate all the information gathered to create the simulations held in the next step. The results and environmental guidelines presented later in Chapter 5 are an outcome of the simulation process that will be analyzed. Each of the research procedures has been based upon scientific criterion to guarantee validated results. The tools and methodology of each process will be clarified sequentially and justified.

### 3.6.1 Step One: Data Collection Process

#### 3.6.1.1 Dubai Climate


**Figure 3.1. UAE location on the world map left and Dubai location on the UAE map right.**

**Source: Online Google maps**

Dubai lies on the coordinates of 25°N 55°E and classified to be a hyper hot arid climate with much lower precipitation levels than other cities in the subtropical zone. Heat stresses are high during summers from June to September with an average high around 40 °C (104 °F) and overnight lows around 30 °C (86 °F). The weather cools down gradually to its minimum values between December to March with an average high of 23 °C (73 °F) and overnight lows of 14 °C (57 °F) minor precipitation levels. The average number of days with rainfall is 28 days over the whole year where most days are sunny throughout the 12 months shown in Figure 3.2 (Dubai Meteorological office, Wikipedia, 2010).

Climatic information regarding the weather in Dubai has been extracted from the Eco-tect software. The information given by the software is based upon the weather data file of a specific city inserted through its database. Eco-tect is validated software widely used by architects to give an idea about the environmental conditions needed in each location.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Maximum Temperature °C (1984-2009) | 23.9 | 25.4 | 28.4 | 33.0 | 37.7 | 39.5 | 40.9 | 41.3 | 38.9 | 35.4 | 30.6 | 26.2 |
| Average Minimum Temperature °C (1984-2009) | 14.3 | 15.5 | 17.7 | 21.0 | 25.1 | 27.3 | 30.0 | 30.4 | 27.7 | 24.1 | 20.1 | 16.3 |
| Mean Rainfall (mm) (1967-2009) | 18.8 | 25.0 | 22.1 | 7.2 | 0.4 | 0.0 | 0.8 | 0.0 | 0.0 | 1.1 | 2.7 | 16.2 |
| Mean # of Days with Rain (1967-2009) | 5.5 | 4.7 | 5.8 | 2.6 | 0.3 | 0.0 | 0.5 | 0.5 | 0.1 | 0.2 | 1.3 | 3.8 |
| Sunshine Hours / day (1974-2009) | 8.1 | 8.6 | 8.7 | 10.2 | 11.3 | 11.5 | 10.7 | 10.5 | 10.3 | 9.9 | 9.3 | 8.2 |
| Mean Sea Temperature °C (1987-2009) | 20.9 | 20.6 | 22.3 | 25.0 | 28.5 | 31.2 | 32.2 | 32.8 | 31.9 | 29.7 | 27.1 | 23. |

**Figure 3.2. Temperature and precipitation all over the year in Dubai**

**Source: Dubai Metoerolical Office, 2010**

The Stereographic diagram below, Figure 3.3, shows the sun path according to the co-ordinates of Dubai. Blue lines represent the months of the year while the radial lines represent the latter showing the sunrise and sunset times and azimuth in the city. The image is taken at 12.00 o'clock on the 21$^{st}$ of August.

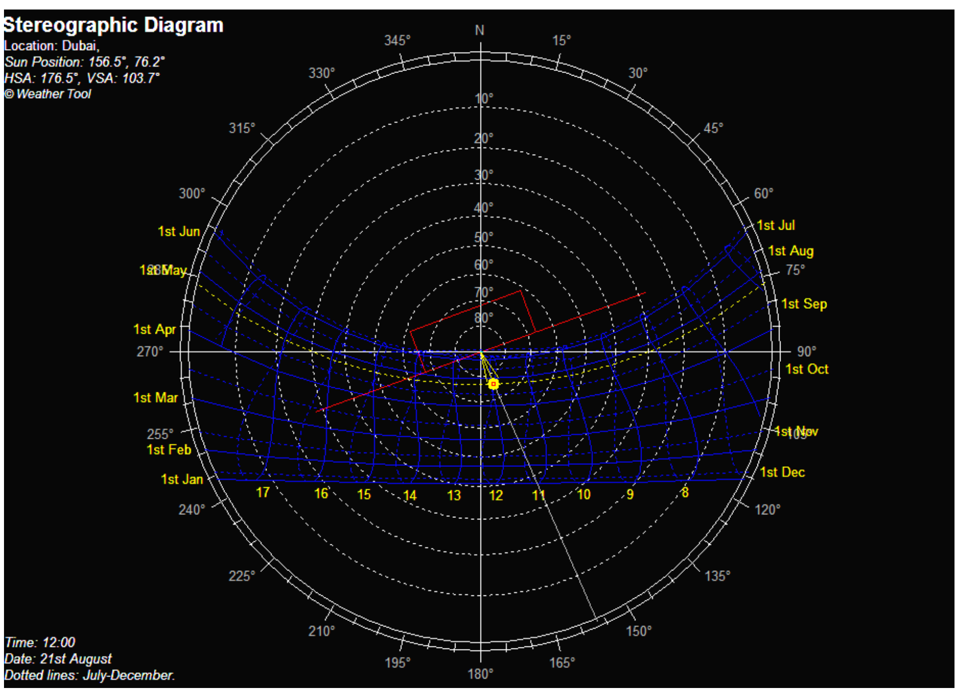



**Figure 3.3. Solar position of Dubai at 12.00 on the 21st of August.**

**Source: Climate Consultant software**

The diagram below, Figure 3.4, shows the climate summary of the daylight, radiation and temperature of the city showing August as the peak thermal stress period above 40°C as the highest temperatures with a slight equal reduction in July and September. The three months of summer consume high levels of artificial cooling. The cooling consumption drops in January which is considered the coldest month of the year with a highest reading of 15°C which is slightly than December and February. No heating strategies are required in the winter season even though the solar radiation is relatively high. May and June have the highest solar radiation levels throughout the year as shown in Figure 3.5. The low sun position facing the city causes high levels of radiation in addition to very high values of daylight all over the year which usually causes glare. One of the main discomforting factors in Dubai's climate is the high humidity levels. The relative humidity levels are high throughout the year, between 30-50% increasing on coastal areas to reach 60% especially between May and September as shown in Figure 3.6.

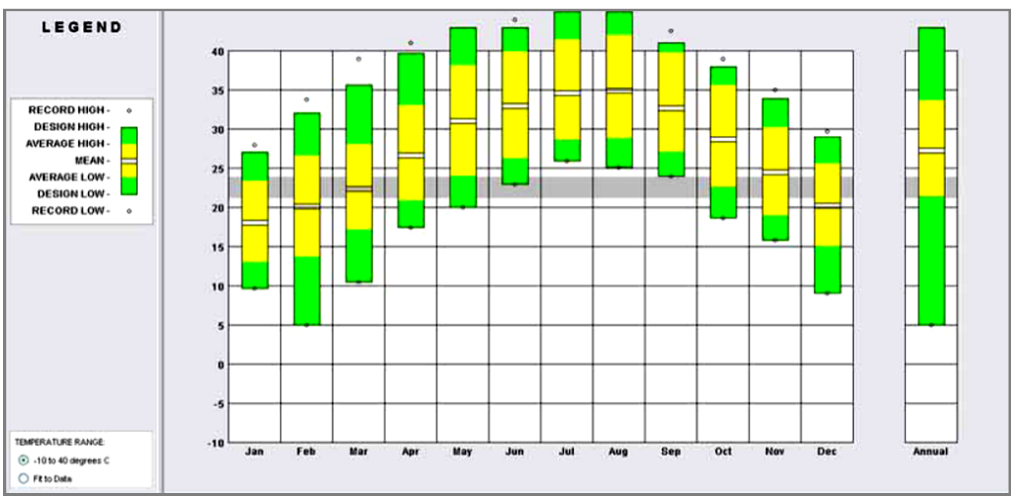



**Figure 3.4. Annual and monthly temperature values.**

**Source: Climate Consultant software**

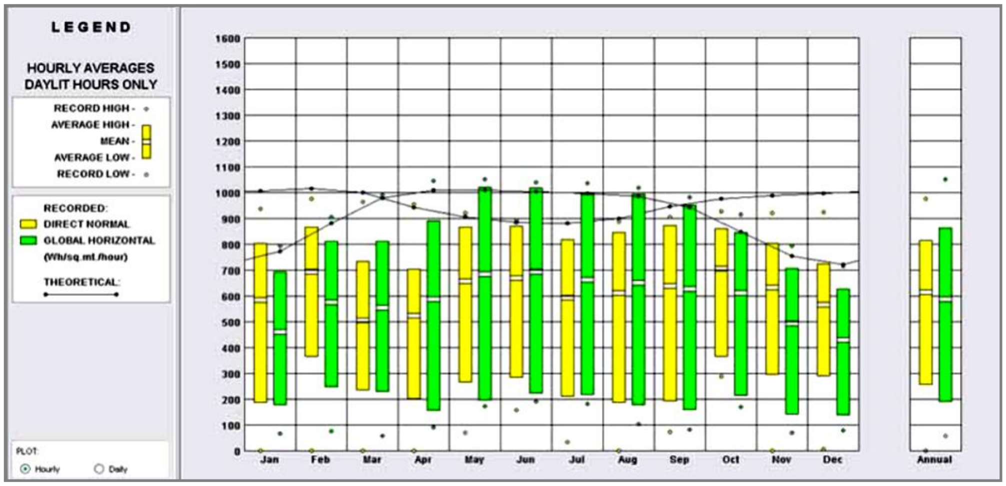



**Figure 3.5. Annual and monthly daylight hours representing the solar intensity.**

**Source Climate Consultant software**

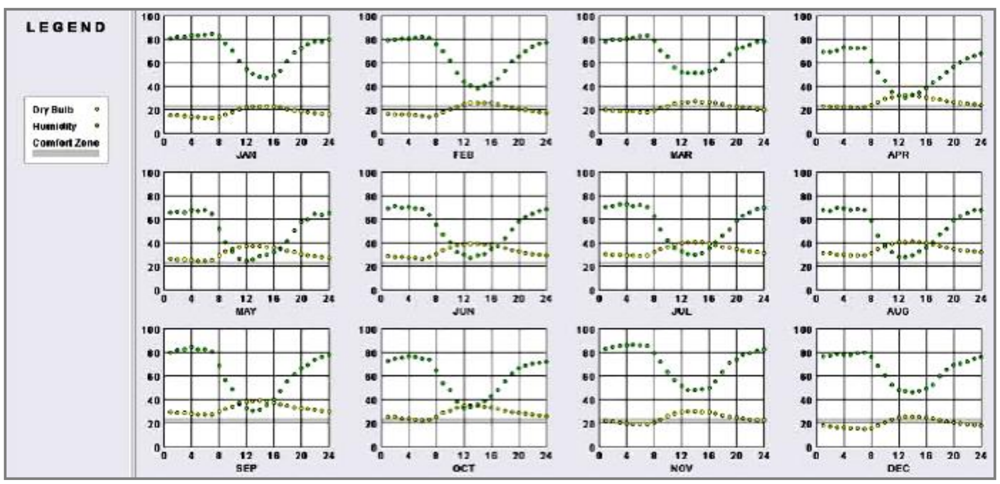



**Figure 3.6. Monthly dry bulb, humidity and comfort ranges.**

**Source: Climate Consultant software**

The prevailing wind in Dubai mainly comes from the North West direction commonly known as ‘Shamal’, recording the highest frequency of 2.7 to 5.5 m/s. Lower levels of wind blow from various directions all through the year as shown below (wind finder, 2010).

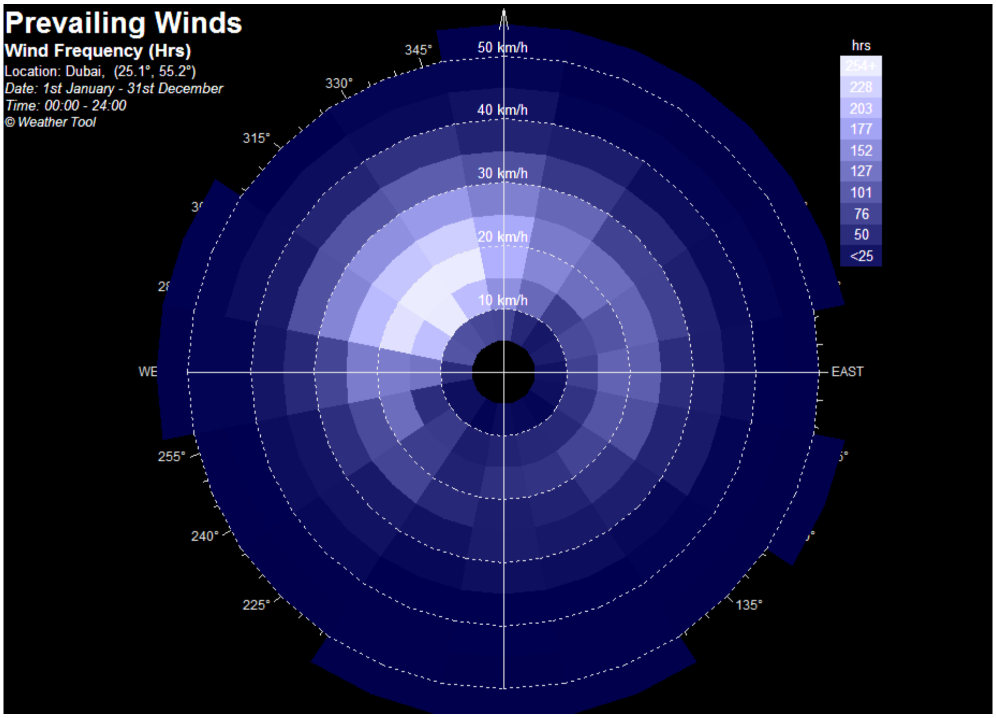



**Figure 3.7. Dubai wind rose representing the wind speed intensity and direction emphasizing the prevailing wind.**

**Source: Climate Consultant software**

Psychometric charts describe the relationship between dry-bulb temperature, and relative humidity, on the horizontal and the vertical axes respectively. The Thermal Comfort Zone is defined according to temperature and relative humidity, as well as the occupants’ involvements such as clothing and activity level. The diagram, Figure 3.8, demonstrates that the climate of Dubai is considered outside the comfort range in summer while in winter the comfort ranges comply with the climate. The comfort percentages represented in Figure 3.9 indicates high levels of discomfort during summer while during winter the comfort ranges are more applicable.

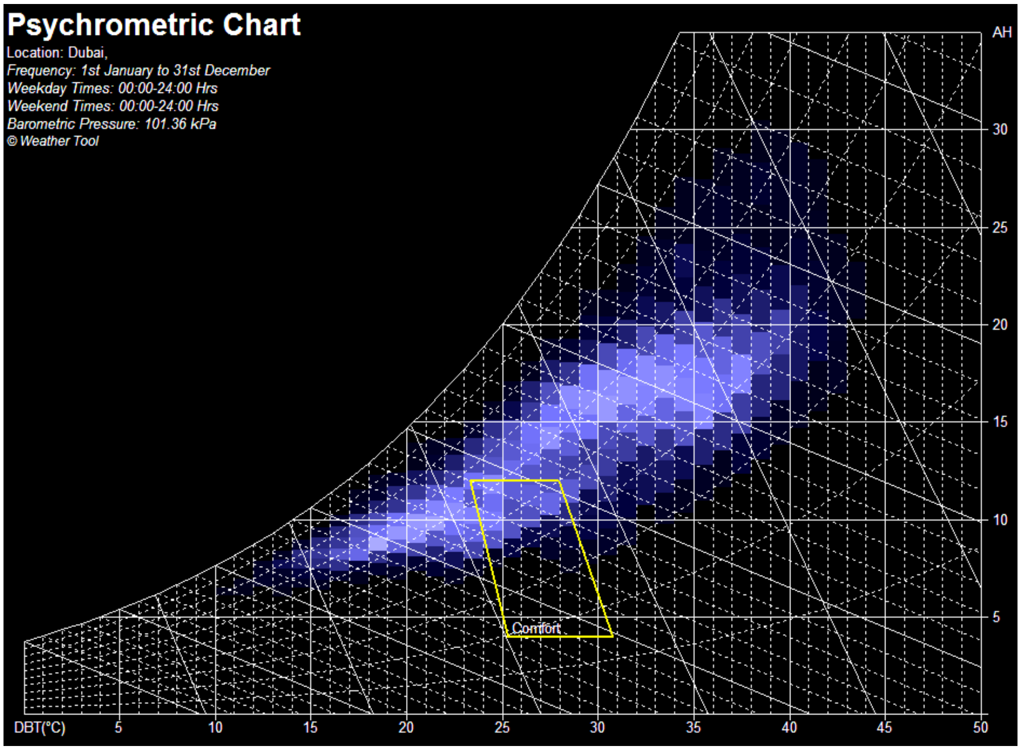



**Figure 3.8. Psychometric chart of Dubai indicating the comfort zone.**

**Source: Climate Consultant software**

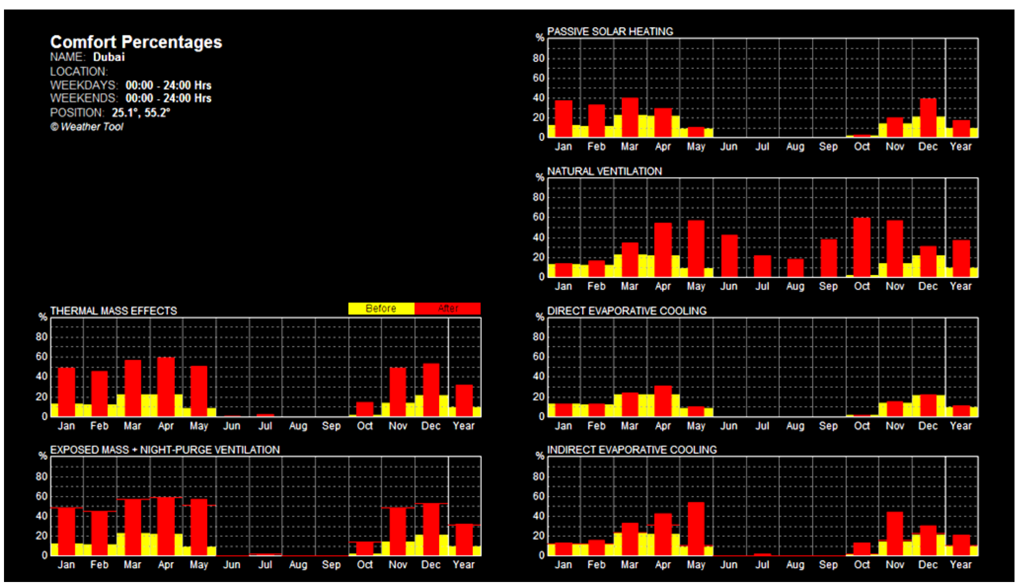



**Figure 3.9. Psychometric chart of Dubai indicating the comfort zone.**

**Source: Climate Consultant software**

### 3.6.1.2 Site Selection

Dubai Knowledge Village DKV has been selected, as shown above in Figure 3.10 & 3.11, as the site for investigation. The site selected lies within the urban area of the city yet is not a directly representative urban form of Dubai's city center. Nevertheless, the Knowledge Village is more similar to the business and touristic urban districts of Dubai since it lies within the Media city and represents the idea of 'city within a city' mentioned in Chapter 2. It lies in Jumeirah district in the center of a typical urban area of Dubai. The site is adjacent to Internet city, both of which are considered of great importance to business life in Dubai and with great similarities to the urban configuration of the DKV. The significance of urban open spaces within the DKV is considerably high as various international educational establishments are located inside DKV giving ultimate importance to such spaces. Climatic conditions of the DKV are very similar to other parts within the city center. The location of the site was not the only justification for selection but the functional requirements of the DKV campus are of great potential as well. An educational campus reflects the essentiality of the usage of the outdoor spaces within. Outdoor spaces in the DKV are used for leisure, social interaction and educational purposes hence the microclimate within the spaces should be enhanced for the users' comfort.

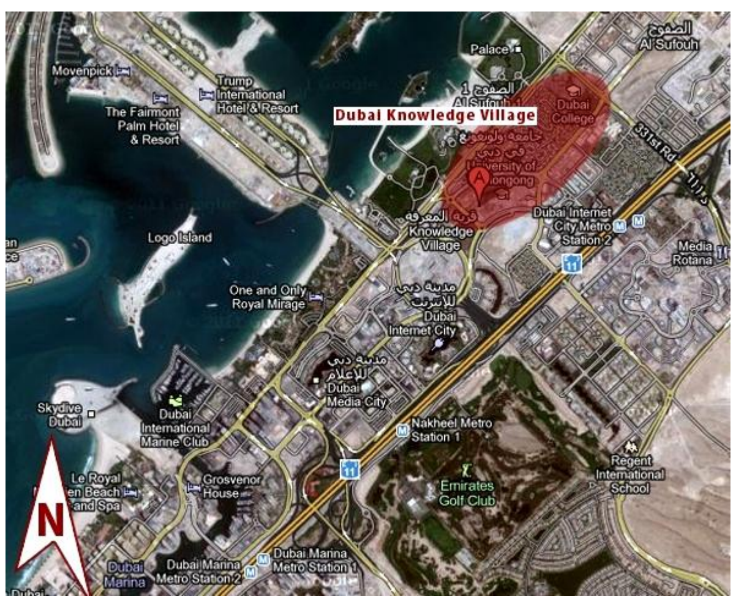



Figure 3.10. DKV location on Dubai's sea coast.

Source: Online Google Earth


**Figure 3.11. Selected area of study within DKV.**

**Source: Online Google Earth**

Since the focus of the study is mainly upon outdoor social spaces rather than large urban configurations therefore an up-close investigation of livable open spaces was the main concern. The area selected for simulation within DKV had to have certain characteristics. The site selection criterion was mainly based upon several factors;

- A representative configuration for conventional linear form of open spaces in the DKV and within Dubai to widen the benefit of the current study.
- A simulated area needs to be symmetrical in terms of urban geometry to exclude other parameters affecting the simulation results.

#### 3.6.1.3 Site Characteristics

Dubai Knowledge Village is one of the districts within Dubai with beautiful internal spaces for pedestrian use that creates a stunning calm. The site is well known for its pleasant outdoor spaces that surround all the educational buildings and bonds them together. The outdoor space under investigation is surrounded by a two story building on each side of the space with 8 meters height and some lanterns on the buildings' corners that reach 13m. The buildings take rectangular forms with various façade levels and recesses that create a beautiful non monotonous essence. The variation created within the building planes gives each building a special appearance within the same context. The building is coated mainly by stone paint varying between several light colors. The buildings have average size openings of one meter width and two meters height covered with reflective glass. The ground level usually has arcades for beauty purposes rather than having a functional use.

The alley space separating the buildings is covered with stone tiles. The vegetation within the site is mainly palm trees of varying height between 8 and 11m. Palm trees are scattered in a linear form with 12 meter spacing.


**Figure 3.12. Image of the Building within the area of study.**

**Source: Online Google Earth**

**Figure 3.13. Image of the Building within the area of study.**

**Source: Online Google Earth**

#### 3.6.1.4 Data Collection Tools

Information regarding site measurements and buildings' dimensions were obtained through online scaled Google maps from 'Google Earth'.

A site survey measurement was done to reassure the preciseness of the maps in hand. A 'Laser meter' was used for the site measurements such as building dimensions, building heights, trees heights and spacing. A digital camera was used for site photos and detailed images used in site description.

### 3.6.2 Step Two: Simulation Process

#### 3.6.2.1 Parameters of the Study

Factors that impact the outdoors air temperature were found to be numerous. Environmental designs are that which incorporate passive cooling techniques to the outdoor spaces. During the investigation of the bioclimatic design principles that has a cooling effect on the outdoor spaces in hot regions, the parameters were summarized as follows:

Materials of the space

Materials have a tremendous role in enhancing the outdoor air temperature (Bar and Hoffman, 2003 and Ferrante and Mihalakakou, 2001), however computer simulations are considered to be quite limited in terms of outdoor material library. Furthermore, the materials selection ranges given by the softwares testing the outdoors are still limited. The selected software 'ENVI-Met' considers the materials generally such as pavement concrete, brick road, asphalt road, sandy soil, deep water or granite pavement. Had it been the case that an investigation was to be launched on materials specifically, those choices given previously would have not been enough. Therefore the material parameter has been excluded from the current study.

Geometry: Height to width ratio

The geometry of the space in terms of height to width ratio is considered the most effective factor controlling the impact of geometry on air temperature. The manipulation of such factor gives the designer the chance to create pleasant spaces through shade and wind in spite all the other geometry factors such as space enclosure, and shape.

Geometry: Space composition (enclosed, semi enclosed)

The effect of the space composition on the air temperature revealed to be dependent on other factors within the space geometry such as H:W ratio of form where this aspect on geometry cannot be studied independently. Therefore such parameter was excluded.

Geometry: Form of the space (circular, rectangular, linear, staggered)

Earlier studies done to examine the effect of the space form on the microclimate concluded that such parameter has an insignificant effect whereas the space ratio has a more relevant impact which made this parameter to be excluded.

Size of the space (usually represented in volume)

The size of the space was excluded since it is a relative aspect to several other parameters and has a very small impact in which makes it irrelevant to be tested independently

(Masmoudi and Mazouz, 2004). Furthermore, spaces with the same volume but with different ratios have totally different impacts on the microclimate.

Orientation of the space

The other parameter that proved to have a great cooling effect along with the H:W ratio is the orientation. Orientation is a parameter that has a minor effect on its own yet this effect is augmented with proper space geometry.

Vegetation

The cooling effect of greenery has been over killed and proved to be the most influential factor in the bioclimatic principles. Adding the parameter of vegetation is considered essential for the current study’s goal.

Water features

Adding water features to the space is highly recommended in hot dry climates which increases the cooling sensation of wind. Water elements such as fountains which would increase the damp sensation in an arid climate have been excluded from the current investigation.

Sheltering elements (canopy, pergolas)

This paper is testing the impact of the natural bioclimatic parameters rather than manmade one. If artificial bioclimatic study was to be done such aspect has a promising impact that needs further investigation.

Most of the principles mentioned above have been investigated previously and contributed to creating more pleasant spaces. Earlier attempts described the cooling level of each of the parameters tested, in which assisted the selection process of the current study. Three of the above mentioned principles have been selected for a further investigation within the climate of Dubai; orientation, H:W ratio and vegetation.. These parameters have contributed the most effectively in a hot arid climate where extensive shadowing and ventilation through air movement is highly recommended (Golany, 1996). The selected parameters will be investigated on two bases:

- Each parameter would be tested separately focusing on several variations within.
- An enhanced scenario incorporating the coolest orientation, geometry and vegetation strategy is to be compared to the worst case scenario incorporating the warmest variables.

#### 3.6.2.2 Variables of the Analysis Matrix

The current study is set out to investigate the effect of several concepts. The relationship between the different concepts has to be casted in a certain manner to make it easy in principle. The concepts involved in the relationship will be known as variables (Abu Hijleh, 2010). There are a set of dependent and independent variables involved in the simulation process. The independent variable is supposed to govern the values of the dependent variables which can be explained as the ‘cause’ and ‘effect’ consequently.

In the current investigation the independent variables will be the bioclimatic parameters selected previously (geometry, orientation and vegetation). Each parameter will be addressed to test its effect on the outdoor space. For instance, changing the orientation of the selected open space would have an effect on the air temperature. Furthermore, a North-South orientation has a bigger effect of the outdoor air temperature than an East-West orientation. In this case the North-South and the East-West orientations are the independent variables being manipulated by the researcher to test their effect on the air temperature. The dependent variable in this case is the air temperature which is the outcome of the study. A dependent variable will always be the output of the study known as an ‘effect’ to the ‘cause’ of the independent variable which is the researcher’s input.

<u>Independent variables</u>

- Orientation: North-South, East-West, Northwest Southeast and Northeast Southwest orientations
- H:W ratio: 1:2, 2:1 and 3:1
- Vegetation: Continuous grass, continuous linear tree, tree groups, grass areas, continuous grass and tree groups

Dependent variables

- Ambient air temperature

During the manipulation of the various variables some factors must remain constant during the simulation. To be able to check the effect of one or more variables, other variables have to be set as a fixed value since they cannot be excluded from the test. For instance, during all tests conducted upon any of the parameters such as orientation, geometry or vegetation all the buildings surrounding the space have to be of neutral effect to the space. Moreover, projections on the buildings facades have proved to cause a cooling effect on the adjacent spaces due to the shadowing provided. If such factor is included in the simulation testing the effect of NS orientation on the outdoor space, this means that the outcomes presented will be representative of the orientation effect along with the building shading effect due to the façade projections. Thus to guarantee accurate outcomes that are representative of the particular parameter under investigation some factors will be considered fixed. The buildings will be simplified where the recesses on the facades will not be considered to prevent any confounding in the derived results.

Fixed variables

- Building line is horizontal rather than having a slight curvature
- Flat building facades with no recesses or projections
- Building heights to be 8m excluding lanterns
- Buildings to be of flat roofs
- Building materials unified as Albedo walls (defined by the software)

Test matrix

Due to the various numbers of variables investigated, a test matrix has been created for the easiness of the simulation procedures. The matrix is composed of the three independent variables under investigation vertically, which are orientation, geometry and vegetation. Distributed vertically is the different scenarios simulated with the base composition of the existing site scenario. In each of the simulations run one single parameter of each independent variable will be tested simultaneously. Furthermore, the breakdown of the following matrix is based upon changing only one parameter of the four independent variables in each column. The variable to be fixed in the existing scenario is represented in red shown in Table 3.2 when the other variables of the matrix are being tested. Table 3.3 clarifies the breakdown of the simulations matrix represented in Table 3.2. The breakdown table is consisted of 19 simulations that have been done consecutively based upon their numbering. Each simulation has its own conditions, duration and date depending on the examination methodology criteria explained previously.

**Table 3.2. Test matrix used for the simulation analysis. Red cells represent the fixed variables during simulation.**

| Independent variables | Orientation | H:W ratio | Grass | Trees |
|---|---|---|---|---|
| **Existing scenario** | $20^{o}$NW-SE | 0.8 | No | Tree every 12m |
| **Independent variables** | NS | 0.5 | Continuous | No |
| | EW | 2 | Grass pieces | Continuous linear |
| | SE-NW | 3 | No Grass | Tree groups |
| | NE-SW | | No Grass | Tree every 12m |
| **Enhanced scenario** | NE-SW | 0.5 | Continuous | Tree groups |
| **Worst case scenario** | EW | 3 | No | No |

**Table 3.3. Break down matrix identifying all simulations done and their configurations.**

| Independent parameters | Simulation number | Simulation time | Date of simulation | Orientation | Geometry H:W | Grass | Trees |
|---|---|---|---|---|---|---|---|
| Existing scenario | 01 | 8.00-22.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 0.8 | No | Tree every 12m |
| | 02 | 8.00-22.00 | January $21^{st}$,2010 | $20^{o}$NE-SW | 0.8 | No | Tree every 12m |
| Orientation | 03 | 8.00-18.00 | August $21^{st}$, 2010 | NS | 0.8 | No | Tree every 12m |
| | 04 | 8.00-18.00 | August $21^{st}$, 2010 | EW | 0.8 | No | Tree every 12m |
| | 05 | 8.00-18.00 | August $21^{st}$, 2010 | SE-NW | 0.8 | No | Tree every 12m |
| | 06 | 8.00-18.00 | August $21^{st}$, 2010 | SW-NE | 0.8 | No | Tree every 12m |
| Geometry H:W | 07 | 8.00-18.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 0.5 | No | Tree every 12m |
| | 08 | 8.00-18.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 2 | No | Tree every 12m |
| | 09 | 8.00-18.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 3 | No | Tree every 12m |
| Vegetation | 10 | 8.00-18.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 0.8 | Continuous | Tree every 12m |
| | 11 | 8.00-18.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 0.8 | Grass pieces | Tree every 12m |
| | 12 | 8.00-18.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 0.8 | Continuous | Tree groups |
| | 13 | 8.00-18.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 0.8 | No | Tree groups |
| | 14 | 8.00-18.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 0.8 | No | Continuous line |
| | 15 | 8.00-18.00 | August $21^{st}$, 2010 | $20^{o}$NE-SW | 0.8 | No | No |
| Enhanced scenario | 16 | 8.00-22.00 | August $21^{st}$, 2010 | NE-SW | 0.5 | Continuous | Tree groups |
| | 17 | 8.00-22.00 | January $21^{st}$, 2010 | NE-SW | 0.5 | Continuous | Tree groups |
| Worst case scenario | 18 | 8.00-22.00 | August $21^{st}$, 2010 | EW | 3 | No | No |
| | 19 | 8.00-22.00 | January $21^{st}$,2010 | EW | 3 | No | No |

#### 3.6.2.3 Simulation Initialization

According to the previous test matrix breakdown, nineteen simulations have been run, investigating three scenarios each in summer and winter in addition to the examination of three main parameters of the bioclimatic principles which are the orientation, geometry and vegetation. Each of these parameters had several variables within, whereas there were four orientations (NS, EW, NW-SE, SW-NE), three height to width ratios (0.5, 2, 4) and six strategies for vegetation (no tree, continuous linear trees, tree groups, grass pieces, continuous grass). To be able to test any of the mentioned parameters with no confounding, one parameter will be tested at a time during the extreme thermal stress conditions while all others are fixed according to the existing site of DKV conditions.

According to Fabros (2009), the summer season usually starts in June until September with August being the hottest month with the highest levels of humidity. Temperature during this month can reach more than 50ºC but the average monthly temperature is around 41°C. The cooler months of winter which occurs from December to February can have average maximum temperatures between 23-26ºC but can drop to around 14ºC at night time (Fabros, 2009). The current study aims at investigating the ability of the bioclimatic principles to enhance the outdoor air temperature during the extreme conditions of the year. If those principles succeed to even have a slight effect during the peak conditions of the year then they will definitely have a wider effect all through the other seasons. Therefore the independent variables will be tested during the worst case conditions which are during summer daytime (August 21$^{st}$ from 8am to 6 pm). Since the effect of the passive techniques varies in summer than in winter, therefore the three main comparative scenarios (existing, enhanced and worst) will be tested during both summer and winter time during day and night time (August 21$^{st}$ and January 21$^{st}$ from 8am to 10 pm).


**Figure 3.14 Selected area of study within DKV used for the simulations.**

**Source: Online Google maps**

The first model is for the existing area in the DKV referred to as ‘existing’ on the 21st of August which is the extreme summer conditions. The existing site had a 20° NE-SW orientation, a H:W ratio of 0.8, no grass and a tree planted every 12m. The exact same configuration was used for testing the existing site conditions for extreme winter on the 21st of January.

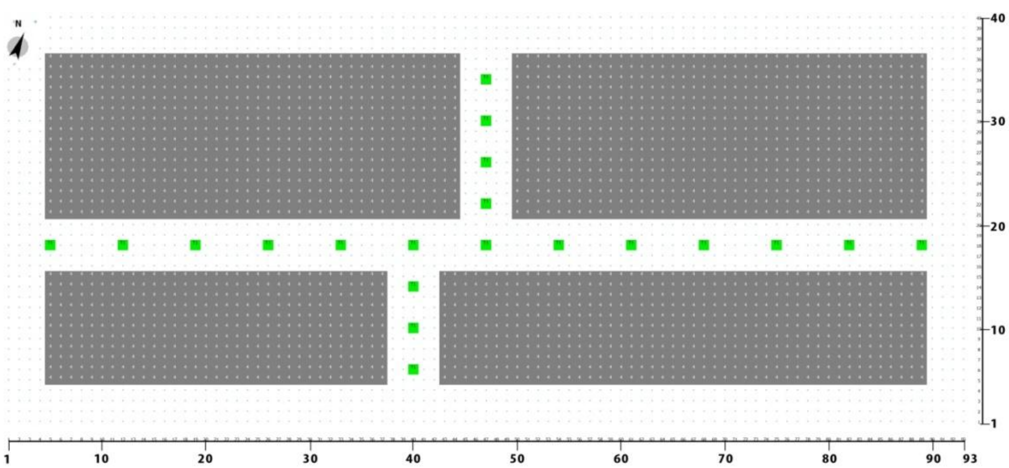



**Figure 3.15. The ‘existing’ case scenario representing simulations one and two (August 21st and January 21st)**

The third simulation was testing the NS orientation on the 21st of August whereas the North direction was tilted to be parallel to the linear space. All the other conditions of the 'existing' model were fixed. The model had a NS orientation, H:W ratio of 0.8, no grass and a tree planted every 12m.

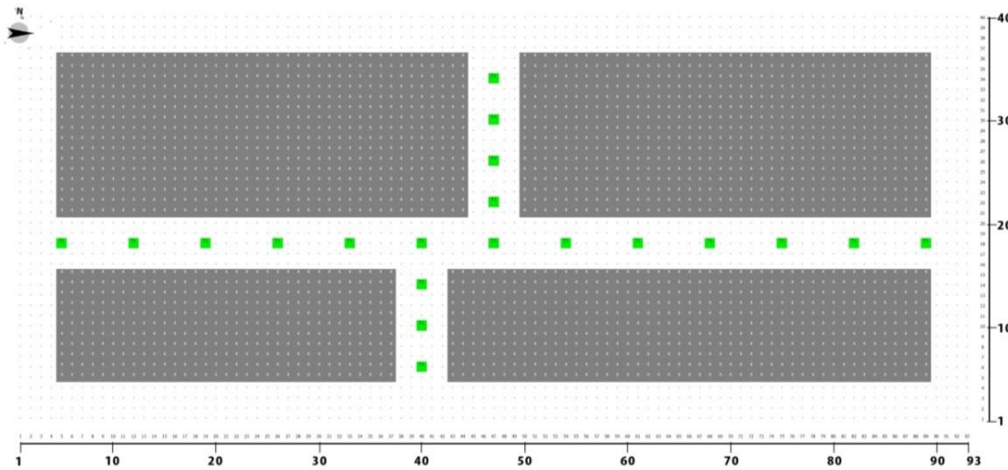



**Figure 3.16. The 'NS' testing the orientation variable representing simulation three (August 21st)**

The fourth, fifth and sixth simulations tested the EW, SE-NW and NE-SW orientations consecutively. The models where run on the 21st of August with a H:W ratio of 0.8, no grass and a tree planted every 12m which are the 'existing' site conditions. The NE-SW oriented model is very similar to the existing condition model since they both have very similar orientations but with different tilting. The existing model is tilted 20$^{o}$ NE-SW while the NE-SW model is tilted 45$^{o}$.

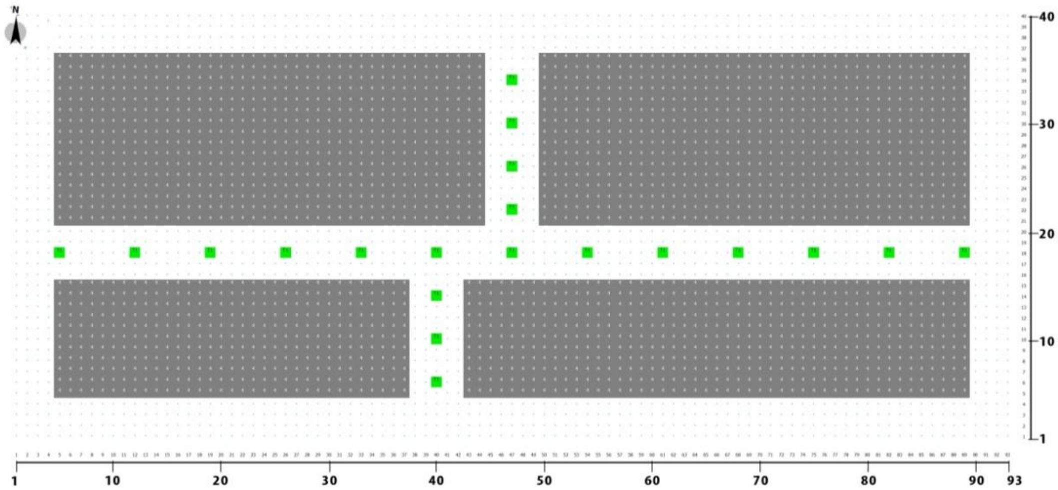



**Figure 3.17. The 'EW' testing the orientation variable representing simulation four (August 21st)**

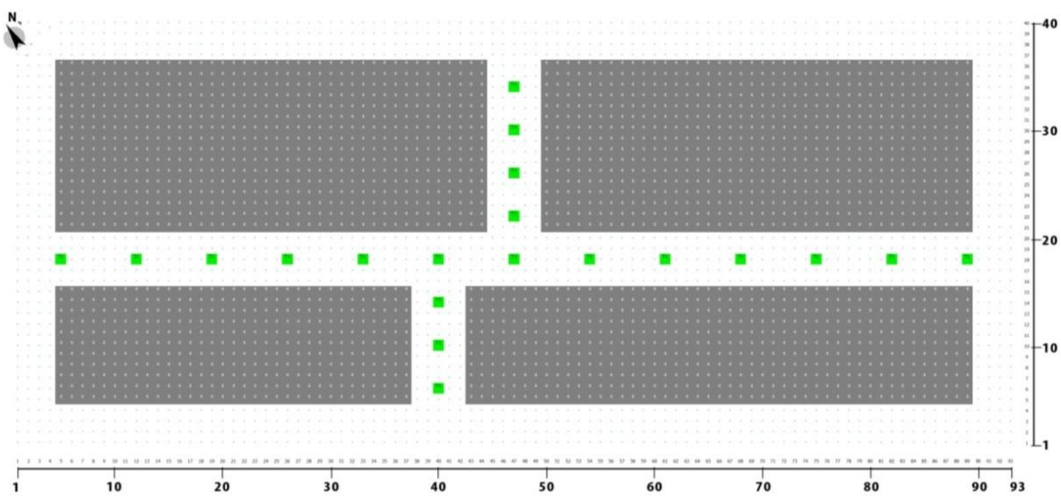



**Figure 3.18 The 'SE-NW' testing the orientation variable representing simulation five (August 21st)**

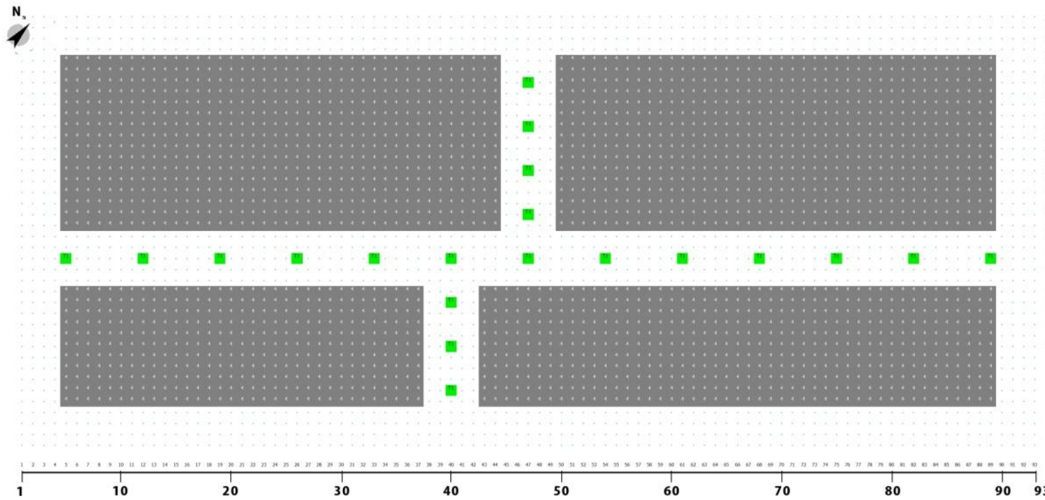



Figure 3.19. The 'SW-NE' testing the orientation variable representing simulation six (August 21$^{st}$)

The following three simulations were set with three different H:W ratios on the 21$^{st}$ of August. The seventh model was designed with a 0.5 ratio based upon 8m height of buildings and 16m width of space. The eighth model had a ratio of 2 with 20m building heights and 10m space width. The space length of 170m was always constant in all ratios and all models of the research as well to limit the confounding of such parameter. The ninth model used a higher ratio of 3 with a 30m height of buildings and 10m width of space. The tests were confined with relatively small ratios whereas the case of extreme large ratios was desired yet difficult to attain comparable results since larger grids for simulation will be required. The grid space used for the drawing was intended to be kept in similar ranges in all models to guarantee the fairness of the outcomes. Since all simulations of the current study are based upon a 100x100x30 grid, large H:W ratios were considered to have irrelevant outcomes.

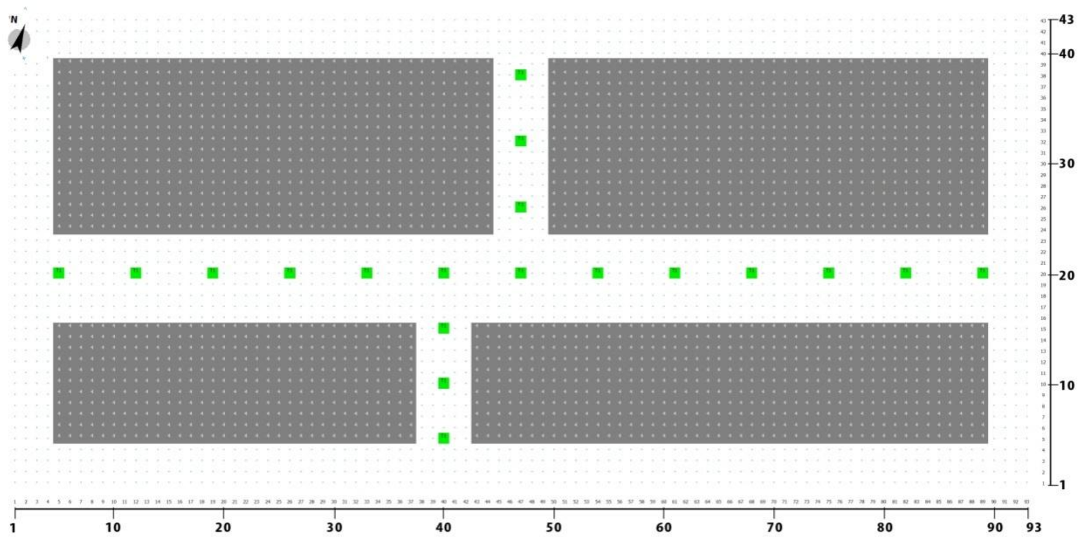



**Figure 3.20. The 'H:W 0.5 ratio testing the geometry variable representing simulation seven (August 21st)**

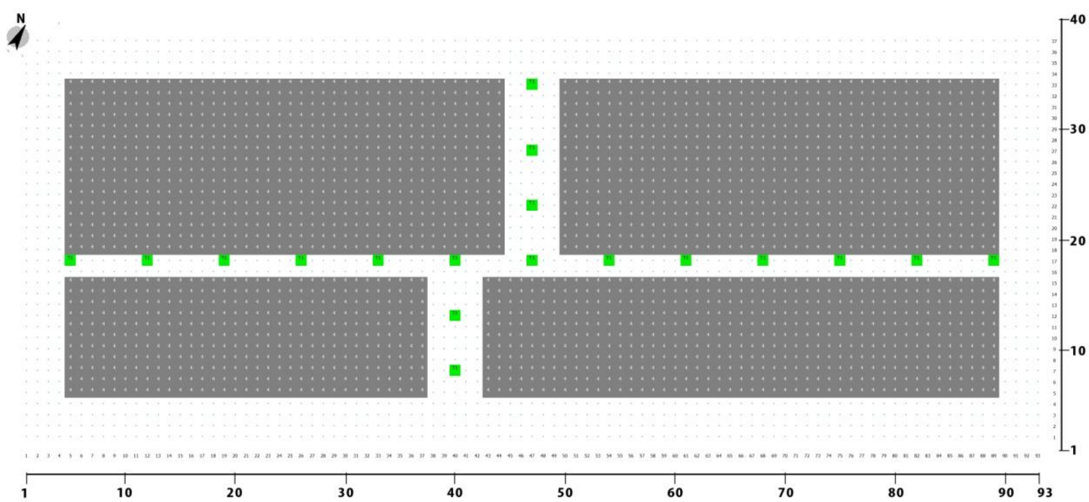



**Figure 3.21. The H:W 4 ratio testing the geometry variable representing simulation nine (August 21st)**

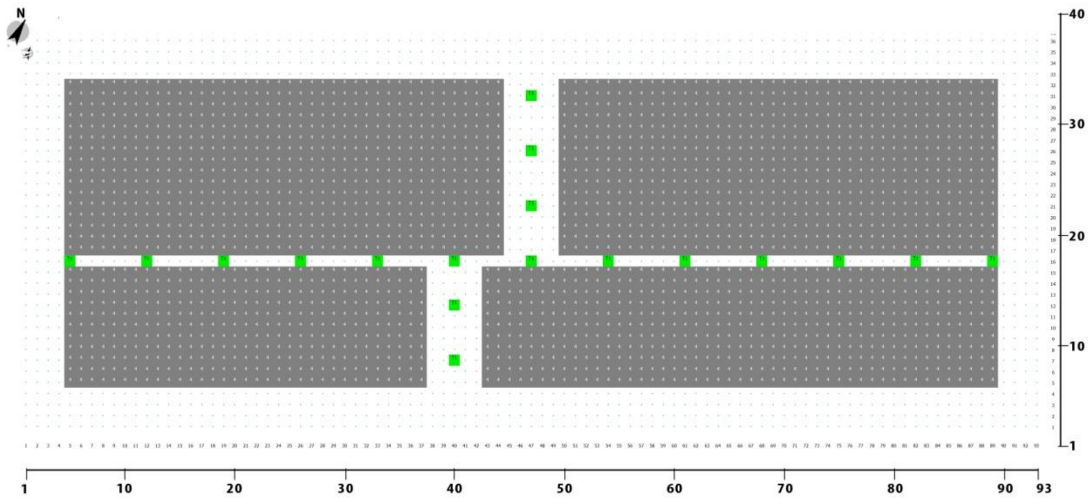



**Figure 3.22. The 'H:W ratio 2 testing the geometry variable representing simulation eight (August 21st)**

The following five simulations set were targeted to investigate the effect of the vegetation on the outdoor air temperature in summer conditions on the 21st of August. The ground surface of the outdoor space was replaced by continuous grass in the tenth model under the same conditions of a 20$^{o}$ NE-SW orientation, a H:W ratio of 0.8 and a tree planted every 12m. The grass surface was then distributed in a simplified manner in the eleventh model taking the form of rectangular 8x6m pieces with a spacing of 8m in between and a buffer of 4m from the building line. The purpose of such design is to examine the effect of different grass surface areas on the air temperature. In addition to the scenario of continuous grass, groups of trees was substituted with the existing condition to form a 'continuous grass and tree groups' scenario as the twelfth model. The concept of tree groups was then tested independently in the thirteenth simulation with the conditions of a 20$^{o}$ NE-SW orientation, a H:W ratio of 0.8 and no grass. The fourteenth model configuration was based upon the addition of a continuous line of trees along the space. Moreover, the fifteenth simulation scenario abandoned the vegetation aspect which neither included grass nor trees. The six vegetation strategies tested were intended to present the cooling effect level each strategy would provide.

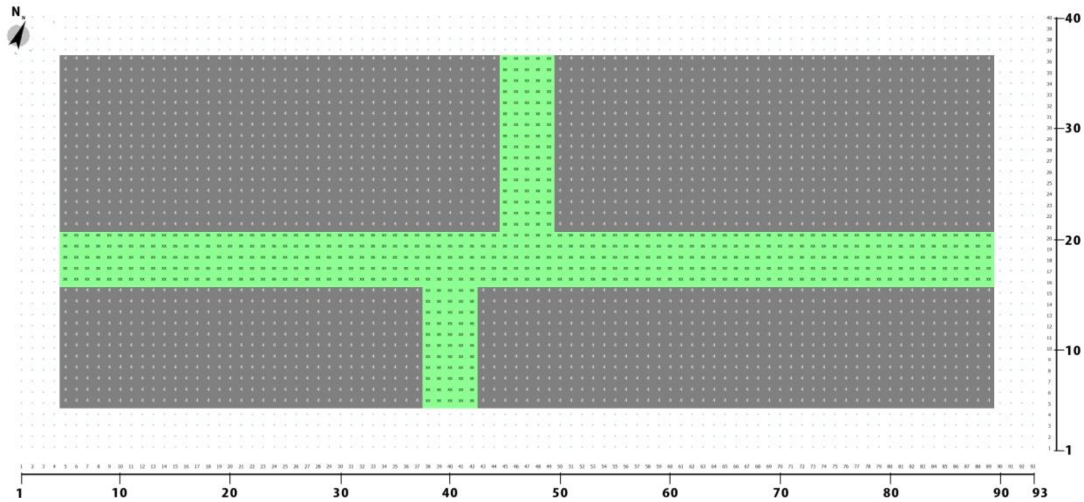



**Figure 3.23. The 'continuous grass' testing the vegetation variable representing simulation ten (August 21st)**

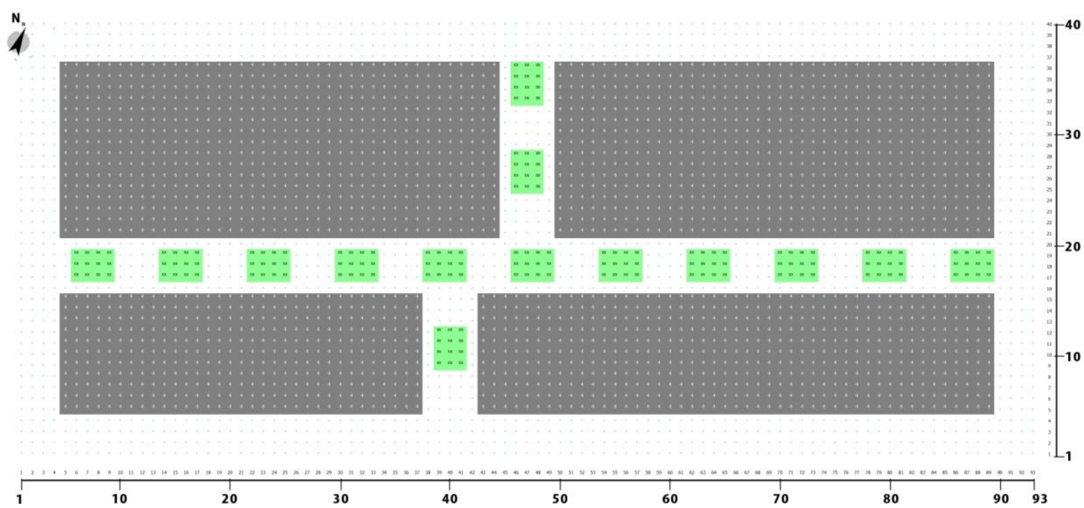



**Figure 3.24. The 'grass pieces' testing the vegetation variable representing simulation eleven (August 21st)**

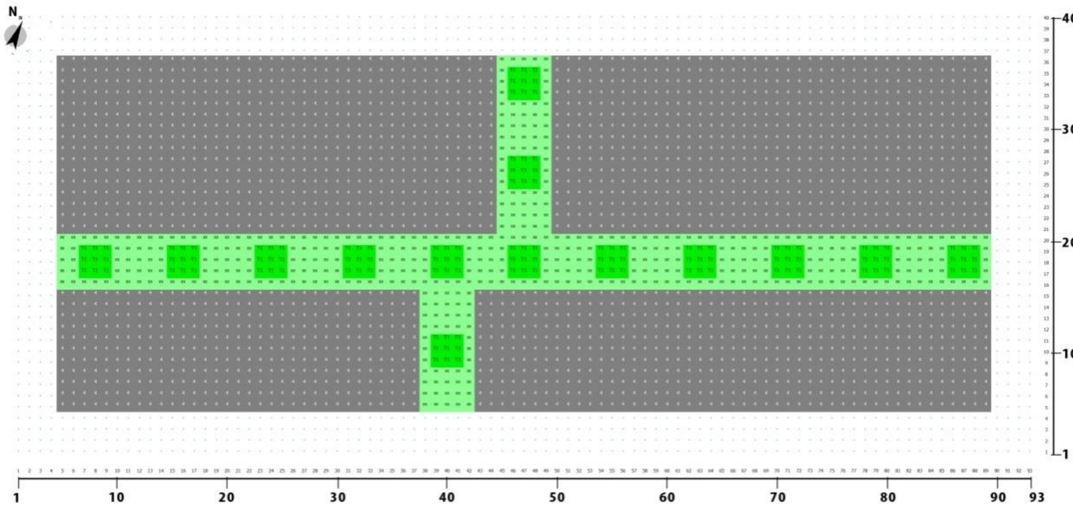



**Figure 3.25 The 'continuous grass & tree groups' testing the vegetation variable representing simulation twelve (August 21st)**

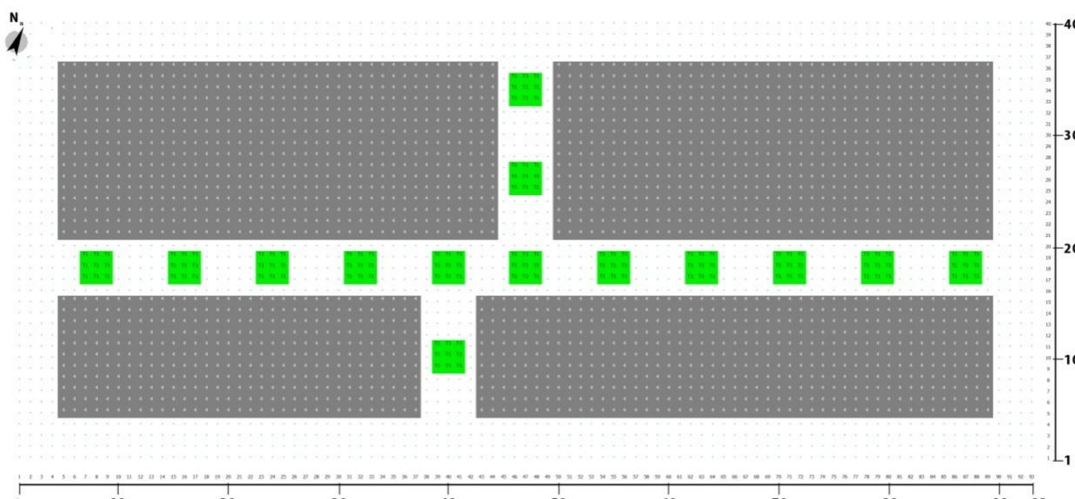



**Figure 3.26. The 'tree groups' testing the vegetation variable representing simulation thirteen (August 21st)**

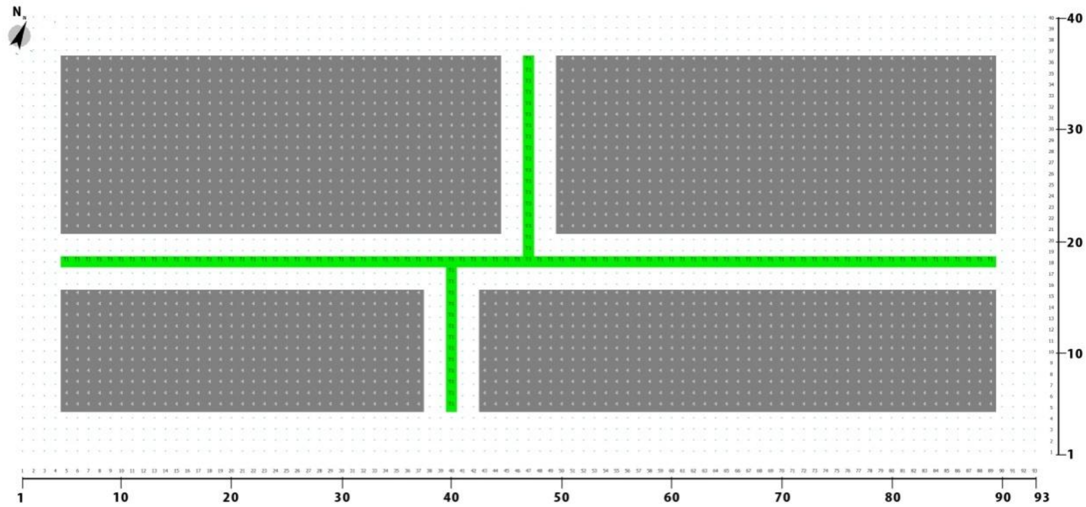



**Figure 3.27. The ‘continuous trees’ testing the vegetation variable representing simulation fourteen (August 21st)**

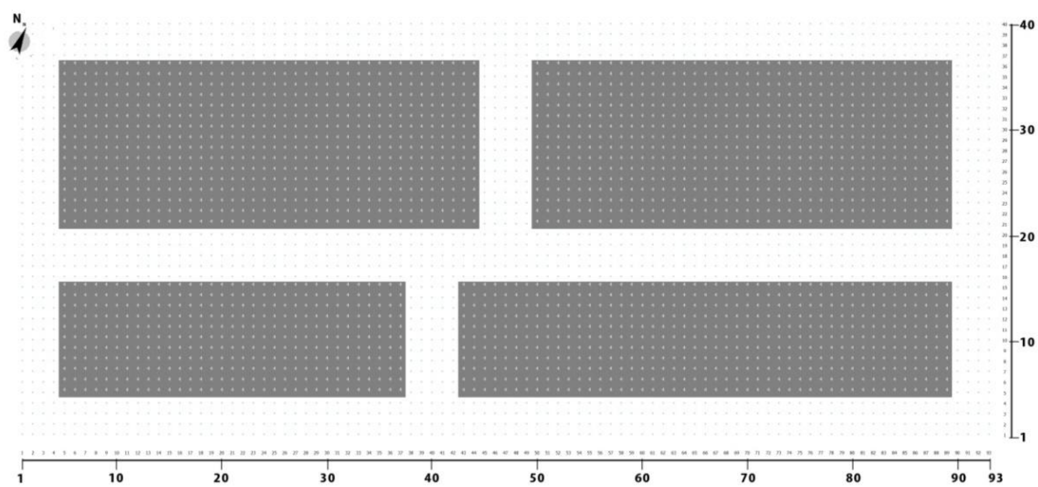



**Figure 3.28. The ‘no tree’ testing the vegetation variable representing simulation fifteen (August 21st)**

The outcomes of the thirteen previous simulations will be combined in one scenario known as the 'enhanced' model. Variables that showed the highest potential to reduce heat stresses were synthesized in an enhanced scenario and tested during both extreme summer and winter conditions. The sixteenth simulation being the 'enhanced' model will incorporate the orientation, geometry and vegetation strategy that proved to record the lowest temperature during summer to be tested on the 21$^{st}$ of August. Then the exact following configuration will be run during winter on the 21$^{st}$ of January in the seventeenth simulation to be able to set a comparison between the outcomes obtained and between the existing conditions (second model).

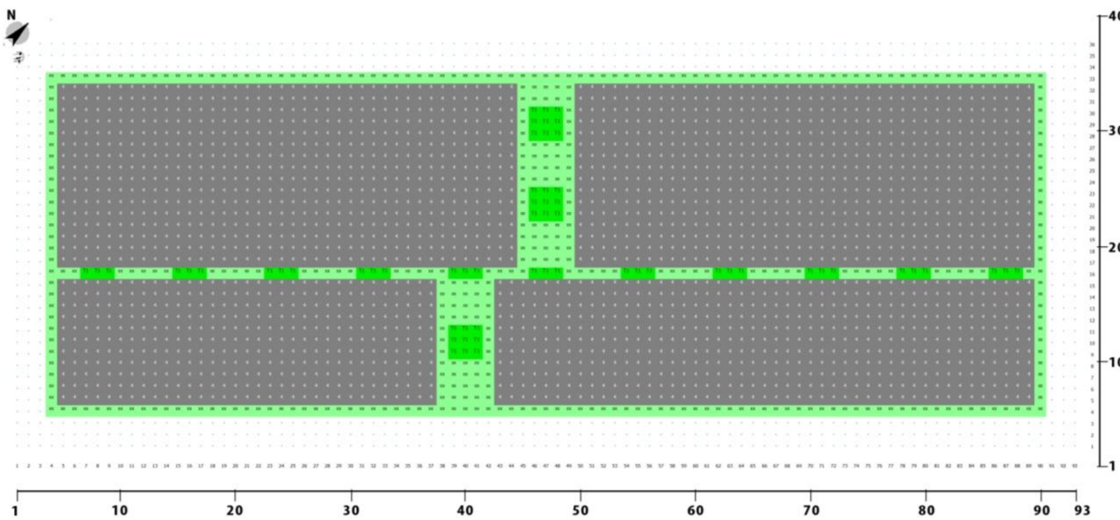



**Figure 3.29. The 'enhanced' scenario testing the all the bioclimatic principles representing simulation sixteen and seventeen two (August 21$^{st}$ and January 21$^{st}$).**

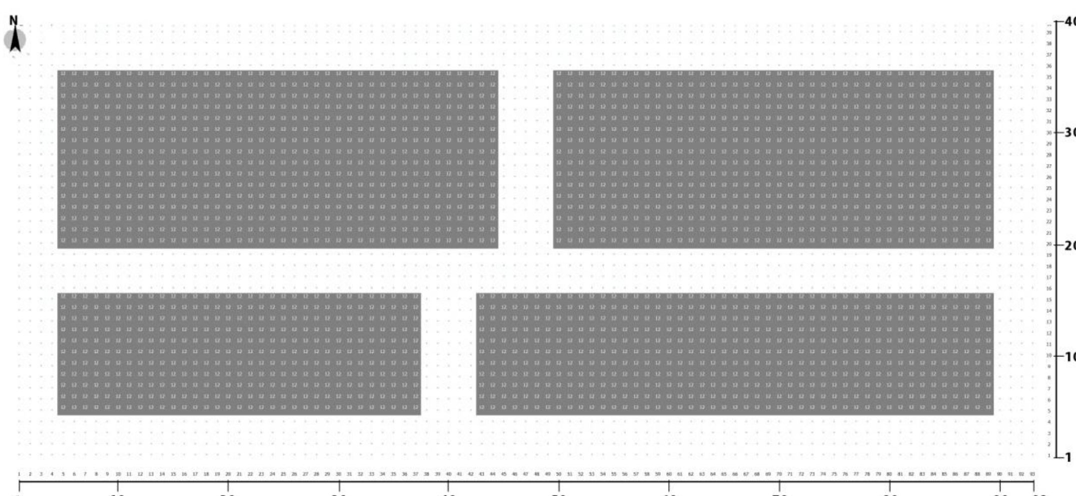



**Figure 3.30. The'worst' scenario testing the non existence of any of the bioclimatic principles representing simulation eighteen and nineteen two (August 21$^{st}$ and January 21$^{st}$)**

To be able to evaluate the bioclimatic techniques' effect on the temperature, a scenario that does not incorporate any of those principles will be configured accordingly. The eighteenth model known as 'worst' case scenario will be based upon the parameters that recorded the highest temperature in simulations three to fifteen. A comparative analysis including the three models simulated during summer and winter (existing, enhanced and worst) will be conducted.

**Table 3.4 The simulations were based upon the current data where some are fixed data in the software and some are input data**

| | | |
|---|---|---|
| **The simulations run using ENVI-Met were based upon the following constant information given by the software that cannot be changed** | Building properties | • Inside temperature of buildings during simulation 293K<br>• Heat transmission walls 1.94 W/m$^2$k<br>• Heat transmission roofs 6.0 W/m$^2$k<br>• Albedo walls: 0.2 (20% reflectivity)<br>• Albedo roofs: 0.3 (30% reflectivity) |
| | Solar radiation | The shortwave is 100% |
| | Specific humidity | in 2500m is 7(g water/kg air) |
| | Background $CO_2$ | The concentration is 350 ppm to calculate transpiration of plants |
| | Timings | • Update surface data each 30 sec<br>• Update wind and turbulence each 900 sec<br>• Update radiation and shadows each 600 sec<br>• Update plant data each 600 sec |
| | Soil data | • Initial temperature of the upper layer of the soil is 293K<br>• Initial temperature of the middle layer of the soil is 293K<br>• Initial temperature of the deep layer of the soil is 293K<br>• Relative humidity of the upper layer of the soil is 50%<br>• Relative humidity of the middle layer of the soil is 60%<br>• Relative humidity of the deep layer of the soil is 60% |

| | | |
|---|---|---|
| **The simulations run were also based upon a set of variable information inserted based upon the climatic data gathered and the conditions of the current investigation** | The geographic position | Dubai, UAE. Latitude: 25.25$^o$ and longitude: 55.33$^o$ |
| | Base grid size in X,Y and Z | 2,2 and 2 respectively, where each grid cell in the drawing space represents two meters in reality (the default setting) |
| | Simulation grid size | 100x100x30 grid size as a software standard configuration |
| | Materials | The buildings are surrounded by a 2m concrete pavement from the space periphery (existing curb stone in the site). The ground surface of the space was considered as concrete pavement when no grass was available. |
| | Orientation | The simulation gridline of the existing model was rotated 20$^o$ whereas the North direction becomes tilted to the right side as shown in the output images. The reason for such amendment is to minimize staggered forms during the drawing process and obtain more accurate results since the software is only capable of drawing vertical or horizontal lines. The North direction input in the simulations is compatible with the existing condition. |
| | Duration | • Simulation duration was total of 12 hours from 07:00-19:00 for each of the three independent variables tested (for simulations #03-15) look Table 3.2.<br>• Simulation duration was total of 16 hours from 07:00-23:00 for the existing, enhanced and worst case scenarios (for simulation #01, 02, 16-19) look Table 3.22 |
| | Saving intervals | Every 30 minutes there is an output file that contains all information needed about that specific time. |
| | Wind direction | 325$^o$ at 3.6m/s speed |
| | Initial temperature | 305.15$^o$K (the average temperature of the whole year over the last 10 years) |
| | Sky condition | Clear sky |
| | Relative humidity | in 2m height of 50% (the average humidity of the whole year over the last 10 years) |

### 3.6.3 Step 3: Results Assessment Criteria

The outcomes of the simulations explained previously were synthesized in a comparative analysis to derive the research guidelines and recommendations. The evaluation of the three independent variables (orientation, geometry and vegetation) was done in an organized quantitative process and the same concept was applied to the 'enhanced' and 'worst' scenario to compare the results to the 'existing' scenario'. The output files of the software are basically data (temperature, wind, sky view factor…) representing each single grid point of the drawing space for the model. For instance, the first simulation model used a grid of 40x93 which resulted in 3720 grid points with 3720 temperature points and the same number of wind speed points every 30 minutes. The average of the temperature (K) and the wind speed (m/s) for all the grid points was represented in one figure of temperature (K) and one figure for wind speed (m/s) every 30 minutes. Tabulation of the temperature (K) and the wind speed (m/s) every half an hour was averaged and compared to the same result of each simulation.

A clear comparison between each parameter of orientation is composed to select the one with the lowest average temperature. The process is repeated with each parameter of geometry and each parameter of vegetation to result in a total of three parameters that recorded lowest average temperatures during summer to be used for the enhanced scenario while selection of the highest average temperatures to be used for the worst case scenario.

The main comparison was then conducted between the three main scenarios; existing, enhanced and worst based on the same dependent variables used in the other simulations (temperature and wind speed). Assessment of the findings of such comparison will be related to the earlier studies reviewed in Chapter 2.

Visual maps extracted from the output files of all the simulations by LOENARDO software were done for every 30 minutes. The maps were representations of the temperature gradient distribution within the space in relevance to the wind flow in site. Observations were done between those images and interpretations of the temperature and wind patterns were done simultaneously.

## 3.7 Research Challenges and Limitations

The hypothesis under investigation required a large amount of variables to be involved within the current research which required high levels of organization and more time. The examination of the cooling effect of a bioclimatic design approach to the outdoor spaces required the testing of each of the variables incorporated independently resulting in a huge amount of simulations. One of the early research challenges was the selection of the justified effective variables to be tested and considered to have a cooling effect in which a sense of prediction was required. Testing those variables through a 19 simulation model was very hectic since each model has time duration of around 28 hours for simulation duration only. The saving interval for the output files was every 30 minutes which resulted in a huge amount of output files for extraction for each of the 19 simulation that even consumed more time than the simulations run. Exhaustive accuracy and organization was required to prevent confusions and misreading of any of the results.

The software used for simulation (ENVI-Met) is considered challenging in itself since self learning was required and the online information was insufficient. Errors occurring during simulations were another challenge that consumed a lot of time and effort yet was sometimes untraceable. Therefore the recreating of the whole model was required in some cases to prevent such errors which increased the time needed before any results were obtained. The software is very limited in terms of drawing tools and techniques that burdens the users to achieve their goals in a justified constructed space. Some parameters could have been incorporated in the current investigation that might have lead to a larger cooling effect yet were excluded due to the software limitations yet was substituted by other variables. The main challenge faced when dealing with ENVI-met was the extraction process of the output files. The software output files are un-editable files that required the usage of other software to manually extract each single data file given by each simulation which was considered very hectic. Several errors were done during the extraction process due to the large amount of work within a limited time frame but fortunately mistakes could be detected on the last stage that again required going back and repeating the extraction process.

The alternative choices given by the simulations tool used (same for all outdoor softwares) for material selection was very limited. Softwares used for outdoor simulations are having very restricted types of materials i.e. used for pavement and building facades. Such aspect would reveal influential results if incorporated within a passive design strategy which unfortunately was not.

The time limit for the current study was considered to be relatively small according to the available tools and required task. Due to the time limitation and resources further investigations was not possible however was substituted by thorough research to achieve a holistic vision about the outdoor environments. Unfortunately, longer periods of simulated hours for the independent variables and seasonal changes was not included since each of the independent variables were tested during summer days only. The balance was created by including those aspects in the three comparative scenarios namely; enhanced scenario, existing and the worst case scenario.

Validation of the results obtained was not done through field measurements due to the limitations of the outdoor measurement tools within the institute of learning. Thus a comparison between the obtained results and the earlier validated studies outcomes was done for each of the findings in which and misinterpretation of findings were minimized.

# CHAPTER FOUR: RESULTS AND FINDINGS

## 4.1 Data Presentation

The current chapter transformed the knowledge gained from the literature review in Chapter 2 in accordance with the current findings into a solid form. The assumptions and interpretations done below had supported the earlier studies. Below, sufficient details of the procedures explained in Chapter 3 were identified through the simulations results attained. A thorough explanation to the data extracted from all the simulations run is presented focusing on the significant findings and behaviors. Wind and temperature patterns were highlighted since they were considered to be the dependant variables observed in this study.

The current investigation was based on testing three parameters of the bioclimatic principles to identify the most effective factor of each that would enhance the outdoor air temperature. Constructing a bioclimatic space that respects the environmental requirements was then tested and compared to a realistic case and a worst case scenario. The reason for such comparison is to be able to evaluate the 'ecological' design that responds to the environment in a quantitative manner. Creating a comparison based on the enhanced and the existing scenario only was found to be unrepresentative to the real value of the enhanced scenario since the existing site conditions included several factors of the bioclimatic principles. Composing a worst case scenario had helped disband such problem.

Simulations were run using the same chronological order presented in Chapter 3. Tabulation of the output files every 30 minutes of each single model was organized where graphical representations were prepared. Temperature ranges were the main focus of data extraction observed and named as the Potential Temperature (POT Temperature in Kelvin K). Each simulated model had an excel sheet where its temperature values are recorded every 30 minutes. The averages, minimum and maximum values were extracted for each sheet summarizing the comparative values needed for each variable. More sheets were added to compare the parameters of each variable, the variables to each other and between the different scenarios.

The other variable also observed was the wind speed known as the ‘wind speed (m/s)’. Wind revealed to be an effective parameter in a hot humid climate and has always been known to affect the thermal sensation levels of an individual within a space therefore was tabulated as well. The initial reason for involving wind in the data obtained from the simulations is that during the early trial models some of the temperature patterns found to have an unusual behavior. Trying to understand such patterns it’s was found that wind has an impact on the temperature levels. Involving the wind speed outcomes during the observation procedure had created more logic in understanding the temperature findings. Wind speed records were tabulated in the same sheets with the temperature records where averages, maximum and minimum values was obtained.

The interpretation of the data extracted from the graphical representations below is mainly based upon the differences between the average, maximum and minimum temperature and wind values. The interpretation of these data in the variables comparisons was based upon differences between the same dependant variable (average wind, average temperature, maximum wind …) in the tested parameters. The values referred to as significant values were relative to the results attained where differences within 1 K were still observed and behaviors were extracted. The variations of the results revealed very small standard deviations which was explained and justified in Chapter 5. The real values of temperature and wind speed recorded were relevant to the initial values inserted and defined in Table 3.4. Thus the results of the current investigation are interpreted in consideration to the simulation circumstances mentioned and justified in Chapter 3.

## 4.2 Existing Scenario

The first base model constructed named the ‘existing scenario’ was an imitation to the Dubai Knowledge Village site morphological and climatic characteristics. The model data beneath presents the extreme summer heat stress on the 21$^{st}$ of August and the extreme winter conditions on the 21$^{st}$ of January simulated from 8.00am to 10.00pm. The existing site had a 20$^{o}$ NE-SW orientation, a H:W ratio of 0.8, no grass and a tree planted every 12m.

The average daily temperature and wind patterns on the 21st of August represented below is 301.6 K and 1.17 m/s respectively while that on the 21stof January was 298 K with 1.12 m/s. The hourly values of temperature represented in Figure 4.1 emphasize the duration with the highest heat stress zone during the day in both seasons which is between 12.00 and 15.30 during summer with maximum temperature values of 305 K during summer and 301.7 K during winter. The hourly wind values in summer increases significantly during the peak stress daily period with an average speed of 1.17 m/s, than that during winter average speed of 1.13 m/s as shown in Figure 4.2. The temperature and wind pattern is more stable during winter than that during summer whereas the variation between the maximum and minimum values is significant during summer of 8.9 K while that during winter is 6.7 K as shown in Table 4.1.

**Table 4.1 The average, maximum and minimum temperature and wind values obtained from the simulations during summer on 21st August and winter on 21st January.**

| | Temperature Summer | Temperature Winter | Wind Summer | Wind Winter |
|---|---|---|---|---|
| Average | 301.570 | 298.454 | 1.1676 | 1.1286 |
| Maximum | 305.122 | 301.728 | 1.2317 | 1.1457 |
| Minimum | 297.033 | 294.968 | 1.1332 | 1.1235 |

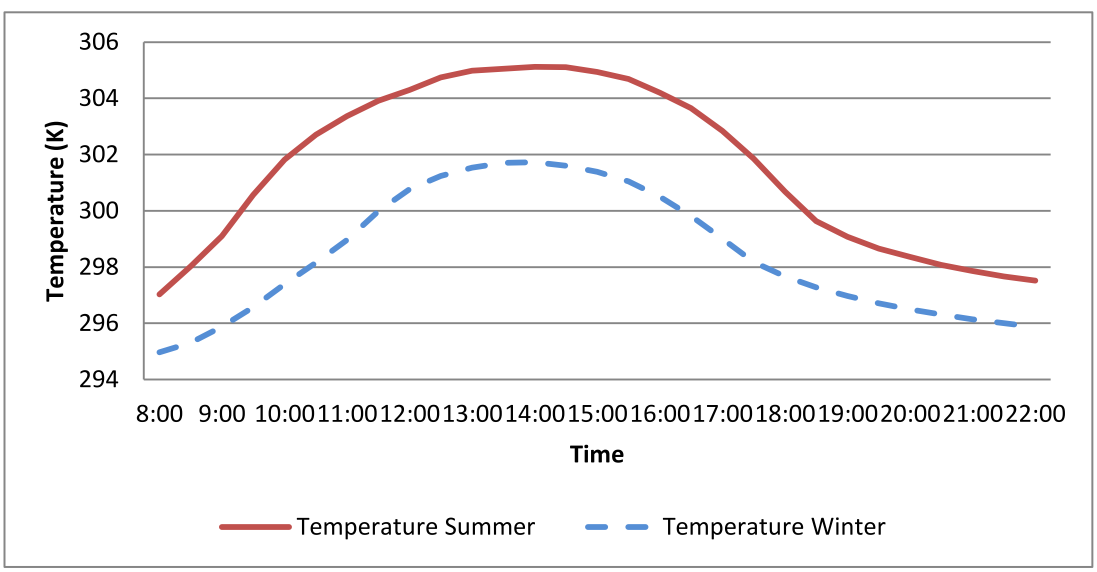



**Figure 4.1. The daily temperature patterns during summer on 21st August and winter on 21st January demonstrating the peak thermal stress zone.**

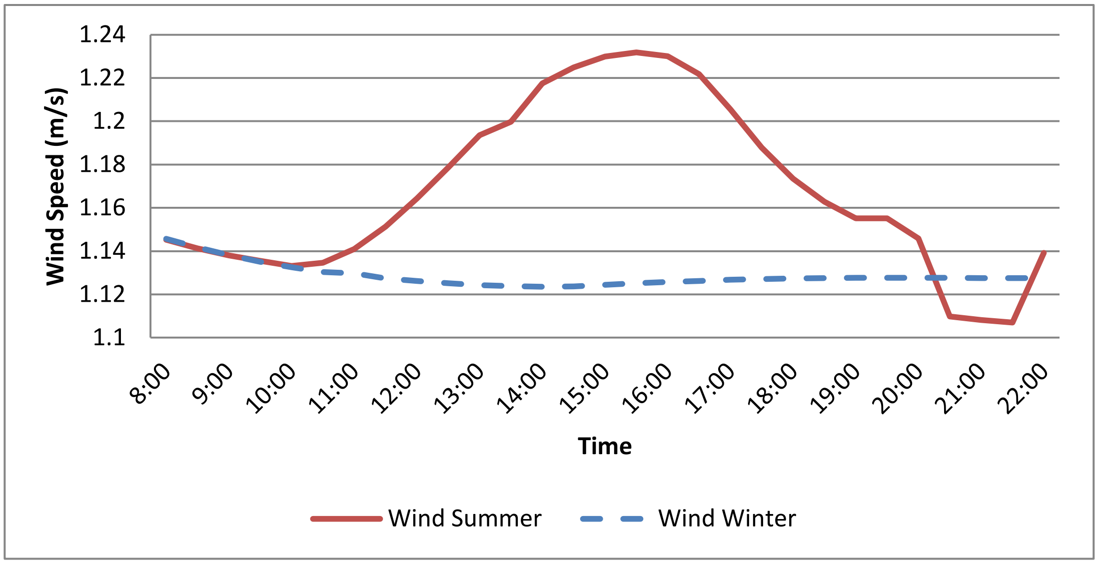



**Figure 4.2 The daily wind patterns during summer on 21st August and winter on 21st January demonstrating the peak thermal stress zone.**

The difference between the average temperature of summer and winter is 3.1 K which is smaller than the difference apparent between the maximum values of 3.4 K, while the difference between the minimum values is 2 K and considered to be the smallest as shown in Figure 4.3. This means that the heat increasing rate between summer and winter is not uniform all through the day. Night time temperatures patterns during summer indicated by minimum values are more stable than daytime values especially during the peak heat stress hours.

The wind speed pattern shown in Figure 4.4 is more stable than the temperature differences yet during hot summer days the maximum values of wind increases more considerably than that during early mornings and night time. The highest wind speed patterns are valid during the maximum temperature hours recorded.

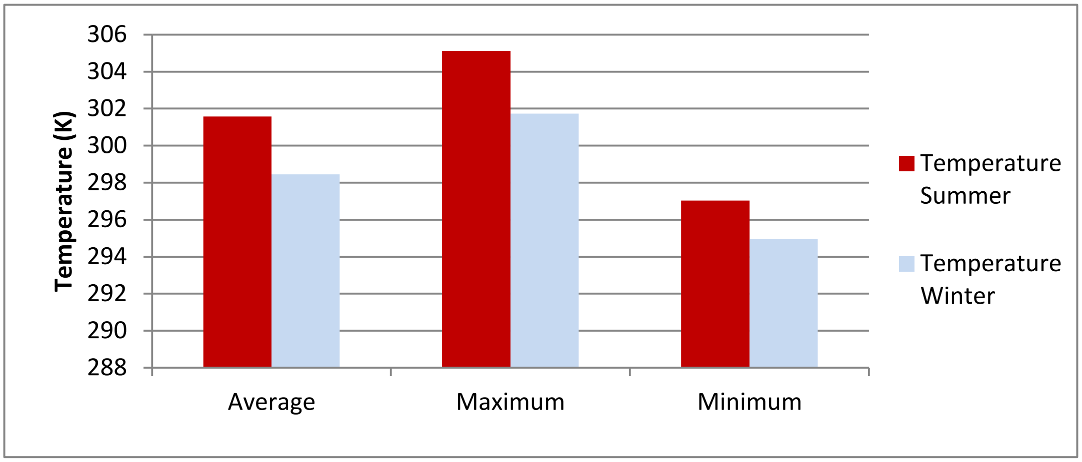



**Figure 4.3 The temperature values behavior during summer on 21st August and during winter on 21st January.**

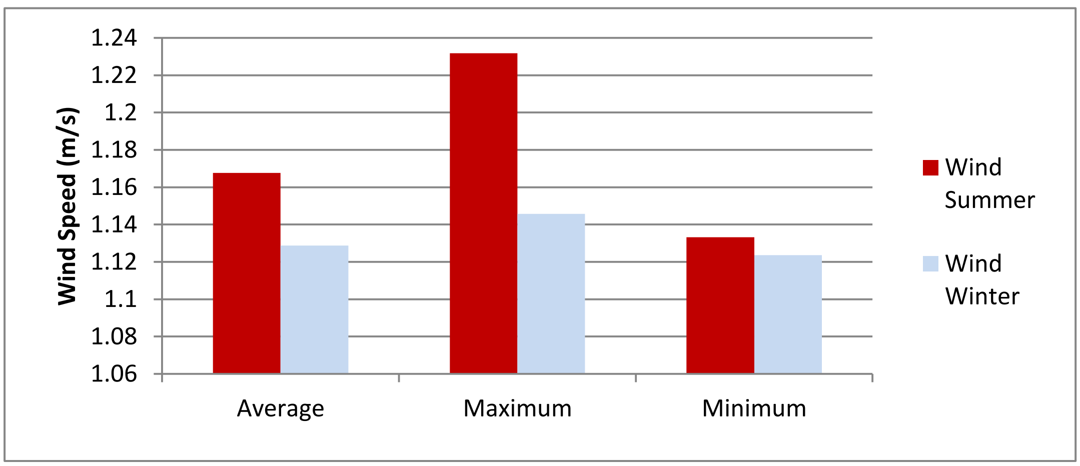



**Figure 4.4 The wind speed values behavior during summer on 21st August and during winter on 21st January.**

## 4.3 Independent Variables

### 4.3.1 Orientation

Four simulations were constructed to test the first independent variable having the exact same morphology of the existing model but with different orientation variance. A H:W ratio of 0.8, no grass and a tree planted every 12m was the models configurations in addition to each of the following orientations at a time NS, EW, SE-NW and SW-NE respectively. Simulations testing the independent variables were run during the climatic extreme conditions of Dubai which is during summer daytime on the 21st of August between 8.00am and 6.00pm. The average, maximum and minimum values were compared between the different orientations yet the selection of the coolest orientation would be based upon the lowest average temperature during that period.

Variation between temperatures values of the four orientations were very minor in which was expected from the literature review done earlier and was justified in Chapter 5. A comparison was made to be able to choose the most suitable orientation that was incorporated in the enhanced scenario. The difference between the highest average temperature of the EW orientation and the lowest average temperature of the SW-NE orientation was 0.5 K nominating the SW-NE orientation for the enhanced scenario. Yet the NS orientation revealed the lowest maximum temperature of 304.8 K rather than 304.9 K of the SW-NE orientation as demonstrated in Figure 4.5. The difference between the minimum temperature values was 0.5 K and the difference between the maximum temperature values was 0.2 K. Observing the maximum and average temperature patterns between the four orientations reveals that during high thermal stress the temperature variation between all the orientations decreases assuring the same pattern observed previously in the existing scenario.

The variation between the temperatures of the four orientations shown in Figure 4.6 was relatively higher than that of the wind values as shown in Figure 4.7. The SW-NE orientation of an average wind speed of 1.08 m/s recorded the lowest average, maximum and minimum wind speed ranges through the four tested orientation as shown in Figure 4.8.

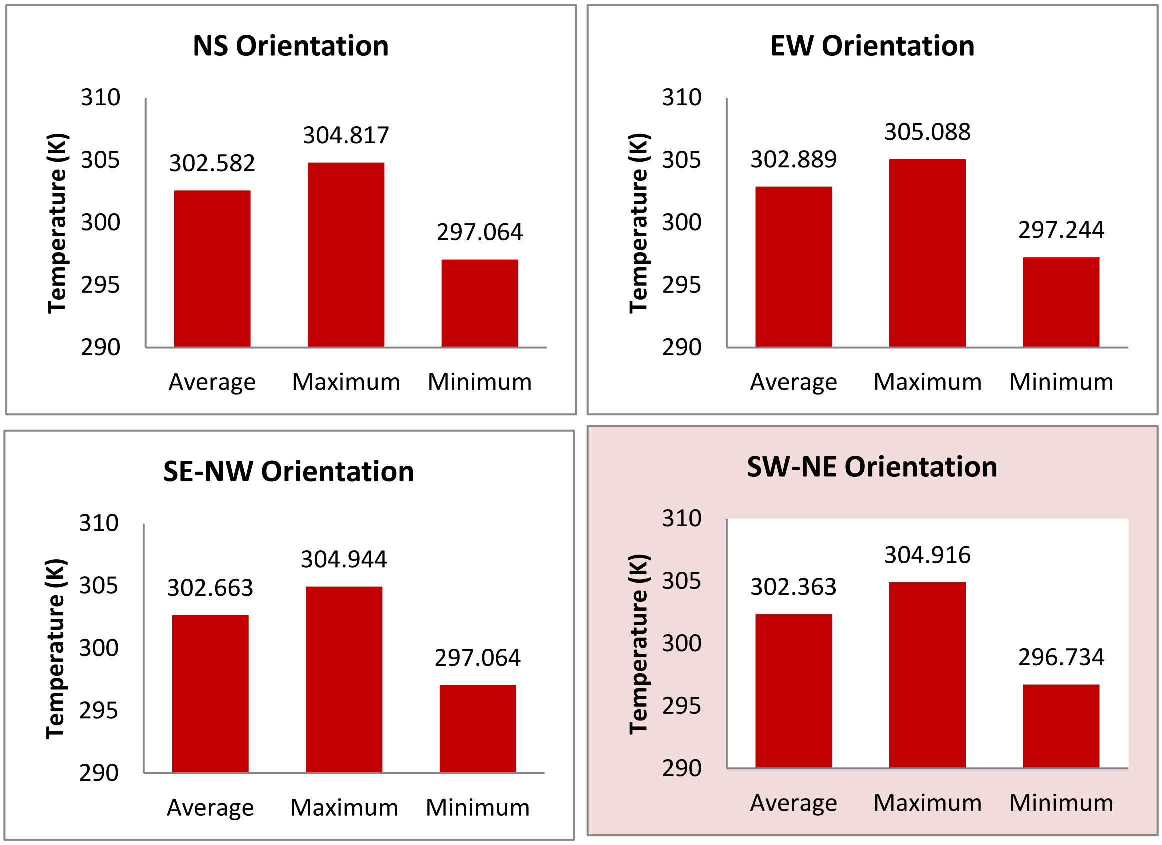



**Figure 4.5 The four orientations demonstrating the average, maximum and minimum temperature values highlighting the SW-NE orientation as the selected parameter incorporated in the enhanced model.**

The prevailing wind blows from the Northwest direction which allows the SE-NW orientation to receive the highest wind flow levels with an average speed of 1.66 m/s followed by the NS orientation with an average speed of 1.59 m/s. The SW-NE orientation prevents the wind breeze infiltration through the space recording the minimum average value of 1.08 m/s. The difference between the average and the maximum values for wind of the four orientations are relatively small compared to those between the temperature values as shown in Figure 4.9. The average wind difference between the highest and the lowest wind orientation ranged between 0.51 m/s shown in Figure 4.8. The wind pattern values shown in Figure 4.10 explain that the wind speed during summer is almost stable during the day. The SW-NE orientation has the lowest average wind speed values along with the lowest average temperature ranges which indicate that the wind does not necessary have a cooling effect on the temperature values.

The existing scenario had a 20° angle towards the SW-NE against a 45° for the selected orientation yet with a temperature difference. The existing scenario represented on the Figures 4.6 & 4.7 indicated a higher value of an average temperature than the SW-NE orientation with a value of 0.4 K. It recorded a closer average temperature value to the SE-NW orientation with a difference of 0.1 K. the maximum temperature values of such scenario revealed to be the highest of all orientations. This finding reveals that the tilting angle has an effect on enhancing the outdoor air temperature along with the orientation.

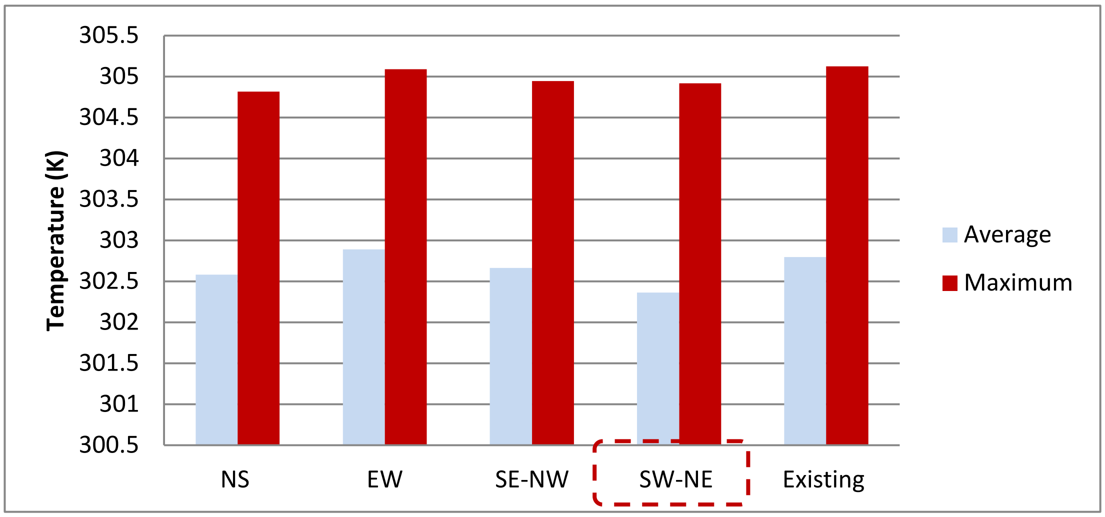



**Figure 4.6 The average and maximum temperatures of the four orientations compared to the existing scenario with the lowest average temperature of the SW-NE orientation.**

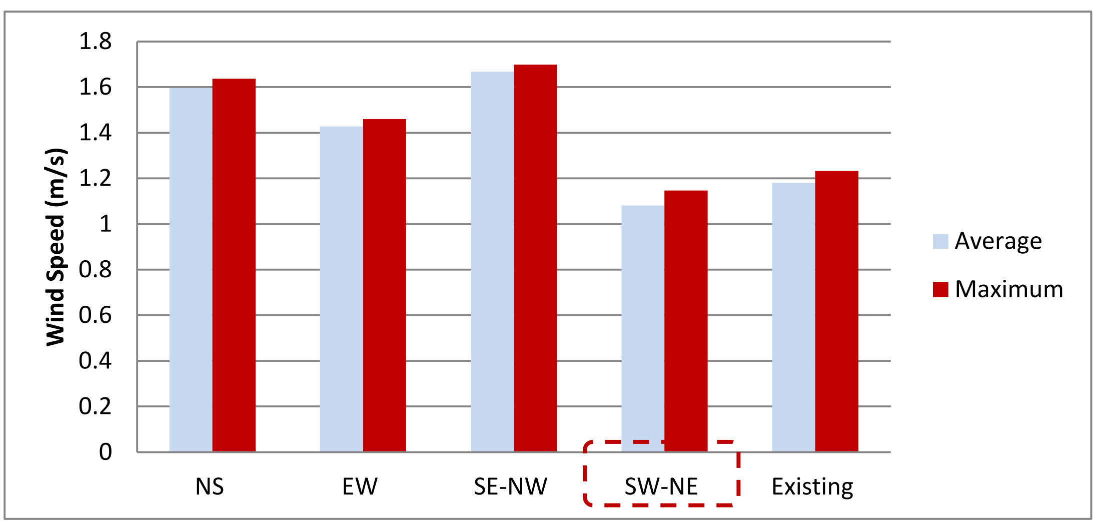



**Figure 4.7 The average and maximum wind speed of the four orientations compared to the existing scenario with the lowest average and maximum wind speed of the SW-NE orientation.**

The sun path circulation represented in Figure 4.11 is based upon the rotation of the space within the original coordinates that provides different shading strategies based upon the 'noon sun' where is the peak heat stress period identified in Figure 4.10. Both the SW-NE and the NW-SE orientations provide the highest levels of the same shading coefficient within the space with a very slight average temperature difference of 0.3 K where the SW-NE orientation proved to be the coolest of all. The reason for such slight difference is due to the wind speed effect on the space where the NW-SE has higher levels of average wind speed being almost parallel to the wind direction, than the SW-NE orientation which blocks the warm wind breeze blowing from the Northwest direction from entering the space. In an extremely hot arid climate where wind has high temperature levels cooling wind strategies should be applied or partial prevention due to its contribution in expanding the warm area through the space.

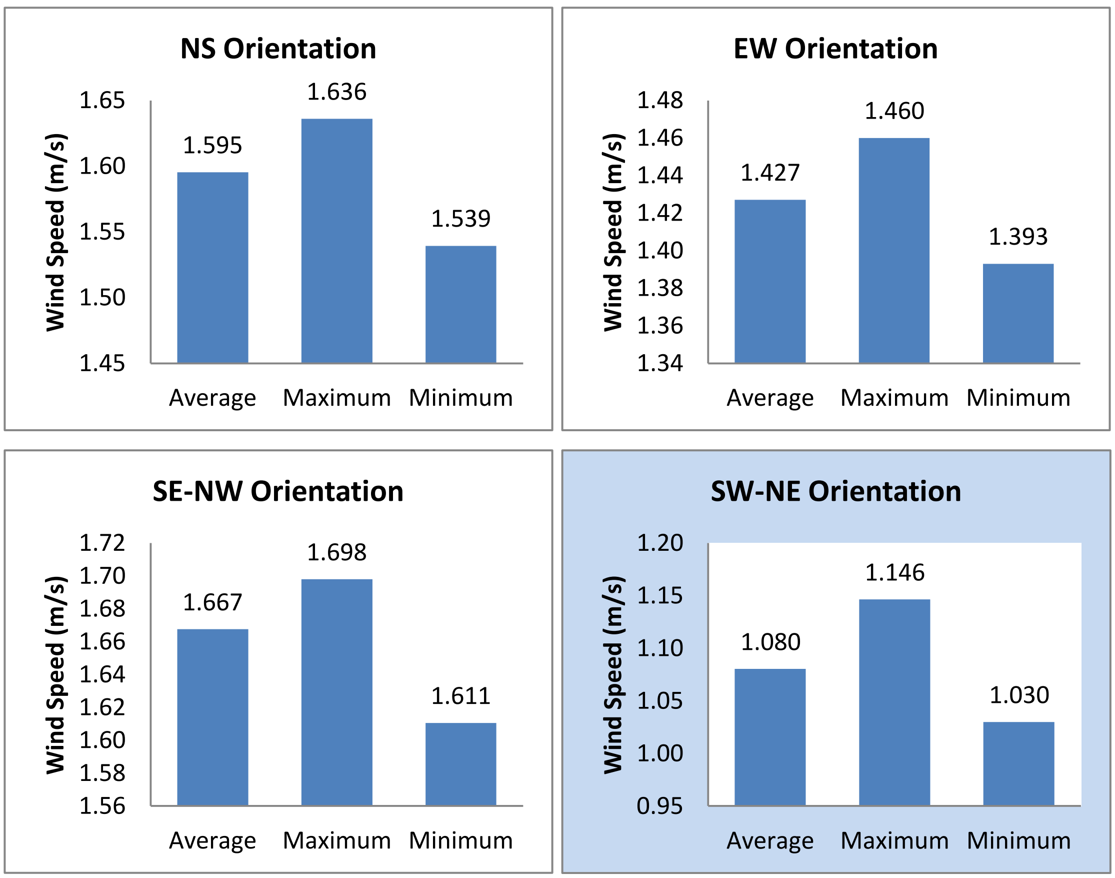



**Figure 4.8 The four orientations demonstrating the average, maximum and minimum wind speed values highlighting the SW-NE orientation as the selected parameter incorporated in the enhanced model.**

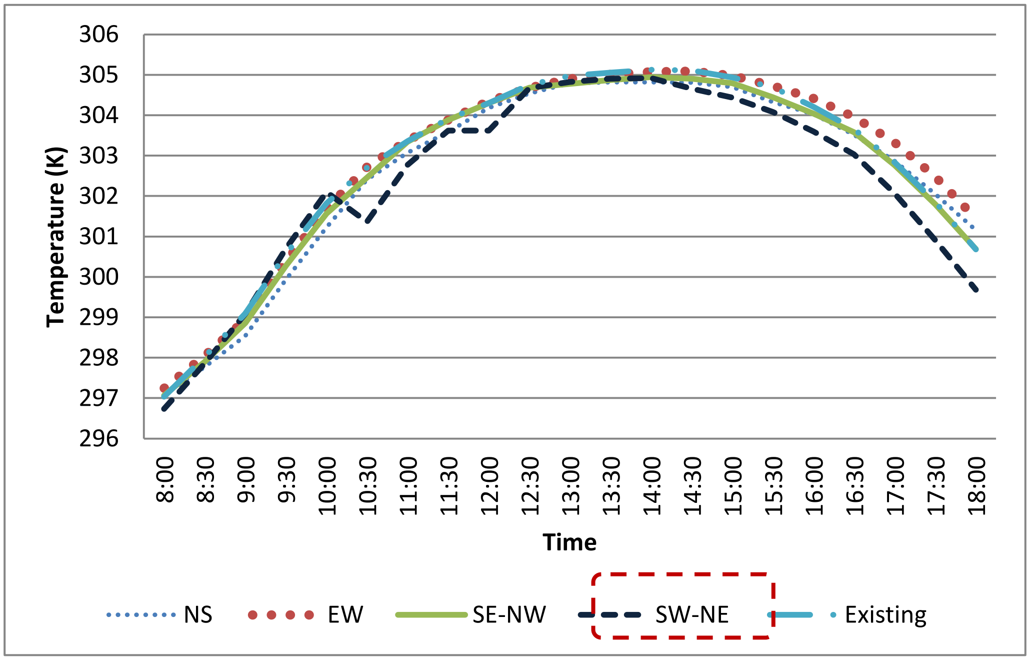



**Figure 4.9 The daily temperature behavior of the four orientations and the existing scenario with the SW-NE orientation of the lowest value and the SE-NW of the highest value with very slight differences.**

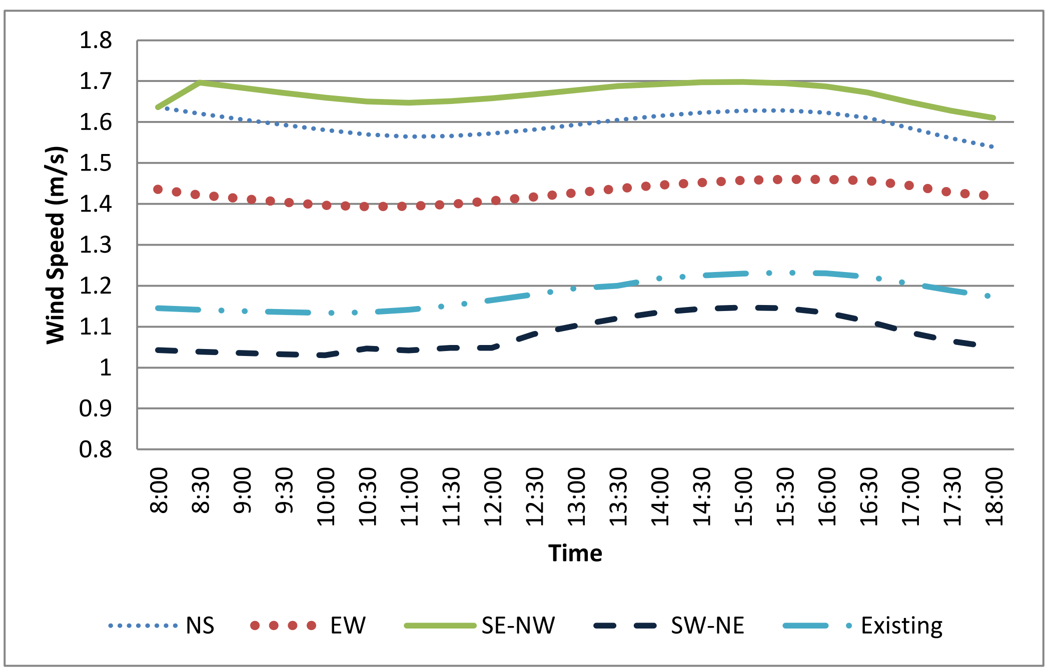



**Figure 4.10 The daily wind speed behavior of the four orientations and the existing scenario with the SW-NE orientation of the lowest value and the SE-NW of the highest value stabilized all during the day.**

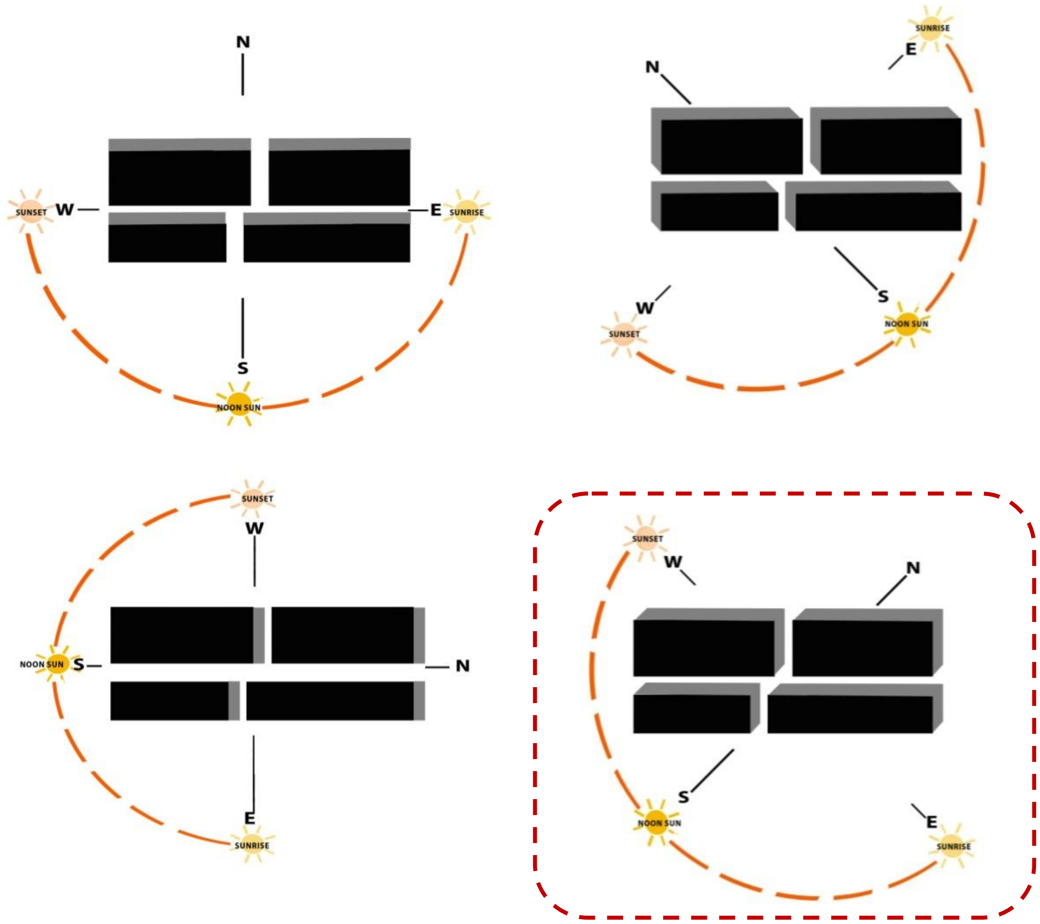



**Figure 4.11 The solar path represents the shading principle provided within the space based upon each orientation. EW space top left, SW-NE space top right, NW-SE space bottom right and NS space bottom left.**

### 4.3.2 Geometry

The height to width ratio referred to as H:W was the factor investigated within the space geometry. Three different ratios where simulated varying between 1:2 ratio equivalent to a 0.5 ratio, 2:1 ratio equivalent to a 2 ratio and 4:1 ratio equivalent to a 3 ratio. The existing model simulated had a ratio of 0.8 which was also compared to the geometry results attained. The three models had a fixed building height of 4m, 20$^{o}$ NE-SW orientation, no grass and a tree planted every 12m. The simulations were run during the highest thermal levels on the 21$^{st}$ of August from 8.00am to 6.00pm as the case will all other independent variables tested.

The examination of the H:W ratio variable proved to be dependent on the values both the height and the width rather than being just an independent ratio aspect. Two simulations were done testing the ratio of 2 equivalent to H=2 and W=1. The first model had a height of 8m and width of the space was 4m 8:4 against the second model of a height of 20m and width of 10m 20:10. Both the models were compared to a third model of a 0.5 ratio where H=8 and W=16 as shown in Figure 4.12. The results for the first two models demonstrated totally different values where the both models had the ratio of 2. The results were in logic sequence based upon the results obtained in similar studies proving that the temperature decreases as the ratio increase was revealed between the first and the third model as shown in Figure 4.13. The first model the same height of 8m the compared to the third model where the only variable changed was the width of the space yet the second model ratio of 2 though had a larger ratio than the third model ratio of 0.5 yet revealed illogic behavior recording higher temperature levels. Manipulation of other models with varying height and width (not shown here) was also done to assure such concept.

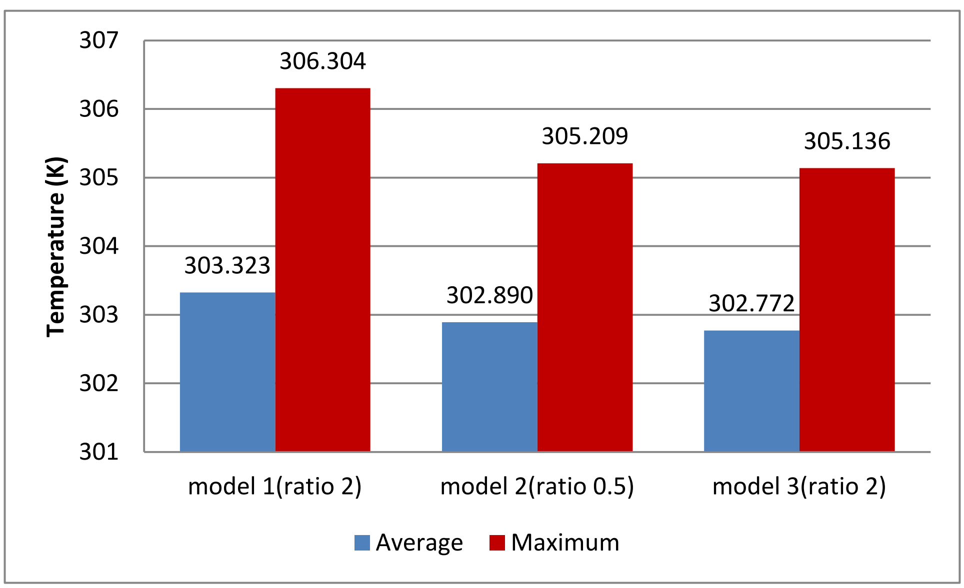



**Figure 4.12 The average and maximum temperatures of the three models where model one and two tests the same ratio versus the third model of a smaller ratio.**

The ability of the height to width ratio to enhance the air temperature is based upon the shading provided within the space that creates shelter from the solar radiation. Higher ratios of create deeper spaces that has more shade while larger ratios are basically wider spaces with more sun penetration. Such criterion depends on other parameters as well such as orientation and space length that interprets the effect of a provided ratio. The principle that higher ratios contribute to lower temperatures and lower ratios contribute to higher temperatures has been over killed.

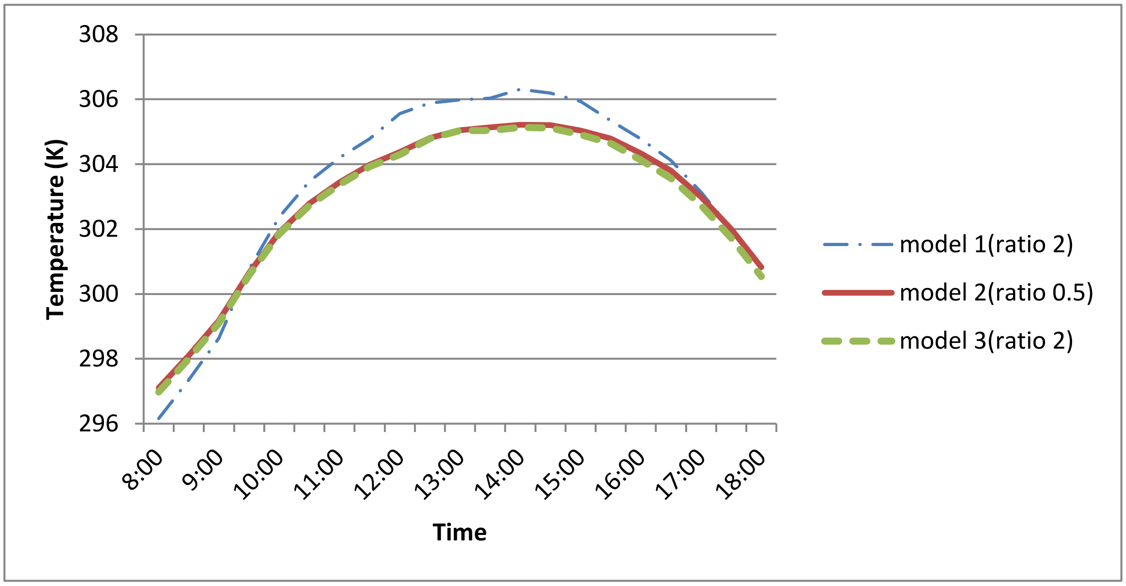



**Figure 4.13 The daily temperatures of the three models where model one and two with the highest and lowest values tests the same ratio versus the third model of a smaller ratio.**

Variations of the space H:W revealed to be less effective on the temperature values in this study more than the orientation whereas the difference of the average temperatures reached 0.2 K and 0.53 m/s of average wind speed. The ratio of 0.5 revealed the highest average temperature levels followed by 2 and 4 respectively as shown in Figure 4.14. As expected, the ratio and temperature distribution has showed an inversely proportional relationship with the average temperature where the temperature increased as the ratio decreased. The ratio of 4 that recorded the lowest average temperature of 302.7 K had the highest average wind speed of 1.23 m/s and a temperature difference of 0.4 K than the 2:1 ratio. The 1:2 ratio has been incorporated in the enhanced scenario and referred to as the best geometry.

The daily temperature values shown in Figure 4.16 opposes the pattern observed in the orientation previously and the current geometry findings whereas it showed that during the peak thermal stress the temperature variations between the three geometries increases. The results highlight that the larger effect of the geometry is during the highest temperature duration where the shading provided acts as a shield to prevent excess heat gain.

The difference between the average and maximum temperature values was stable between the three scenarios yet higher than the difference between those of the wind speed shown in Figure 4.15. The wind variation between the different geometry's was very small where the ratio of 4 had the highest average wind speed values with a difference of 0.06 m/s than the ratio of 2 as shown in Figure 4.17. Such pattern indicates a minor sensitivity level of the wind as a dependent variable to the H:W ratio as an independent variable more than the other dependent variable under investigation which is the temperature shown in Figures 4.16 & 4.18.

The existing scenario tested primarily had a 0.8 ratio that revealed a similar average temperature value to the 0.5 ratio, yet with a very slight decrease. The directly proportional relationship between the H:W ratio and the temperature values was continued in the existing scenario.

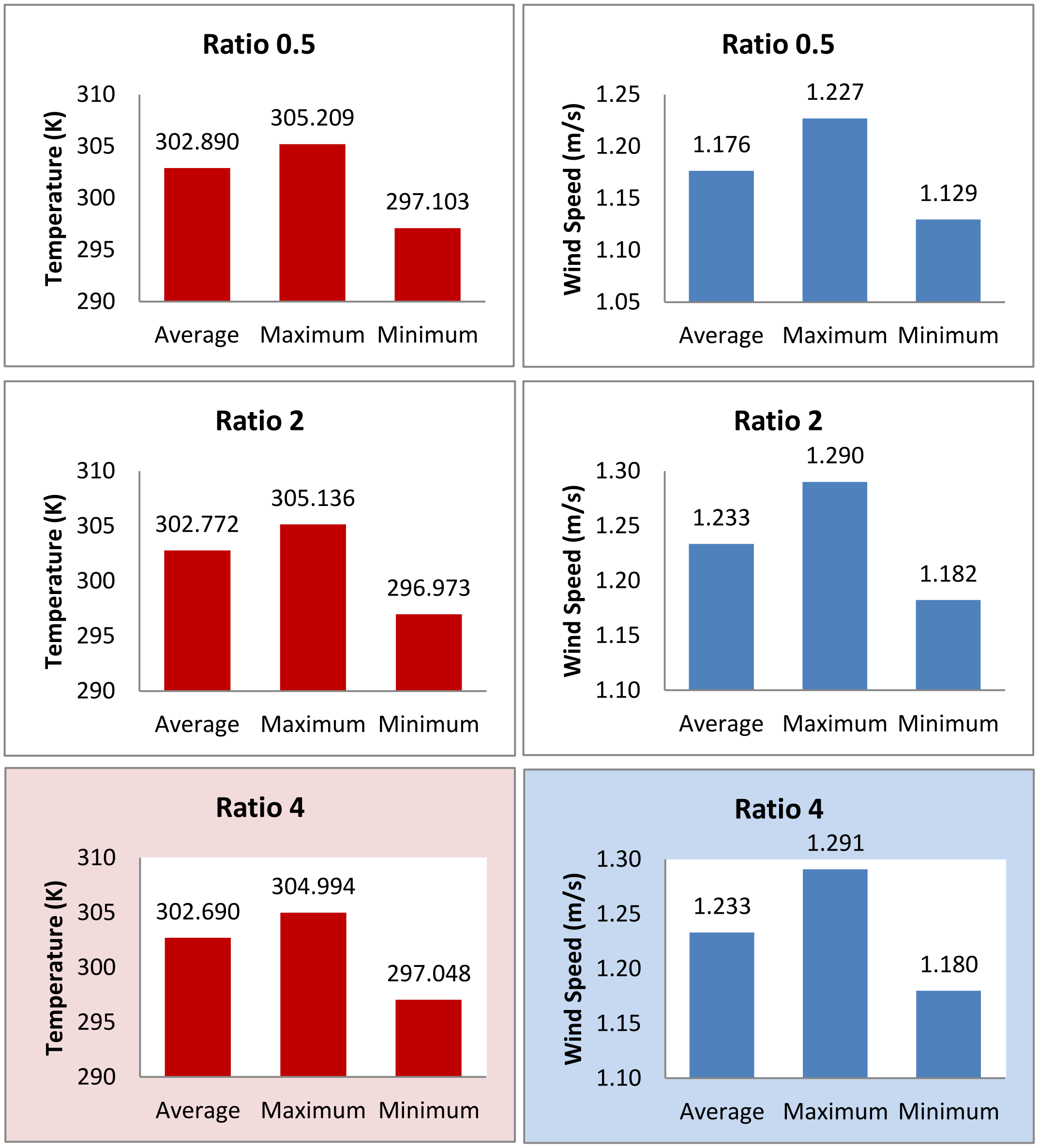



**Figure 4.14 Average, maximum and minimum temperature and wind values of the three different H:W ratios where the nominated ratio records the lowest temperature values and the highest wind speed values.**

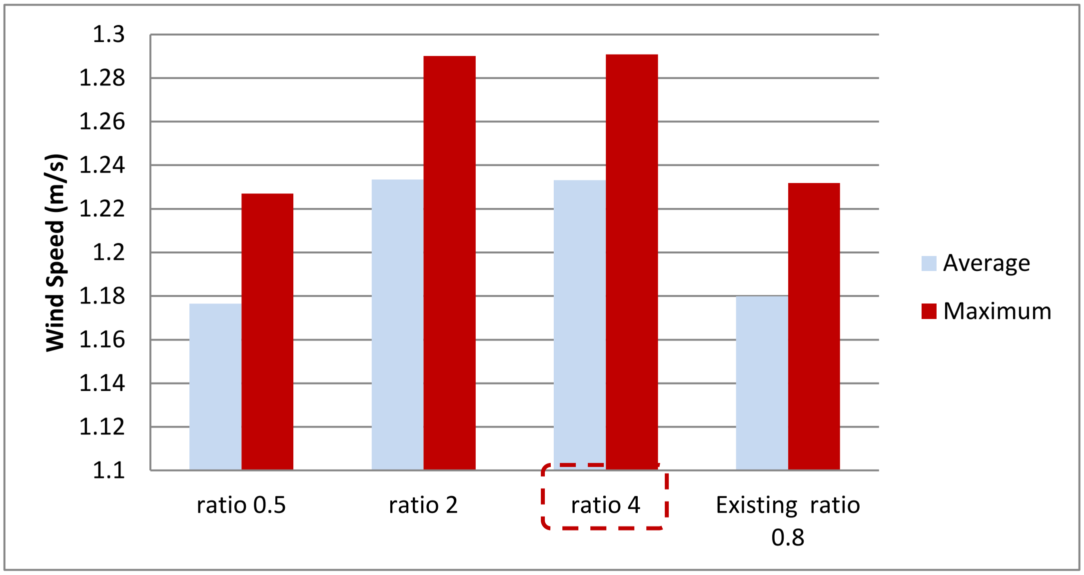



**Figure 4.15 The average wind speed comparison between the three tested ratios and the existing scenario presents a logical sequence with the lowest values for the ratio of 4.**

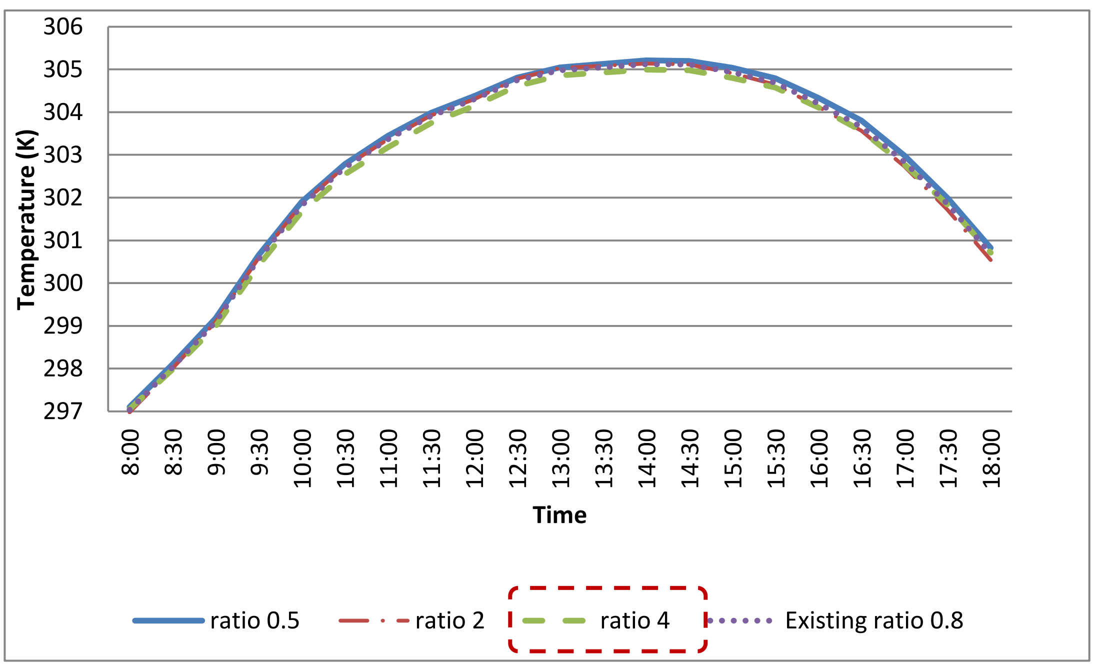



**Figure 4.16 The daily temperature values of the three ratios and the existing scenario with a very slight difference yet in a logical sequence where the highest values belongs to the lowest ratio.**

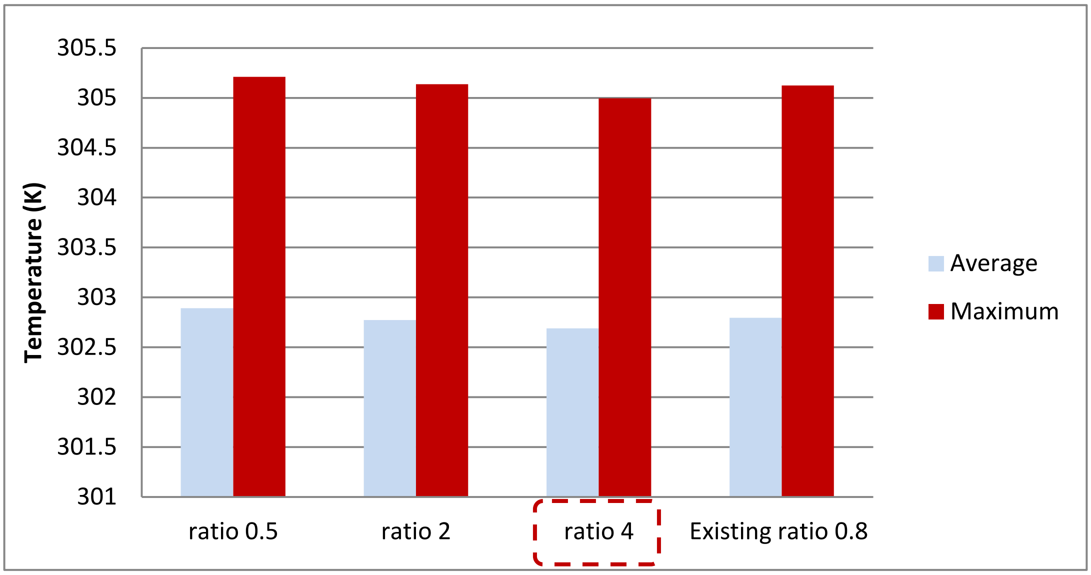



**Figure 4.17 The average temperature comparison between the three tested ratios and the existing scenario presents a logical sequence with the lowest values for the ratio of 4.**

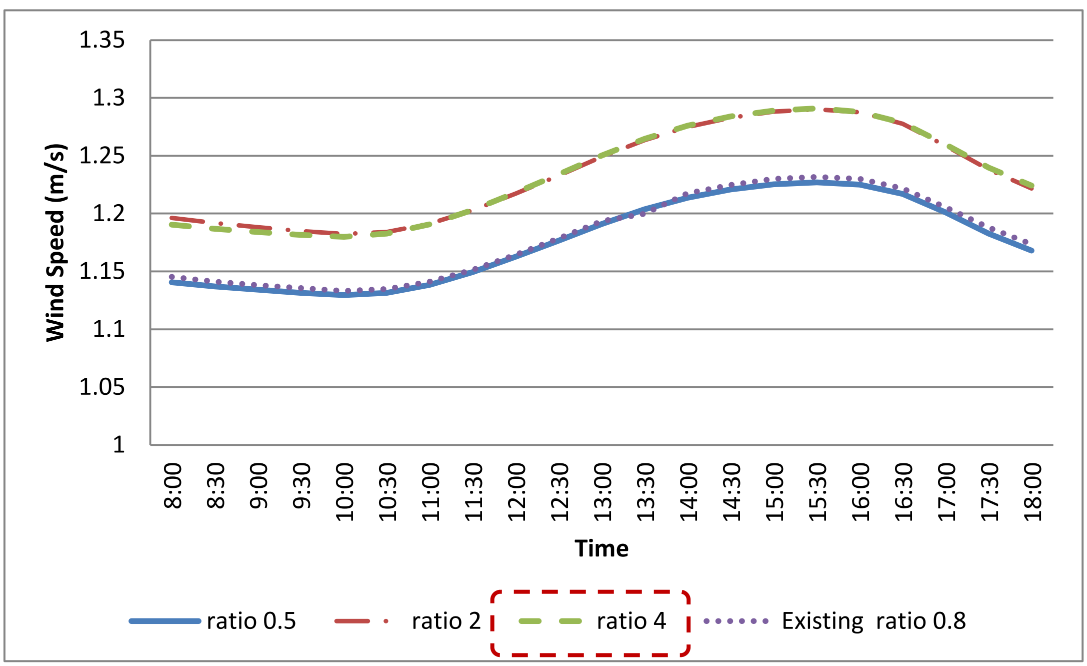



**Figure 4.18 The daily temperature values of the three ratios and the existing scenario with a very slight difference where the highest values belongs to the highest ratio.**

### 4.3.3 Vegetation

Six different landscape strategies that include a grass or trees setting had been carried out through several simulation models testing the vegetation parameter. All simulations had a 20$^{o}$ NE-SW orientation, a H:W ratio of 0.8 and no grass was fixed when trees strategies were tested while a tree planted every 12m was fixed when grass strategies were tested. An outdoor of a continuous grass on the ground surface, small rectangular grass areas known as ‘grass pieces’, continuous grass including groups of trees, group of trees only, a continuous line of trees in the center of the space and a no trees strategy was proposed. The strategies aimed to testify the ability of several vegetation parameters to enhance the outdoor air temperature. The reason for testing several vegetation strategies was that earlier studies mentioned that the distribution of trees within the space sometimes has a negative effect on the air temperature during summer. Application of dense vegetation usually blocks the night flush process which releases the stored heat in the space elements to the air. Such impact should influence the landscape design within the space to enhance the daily average temperature during both seasons. Thus the strategies proposed were designed based upon the same criteria where the tree group’s model applies a bunch of nine trees with large spacing in between. While the continuous line of trees proposes the same amount of trees but with a different distribution. Incorporating the grass into the testing plan was due to the importance of such element to enhance the air temperature.

The proposal of continuous grass and tree groups revealed the least average temperature values of 304.6 K and an average wind speed of 1.12 m/s which was expected due to the incorporation of both the vegetation aspects. The no tree strategy had the highest average and maximum temperature and wind speed values since no vegetation at all was incorporated in the scenario which enhanced the wind flow through the space yet no shade was provided by any of the trees shown in Figure 4.19 & 4.20. The total temperature variations between the six strategies were very small with a maximum value of 0.57 K getting slightly larger when comparing the wind speed average values. The minimum temperature values had the least variation of 0.3 K.

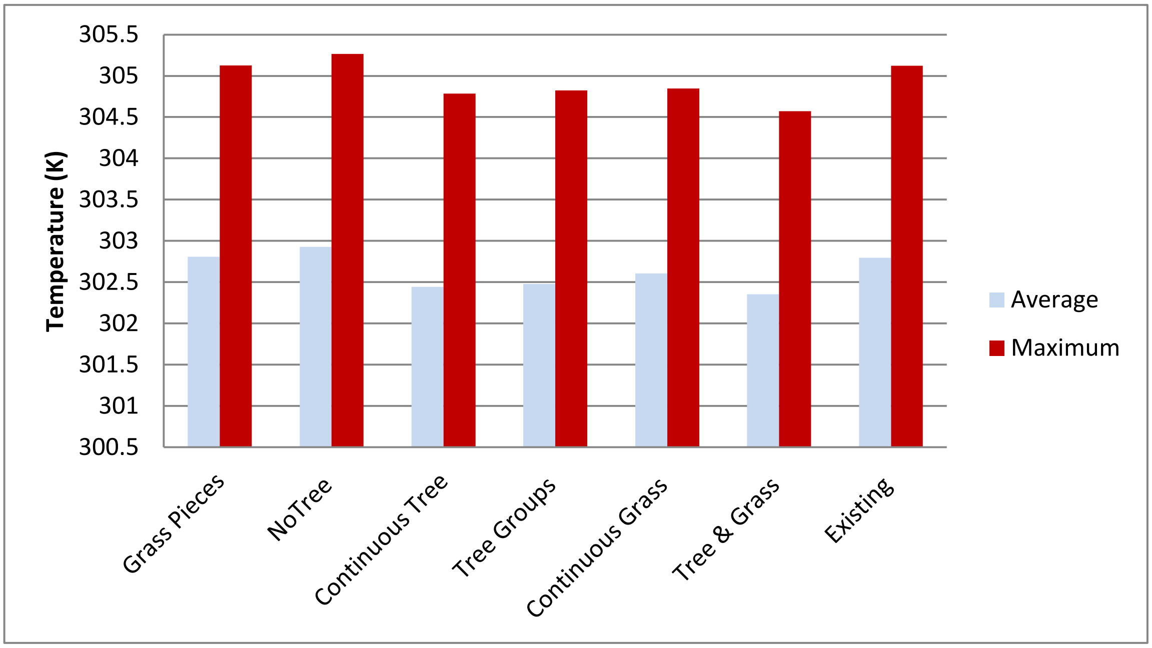



**Figure 4.19 The six landscape strategies average and maximum temperatures and the existing scenario values reveals that the trees & grass proposal has the least values.**

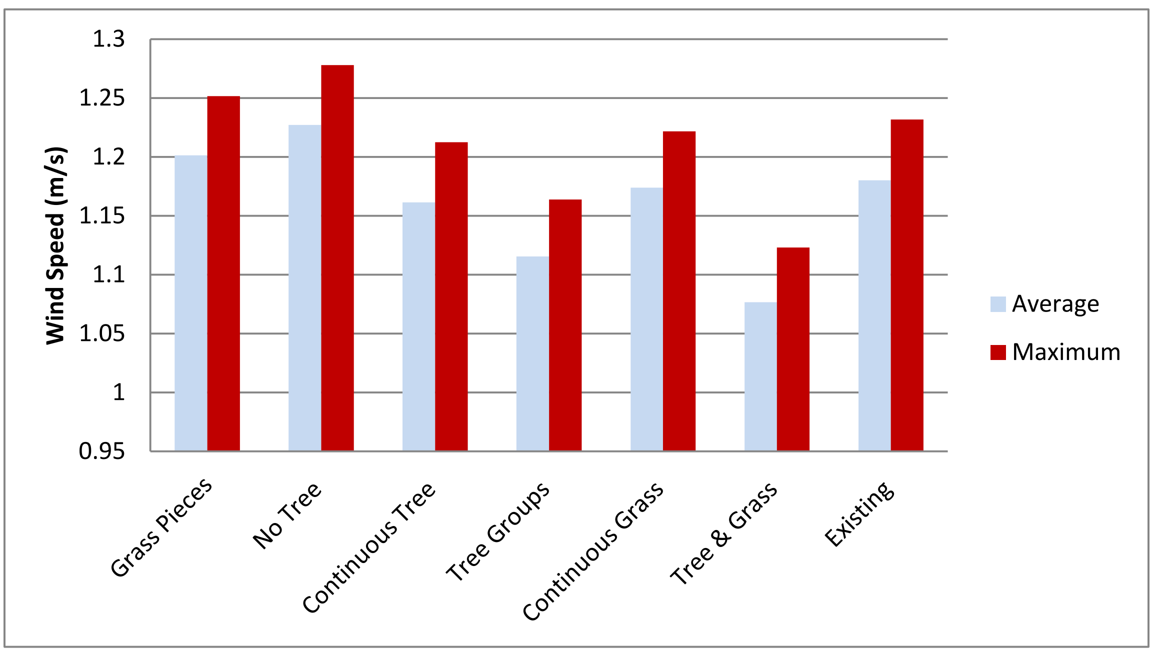
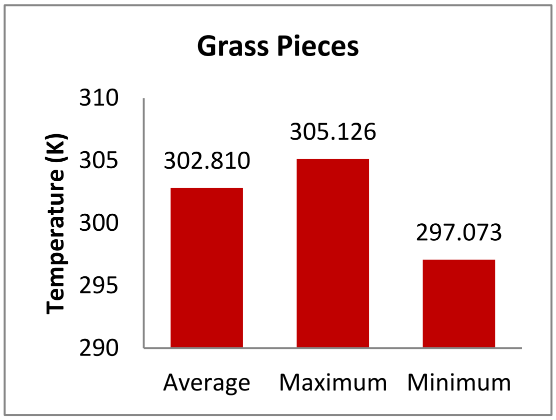


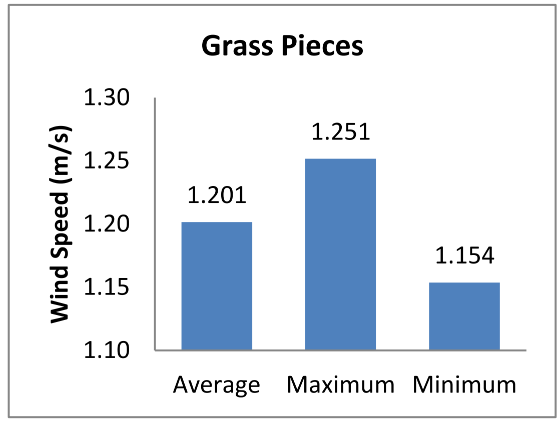

**Figure 4.20 The six landscape strategies average and maximum wind speed values and the existing scenario values.**

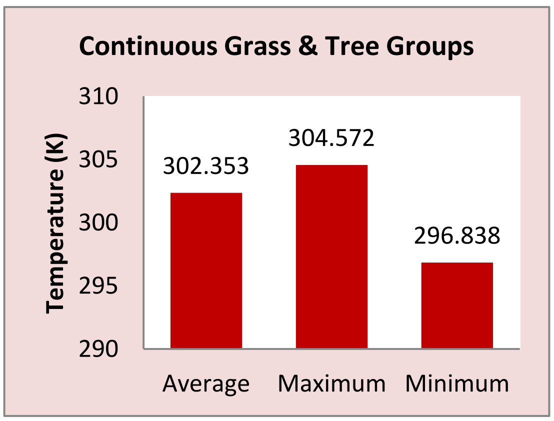
The comparison between the grass pieces results and the continuous grass has a very slight variation yet the comparison between the tree groups and the continuous trees showed the least differences between all strategies of a 0.04 K shown in Figure 4.21. The temperature behavior during the daily peak heat stress corresponds with the geometry behavior where the differences increases during that time while oppose the orientation behavior as shown in Figure 4.21.

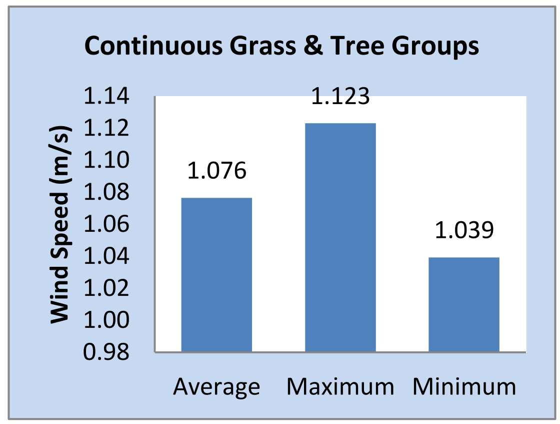
The results reveal the expected sequence for the different strategies where the denser the vegetation applied the lower the temperature values are in respect to the concept that no continuous dense trees are applied to prevent nocturnal heat gain. Trees being more effective than grass seemed to be logic where they provide shade along with the plant characteristics.

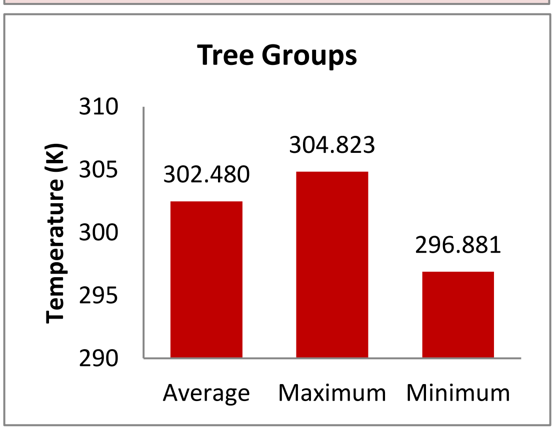
The existing scenario recorded the second highest average and maximum temperature between all vegetation strategies of 302.8 K average temperature, an average wind speed of 1.18 m/s and an average temperature difference of 0.4 K compared to the best vegetation strategy of grass and tree groups shown in Figure 4.20. The pattern shown in Figure 4.22 & 4.23 has a logical sequence based upon the concept of tree groups being the most effective among tree strategies followed by continuous tree line. Grass revealed to be less effective than trees yet continuous grass was more effective than grass pieces strategy. The existing scenario being with no grass and a few number of trees was considered to be within the higher range of temperatures.

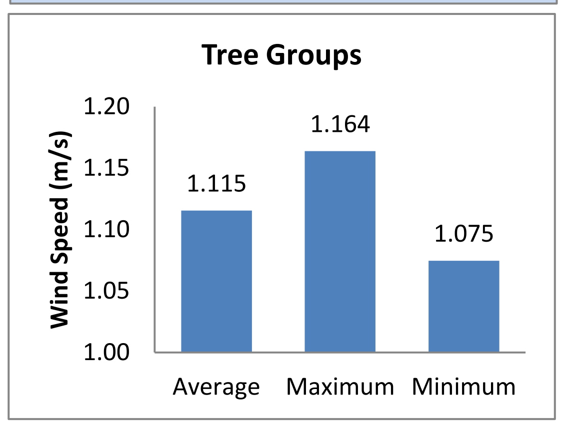

Grass Pieces
Temperature (K)
310
305
300
295
290
302.810
305.126
297.073
Average
Maximum
Minimum

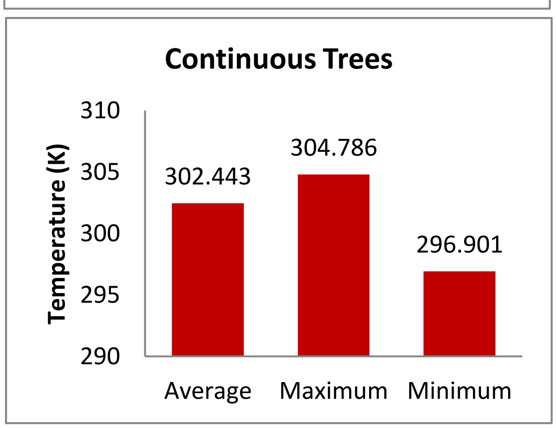

Grass Pieces
Wind Speed (m/s)
1.30
1.25
1.20
1.15
1.10
1.201
1.251
1.154
Average
Maximum
Minimum

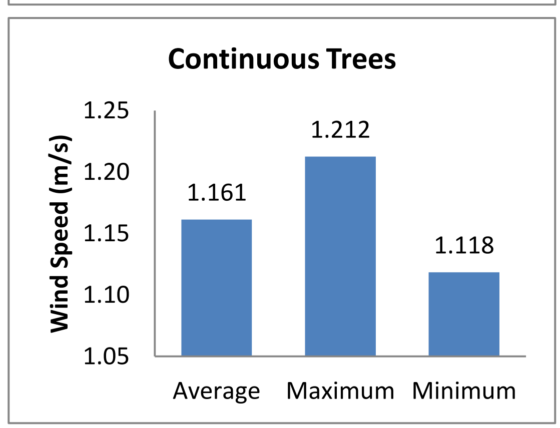

Continuous Grass & Tree Groups
Temperature (K)
310
305
300
295
290
302.353
304.572
296.838
Average
Maximum
Minimum


Continuous Grass & Tree Groups
Wind Speed (m/s)
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.98
1.076
1.123
1.039
Average
Maximum
Minimum


Tree Groups
Temperature (K)
310
305
300
295
290
302.480
304.823
296.881
Average
Maximum
Minimum


Tree Groups
Wind Speed (m/s)
1.20
1.15
1.10
1.05
1.00
1.115
1.164
1.075
Average
Maximum
Minimum


Continuous Trees
Temperature (K)
310
305
300
295
290
302.443
304.786
296.901
Average
Maximum
Minimum


Continuous Trees
Wind Speed (m/s)
1.25
1.20
1.15
1.10
1.05
1.161
1.212
1.118
Average
Maximum
Minimum

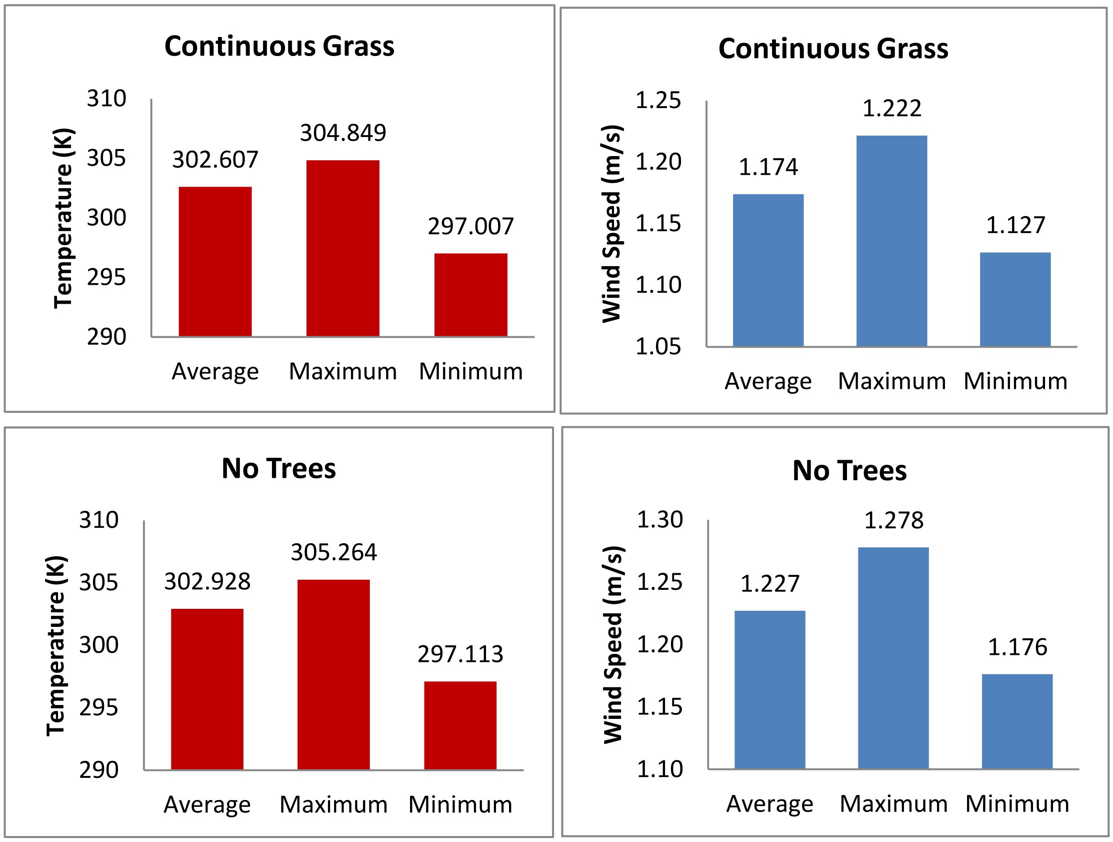



Figure 4.21 The average, maximum and minimum temperatures of the six vegetation strategies.

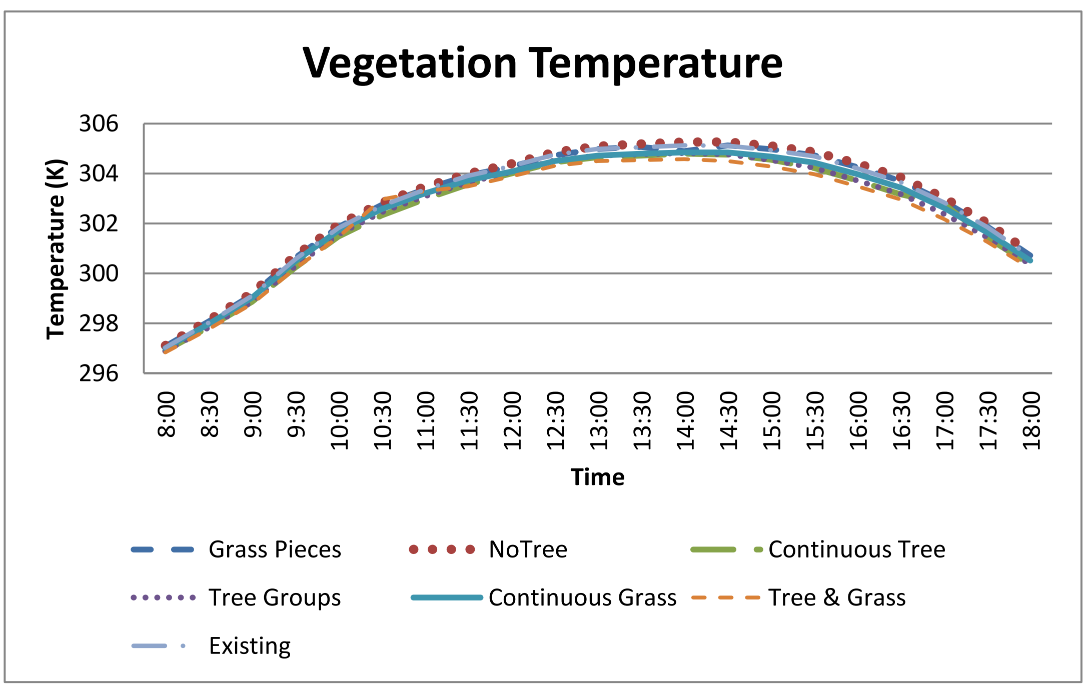



Figure 4.22 The daily temperature values of the different strategies revealing very slight differences yet the trees & grass as the most effective with lowest values.

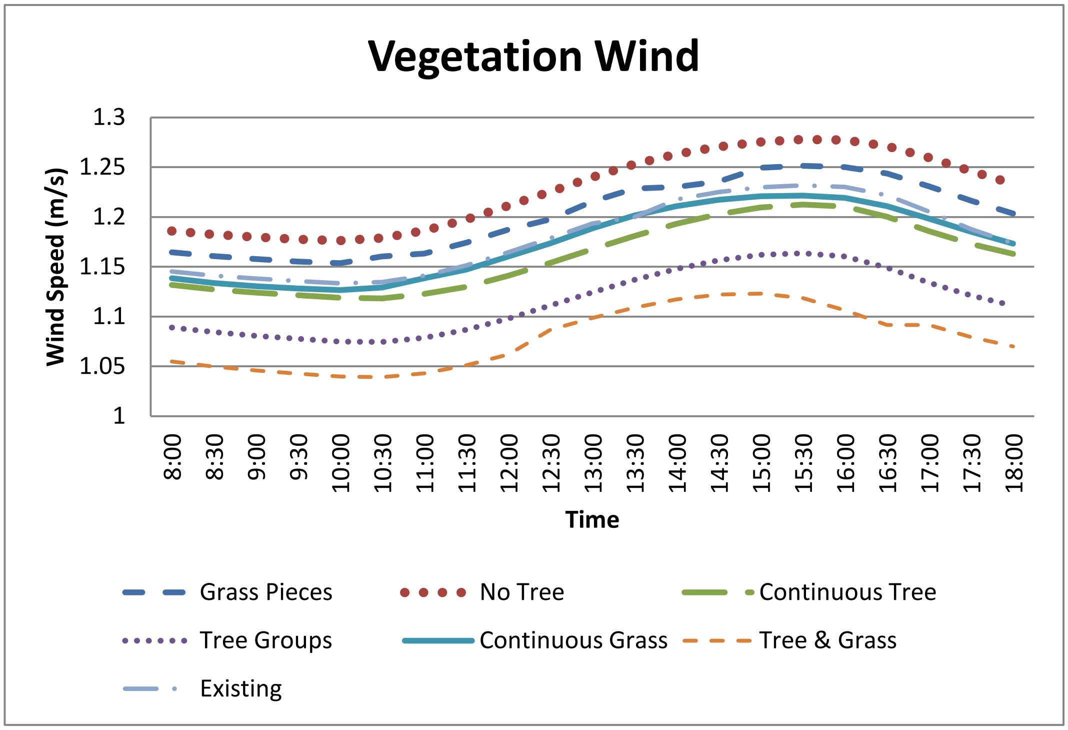



**Figure 4.23 The daily wind speed values of the different strategies revealing more considered differences than the temperature values yet the trees & grass with lowest values.**

### 4.3.4 Comparison of Independent Variables

The bioclimatic parameters selected for the current investigation demonstrated variable results according to the average and maximum temperatures observed. The vegetation parameter revealed to be the most effective parameter in reducing the air temperature with an average temperature difference of 0.6 K than the existing scenario followed by the orientation and the geometry with an average difference of 0.4 K and 0.1 K respectively shown in Figure 4.24. The same hierarchy of variables is applicable for the wind speed yet with an opposite order where the vegetation scenario has the lowest average wind of 1.08 m/s and the geometry as the highest value of 1.18 m/s followed by the orientation and then the geometry shown in Figure 4.25. The temperature differences recorded by each variable are noted to be very small in terms of enhancing the air temperature yet where considered to be analyzed and interpretations are derived from such behaviors. The sequence demonstrated by each of the dependant variables tested reveals a logical sequence compared to the results revealed by earlier studies yet with a relatively lower values which might be due to the scale of the bioclimatic implementation. Analysis for such results will be discussed thoroughly in Chapter 5 trying to investigate the real effect of the bioclimatic design to enhance the outdoor air temperature.

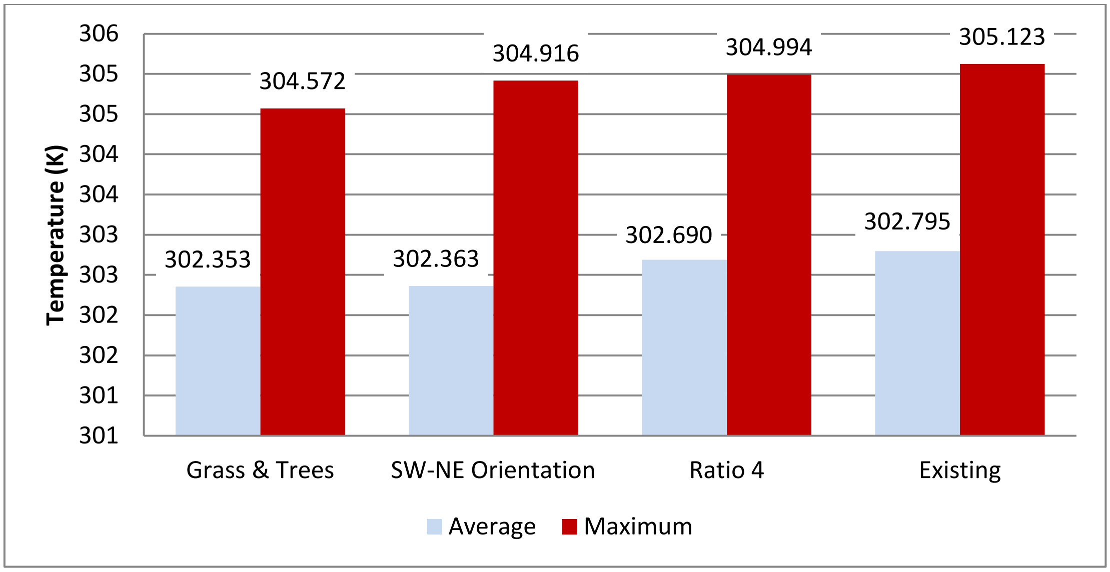



Figure 4.24 The average and maximum temperature values for the most effective independent variable that recorded the lowest temperature values.

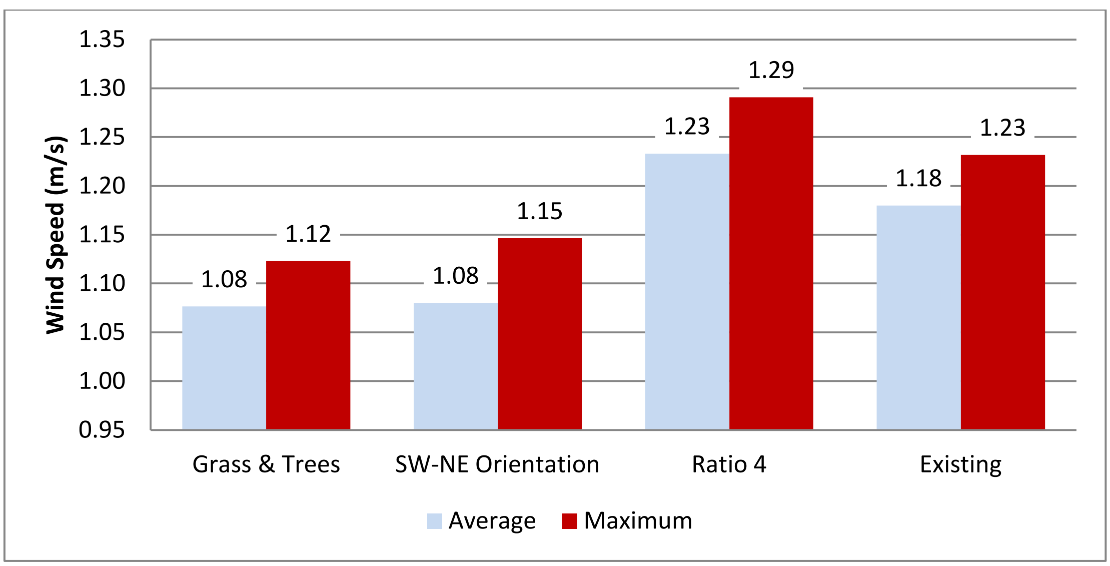



Figure 4.25 The average and maximum wind speed values for the most effective independent variable that recorded the lowest temperature values.

## 4.4 Enhanced Scenario

The enhanced model is considered the conclusion model for the current study where it incorporates together the most effective parameters of the bioclimatic variables under investigation. The results of such model were analyzed to verify the hypothesis set. The current simulation results are based upon a SW-NE orientation, 0.5 ratio, continuous grass and tree group's configuration. Simulations were run on the exact duration of the existing and the worst case scenario which is on the $21^{st}$ of August representing summer and $21^{st}$ of January representing winter from 8.00am to 10.00pm.

Generally the temperature and wind behaviors during both summer and winter revealed very similar to that of the existing scenario since the existing scenario had a similar orientation and geometry. The daily temperature pattern shown below in Figure 4.25 has a peak heat stress zone between 12.00 and 15.00 during summer which records a maximum temperature of 304.7 K. This duration has recorded a significant increase in the wind speed during summer with a maximum value of 1.05 m/s as shown in Figure 4.26. The temperature varies 8.1 K between the maximum and minimum temperature during summer while the gap descends during winter to be 7.4 K as shown in Table 4.2. The enhanced scenario recorded an average temperature value of 301 K during summer and 298 K during winter which is slightly lower than the existing scenario records. The difference in temperature between the two seasons is almost stable for maximum, minimum and average temperatures even through the peak heat stress periods shown in Figure 4.27. This variation is not stable when observing the wind speed results where the maximum values of wind revealed to have a greater difference than that between the average and the minimum demonstrated on Figure 4.28.

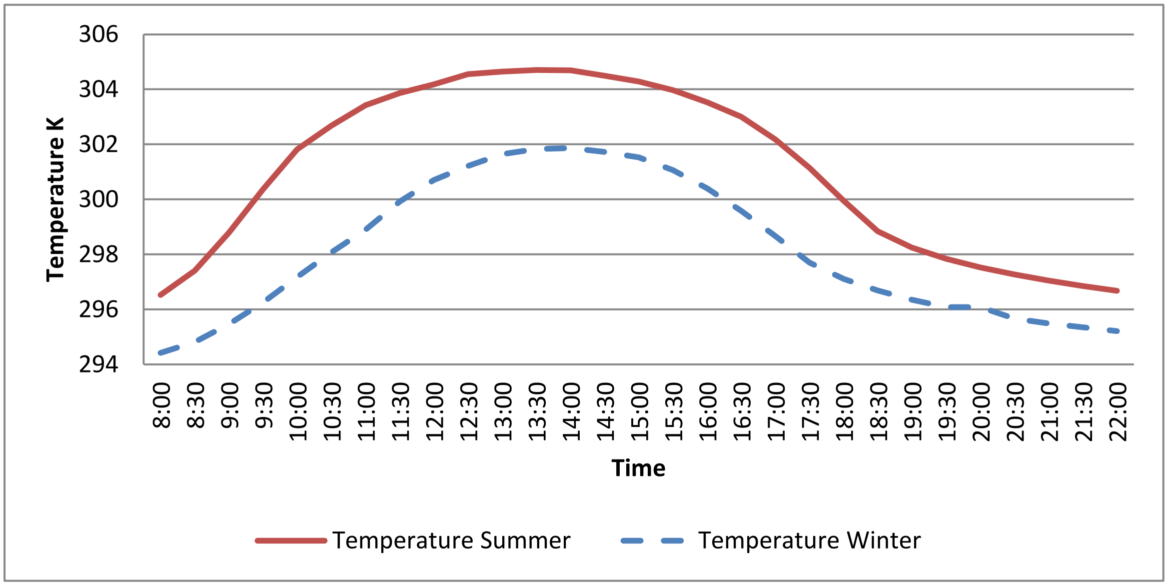



**Figure 4.26 The daily average values of temperature indicates the peak thermal stress zone with the maximum temperature during summer between 12.00 and 15.00 shifted slightly during winter**

**Table 4.2 The temperature and wind speed values of the summer on the 21st August and winter on the 21st January.**

| | **Temperature** | | **Wind** | |
|---|---|---|---|---|
| | **Summer** | **Winter** | **Summer** | **Winter** |
| Average | 301.052 | 298.173 | 0.980 | 0.941 |
| Maximum | 304.698 | 301.867 | 1.054 | 0.960 |
| Minimum | 296.527 | 294.427 | 0.941 | 0.933 |

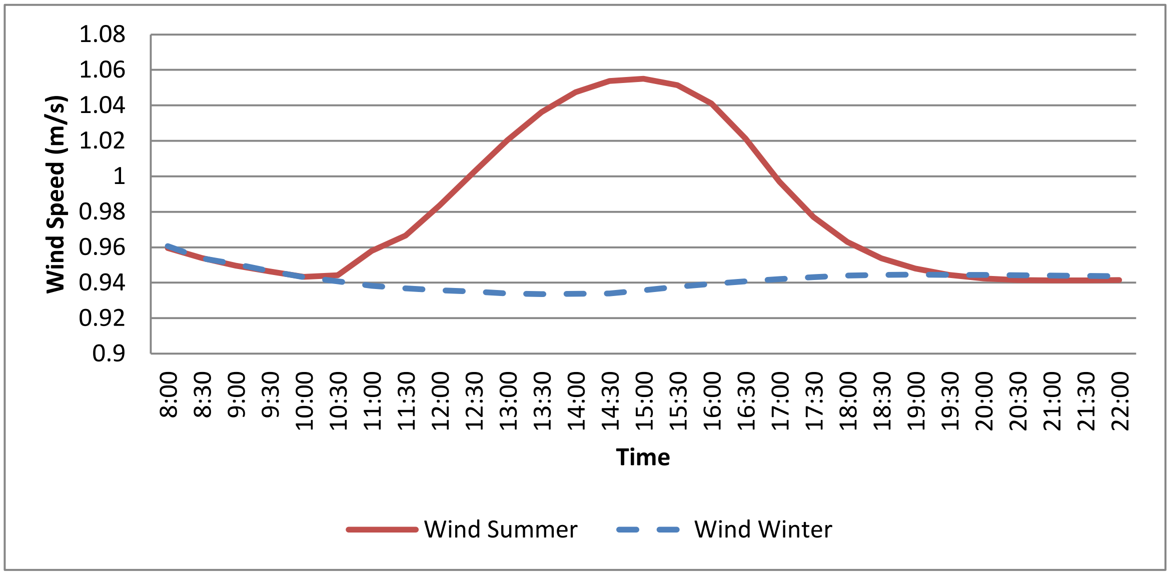



**Figure 4.27 The daily wind speed values with the maximum wind speed period during the peak thermal stress zone during summer and much more stable during winter.**

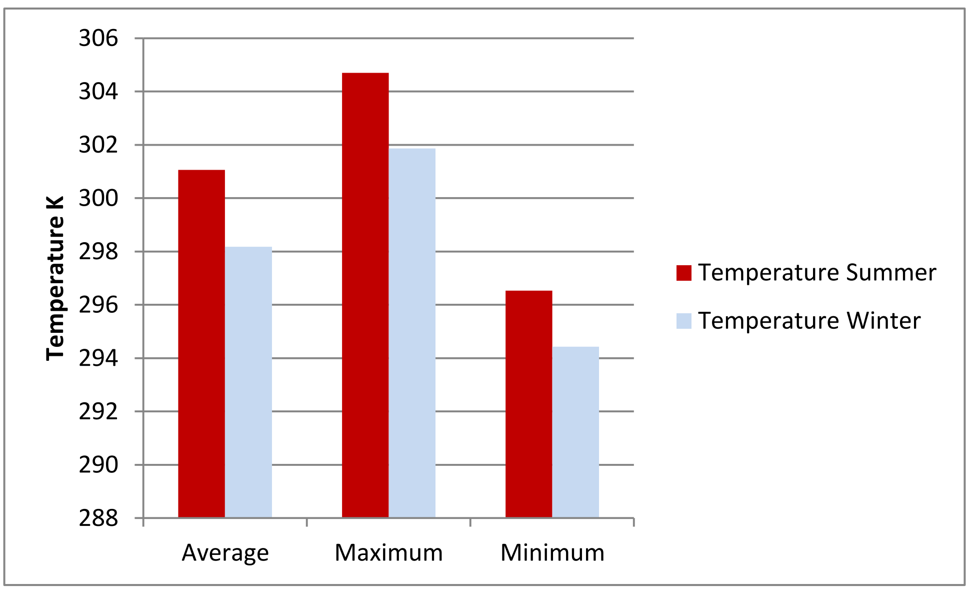



**Figure 4.28 The average, maximum and minimum temperature values of the enhanced scenario during summer on the 21st of August and winter on the 21st January.**

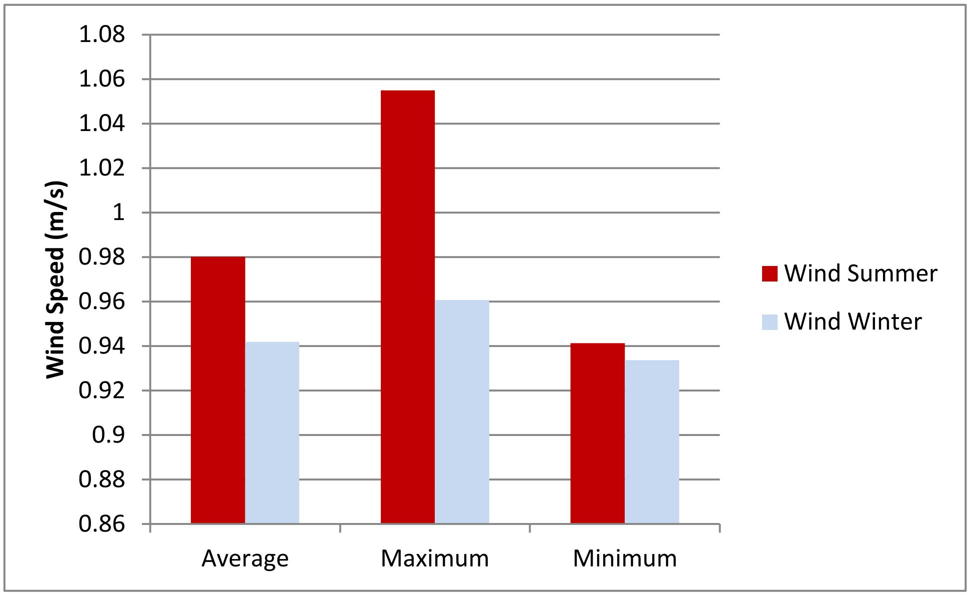



**Figure 4.29 The average, maximum and minimum wind speed values of the enhanced scenario during summer on the 21st of August and winter on the 21st January.**

## 4.5 Worst Case Scenario

This scenario is the last simulation model constructed for the current study aiming to evaluate the bioclimatic scenarios ability to enhance the air temperature. The worst case scenario is based upon incorporating the variables that revealed to have the highest average temperature through the previous simulations. Since the existing scenario had incorporated few variables of the bioclimatic principles as trees and orientation, therefore the comparison held between it and the enhanced scenario would not be considered even, unless a scenario that abandons all bioclimatic principles is compared to the enhanced scenario. The model was based upon an EW orientation, 0.5 H:W ratio and no vegetation within the site.

The wind and temperature patterns shown in Figures 4.29 & 4.30 are different from the enhanced and existing scenarios patterns discussed previously. The results between 12.30 and 14.00 which are considered within the peak thermal stress zone in the previous scenarios reveal to descend slightly in terms of temperature and wind behaviors. The results showed in Table 4.3 highlights the average, maximum and minimum temperatures and wind speed which recorded higher values than the two previous scenarios.

Table 4.3 Temperature and wind values during summer and winter for the worst case scenario.

| | Temperature | | Wind | |
|---|---|---|---|---|
| | Summer | Winter | Summer | Winter |
| Average | 302.184 | 298.061 | 1.937 | 1.897 |
| Maximum | 305.676 | 301.162 | 1.997 | 1.979 |
| Minimum | 296.561 | 294.342 | 1.840 | 1.841 |

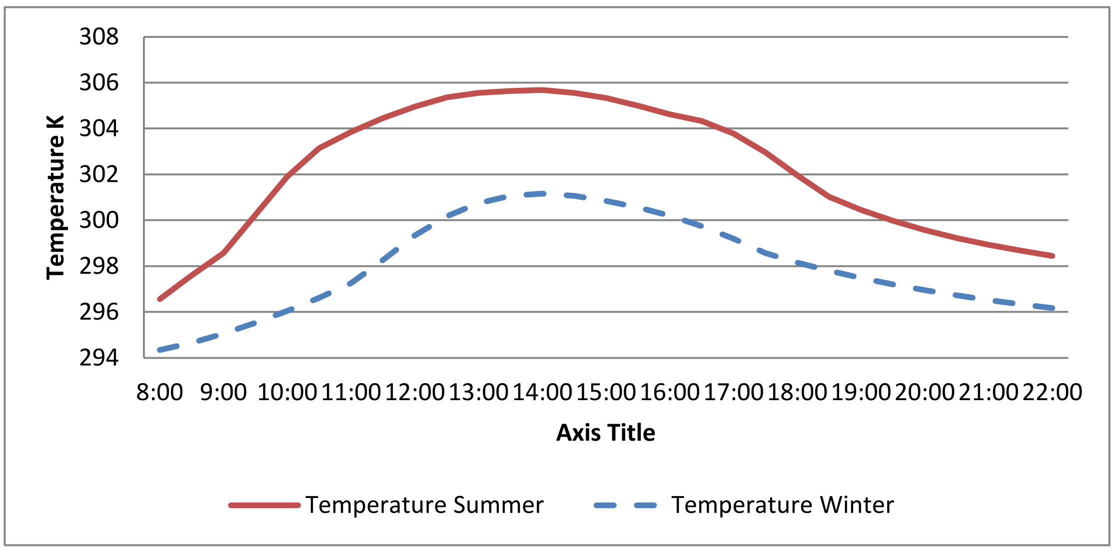



Figure 4.30 The daily temperature values during both summer on the 21st of August and winter on the 21st of January showing the peak heat stress period behavior.

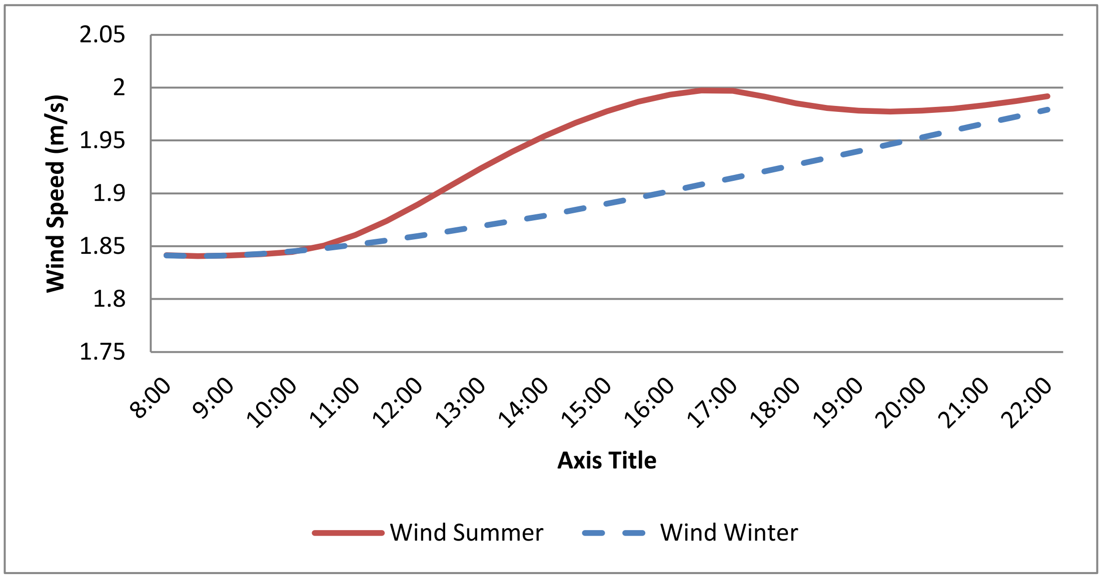



**Figure 4.31 The daily wind speed values during both summer on the 21st of August and winter on the 21st of January showing the peak heat stress period behavior.**

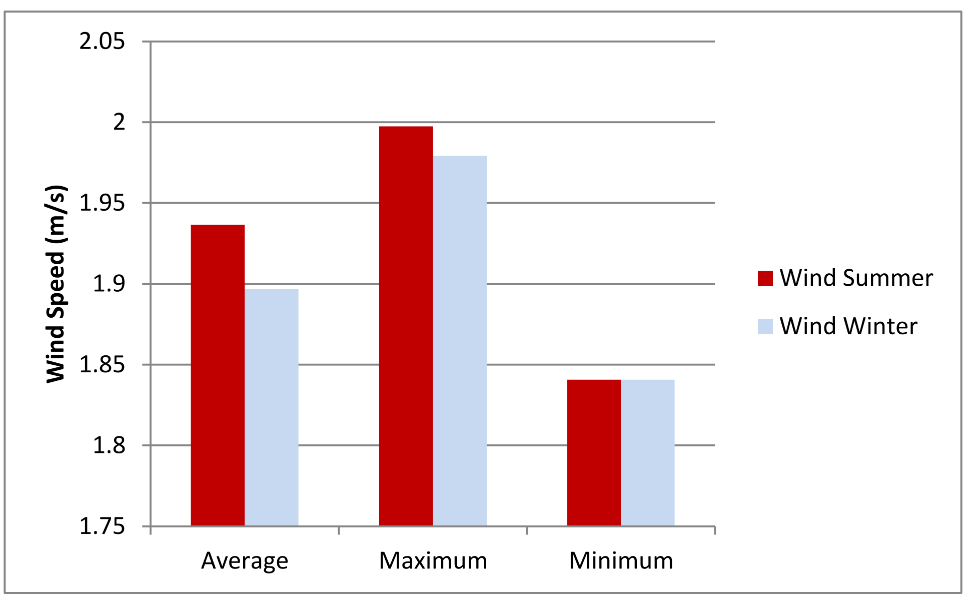



**Figure 4.32 The average, maximum and minimum wind speed values of the worst case scenario during summer on the 21st of August and winter on the 21st January.**

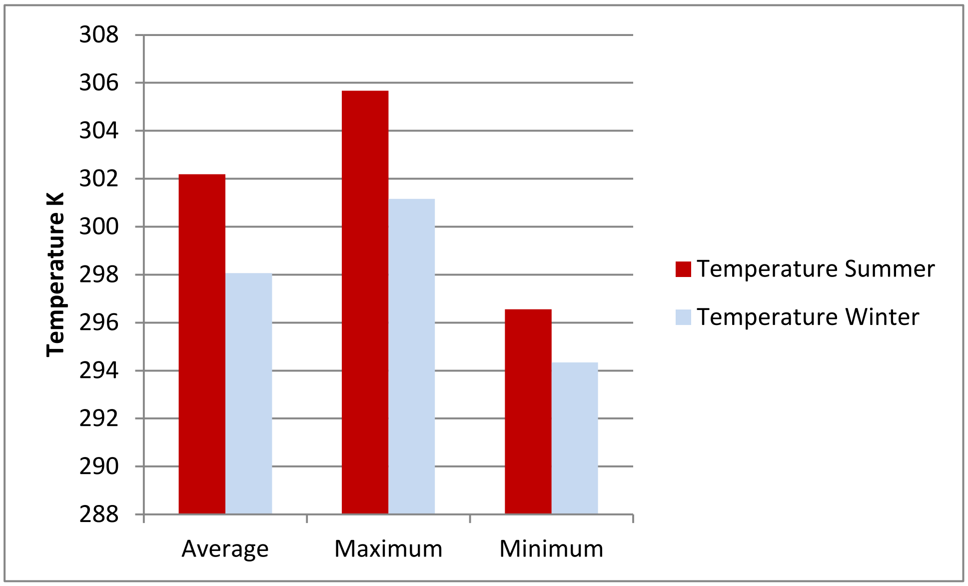



**Figure 4.33 The average, maximum and minimum temperature values of the worst case scenario during summer on the 21st of August and winter on the 21st January.**

## 4.6 Comparative Analysis

Evaluation of the three main scenarios will be done comparing the temperature results trying to investigate the real effect a bioclimatic design could have on an outdoor space. The aim of the enhanced scenario is to record the highest temperature values in winter and lowest values in summer which approaches the thermal comfort levels all through the year. The three scenarios had a full day simulation covering up the time when the spaces might be used between 8.00am and 10.00pm to achieve a balanced solution between the day and night temperature and wind behaviors. Averages were calculated to indicate the balance between the maximum and minimum values of temperature while the wind pattern was observed carefully in accordance to these aspects to examine its impact on the thermal behavior.

The bioclimatic scenario known as the enhanced scenario recorded the lowest maximum temperature during summer of 304.7 K and the largest during winter of 301.9 K as demonstrated in Table 4.4 followed by the existing and the worst case scenario consecutively shown in Figure 4.32 with a difference of 0.4 K and 0.9 K respectively between the maximum values during summer. The order of the three scenarios revealed a logic sequence especially during summer yet with a slight difference in terms of temperature and wind speed values. During summer the enhanced scenario had the lowest minimum temperature values followed by the worst case scenario and the existing scenario consecutively. Unexpectedly, the existing scenario revealed the preferably highest minimum values during winter which is basically the coldest time of the year during the evening where the worst case scenario was expected to record such value. The difference between the minimum average temperature values recorded during summer revealed a slight increase of 0.2 K for the enhanced scenario which highlights the incapability of the enhanced scenario to record the lowest average temperature value as expected.

**Table 4.4 Summary of results of the temperature values of the three scenarios during summer on the 21st of August and winter on the 21st of January highlighting the highest in winter and lowest in summer.**

| | Average Summer | Average Winter | Minimum Summer | Minimum Winter | Maximum Summer | Maximum winter |
|---|---|---|---|---|---|---|
| Enhanced scenario | 301.052 | 298.173 | 296.527 | 294.427 | 304.699 | 301.867 |
| Existing scenario | 301.570 | 298.454 | 297.034 | 294.968 | 305.123 | 301.729 |
| Worst scenario | 302.040 | 298.061 | 296.560 | 294.342 | 305.560 | 301.162 |

The average and maximum temperature patterns shown in Figure 4.32 represents the common behavior where factors that usually record the lowest temperature values during summer are inverted during winter to record the highest values except for the enhanced scenario that did not record the highest average temperature during winter. The wind pattern demonstrated in Figure 4.33 represents the worst case scenario as the highest wind speed in all cases which is due to several reasons. The EW orientation allows more wind into the spaces and moreover the model had no trees which even allow the wind to accelerate within the space raising the maximum wind values particularly in this scenario. The orientation of the existing scenario and the few trees interrupt the wind more than the worst scenario reducing the wind speed values followed by the enhanced scenario. The enhanced scenarios orientation makes it receive the least amount of wind interrupted by the vegetation strategy and high value of H:W ratio. Finally, the results accentuate the enhanced scenario being capable of reducing the air temperature with a value of 1 K.

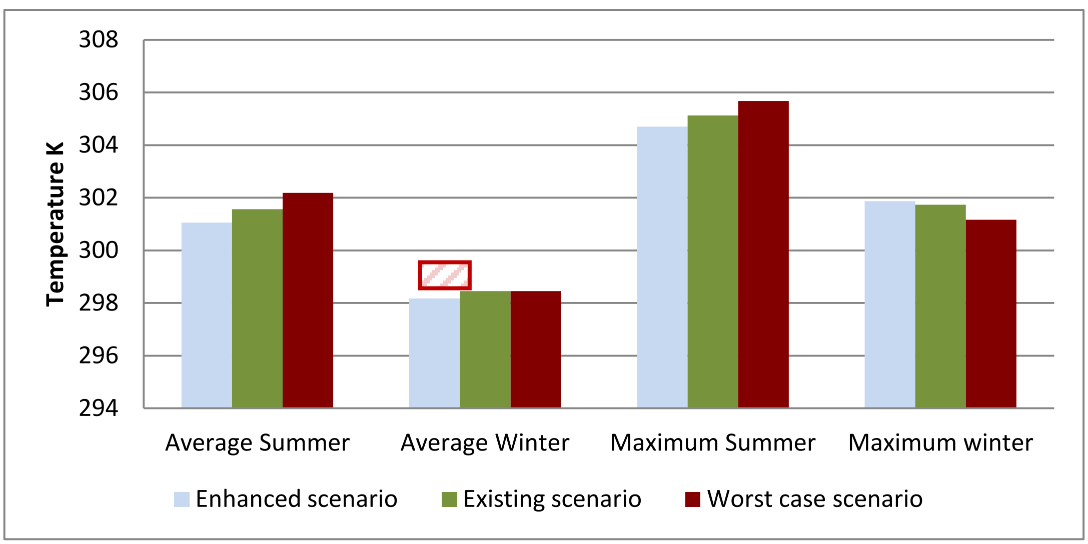



**Figure 4.34 The average and maximum temperatures during summer on the 21st of August and winter on the 21st of January.**

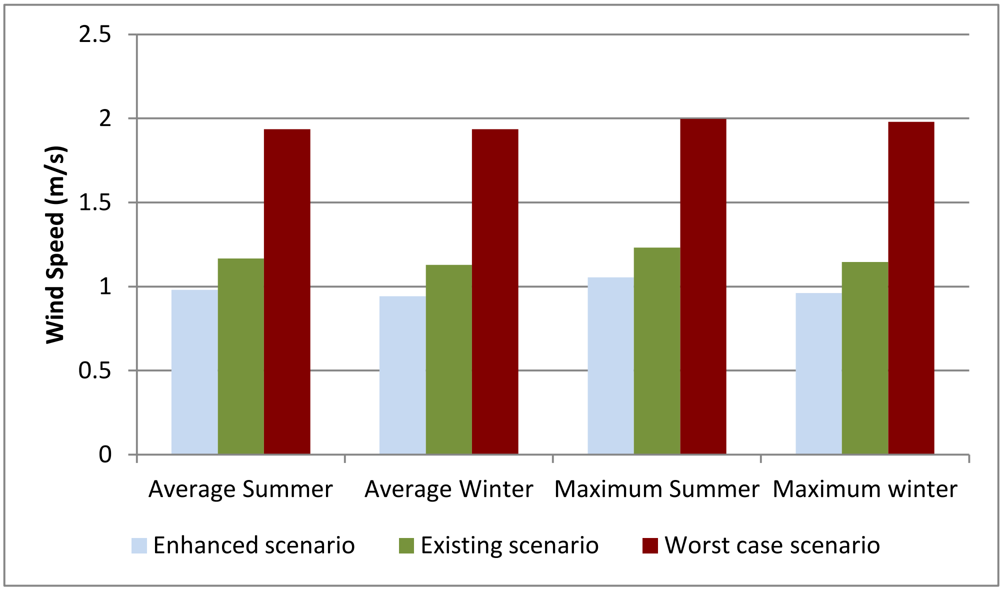



**Figure 4.35 The average and maximum wind speed during summer on the 21st of August and winter on the 21st of January with the worst case as the highest value in all cases.**

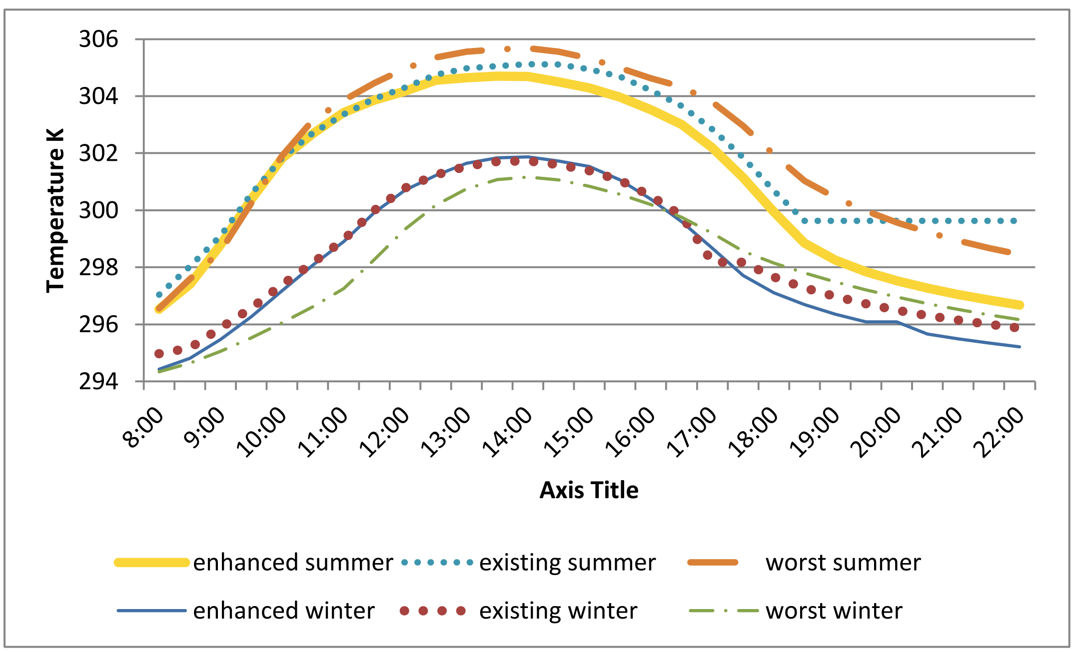



**Figure 4.36 The daily temperature distribution of the three scenarios during summer on the 21st of August and winter on the 21st of January.**

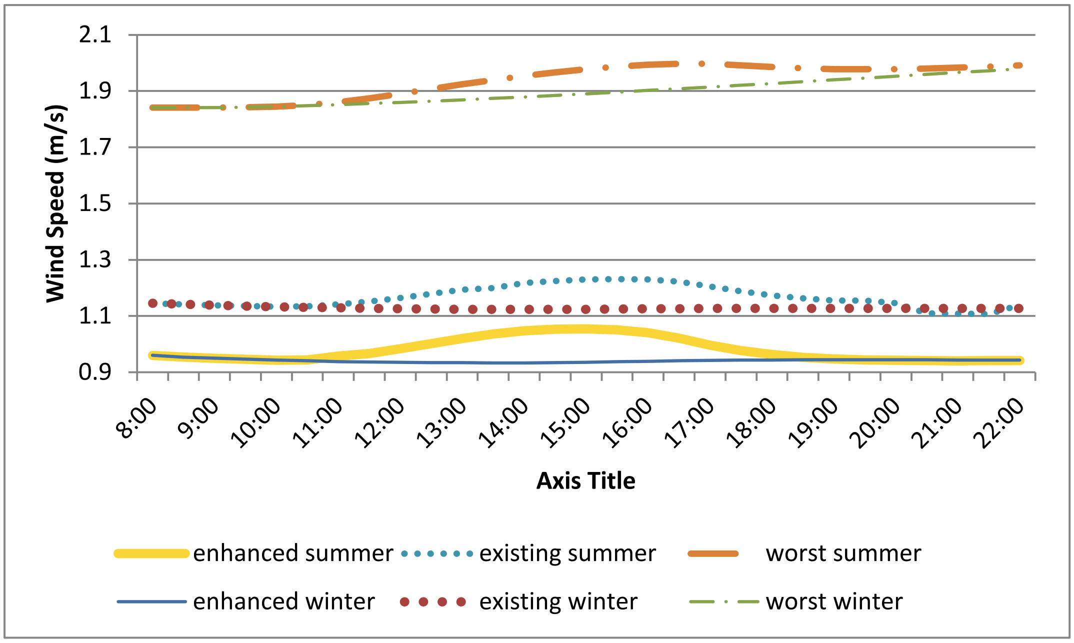



**Figure 4.37 The daily wind speed distribution of the three scenarios during summer on the 21st of August and winter on the 21st of January.**

## 4.7 Summary of Results

The enhanced scenario that incorporated the best independent variables revealed to enhance the air temperature with a value of 1 K compared to the worst case scenario. The best independent variables where selected based upon the average temperatures rather than the maximum temperature values. Simulations for the independent variables that enhanced the air temperature slightly were run during the extreme summer conditions. The vegetation revealed to be the most passive cooling parameter followed by the orientation and the geometry consecutively. The SW-NE orientation, the highest ratio of 4 and the grass in addition to groups of trees were the parameters nominated for the enhanced scenario due to their contribution to the least average temperature values. The addition of the three parameters within the enhanced scenario revealed an enhancement of 1K which has proved to be a higher value than the improvement of each variable independently to the air temperature.

The three scenarios were compared together having the enhanced scenario as the lowest average temperature during summer followed by the existing scenario then the worst case scenario having the highest average temperature values during summer. The existing scenario recorded the highest average and minimum temperatures during winter with the lowest values to the worst case scenario. The worst case scenario was based upon the configuration of the highest average temperature values of the three variables tested which was EW orientation, lowest ratio of 0.5 and no vegetation within the space.

Wind has been noted in comparison to the temperature values. Generally, it was observed that the average wind speed increased as the average temperature decreased having an inversely proportional relationship. The wind aspect in extremely hot climatic conditions similar to Dubai is not considered a cooling parameter it’s just has a spreading effect to the existing temperature.

# CHAPTER FIVE: DISCUSSION

## 5.1 Background

The discussion presented below is the link between Chapters 2 reviewing the earlier researches made on similar subjects and Chapter 4 demonstrating the results obtained from the simulations done. Finding interpretations of the results attained is based upon the understanding of the behavior of each of the variables tested based on earlier findings that either support the current ones or oppose them. Generally, most of the findings were in compliance with the earlier findings except for certain areas that is highlighted and discussed separately. The wide range of parameters simulated requires an organized separation in presenting such reason yet a synthesized vision of all variables and scenarios will be discussed as well. The discussion of the independent variables will be based upon the extreme summer conditions while comparative discussions of the three scenarios (enhanced, existing and worst) is based upon the summer and winter conditions.

Leonardo is the software used by ENVI-met to extract visual maps that shows the gradient temperature distribution within the space. Visual maps indicate temperature through color gradient where extracted for all the output files attained form all simulations. Very slight variations in temperature are not clearly visible on those maps especially when the time frame between them is small. Therefore, visuals with larger time intervals will be used to demonstrate temperature and wind patterns behaviors.

## 5.2 Independent Variables

### 5.2.1 Effect of Orientation

The four orientations tested were the NS and EW orientations and a 45$^o$ inclination for the SW-NE and the SE-NW orientations. The results revealed the SW-NE to have the lowest average temperature followed by the NS, SE-NW and last is the EW orientation that was found to be with the highest average temperature values. Toudert and Mayer (2006), Hoffman and Bar (2003), Mazouz and Masmoudi (2004) supported the result of the EW orientation with the highest temperature levels. The reason is that the EW orientation has the highest maximum temperature which is during the peak thermal stress during the day in which increases the amount of solar gain during that period and accordingly, the average temperature is raised. The South walls of an EW orientated space are considered to receive the highest levels of solar radiation and which is considered to be the crucial aspect raising the temperature levels.

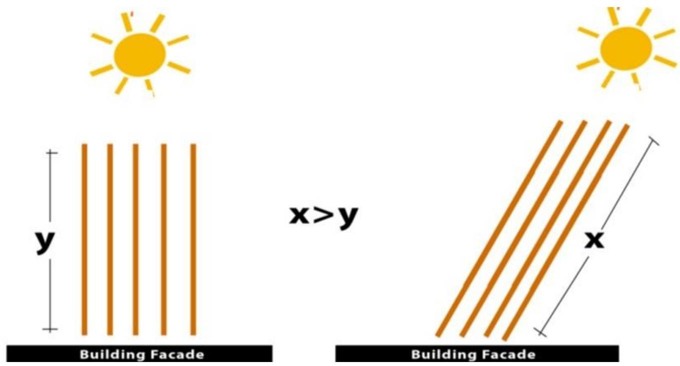



**Figure 5.1. The sun rays incidence on the building surface where perpendicular rays cut shorter distances that makes the rays warmer than if inclined.**

**Source: Nihal AL Sabbagh**

The peak thermal stress zone identified in Figure 4.10 between 13.00 and 15.00 is the time where the sun is in a central position on the solar path represented in Figure 4.11. A facade facing the noon sun receives the highest levels of heat. The sun angle during that time plays a major role as well where planes receiving perpendicular rays are warmer than others that receive inclined sun rays as shown in Figure 5.1. Such concept justifies the variation between the results attained from various studies where the preferable orientation is also based upon the space configuration and building distribution.

Comparing the warmest two orientations (EW and the SE-NW) represented in Figure 4.11 justifies the reason for such values where the South facades in the EW orientations receive high levels of solar radiation followed by the SE-NW orientation. Based on such interpretation the NS oriented space should have recorded the lowest temperature values yet the SW-NE revealed to be the lowest of all. The reason for such behavior identifies the influence of shading within the space as an influential aspect on orientation. The solar path during the day provides shade based upon the space orientation. The higher the amounts of the shaded surfaces are the more reduction in the amount of heat absorbed is obtained. The SW-NE orientation created the balance between the two concepts clarified recording the lowest average temperature values.

Very few studies investigating the orientation aspect tested the four orientations discussed. Yet, Toudert and Mayer (2006) tested the SW-NE orientation and supported the result of it achieving the lowest values. Though their study revealed the SE-NW orientation to be in the next level yet the case for the current investigation revealed the NS orientation to have that record due to the reasons of sun angle and shading percentages explained.

Johansson (2006) argued the effect of orientation on the air temperature where very slight variations were attained in his study similar in which he considered to be not significant enough to be respect. The current variations recorded between the four orientations average temperature of 0.5 K though slight yet needs to be considered for enhancing the outdoor microclimate. Figure 5.2, 5.3, 5.4 & 5.5 are the visual maps result from the simulations at 14.00 during the peak thermal stress zone referring to the temperature variation within the space at that time based upon the orientation. Though the average difference between the four orientations where considered to be small yet a wide variation between the temperature distribution is valid which indicates the importance of the orientation to improve the outdoor temperature. The maps indicate lower intensity of maximum temperature in the SW-NE orientation in Figure 5.5 versus that of the EW and SE-NW orientation in Figure 5.2 & 5.4 consecutively.

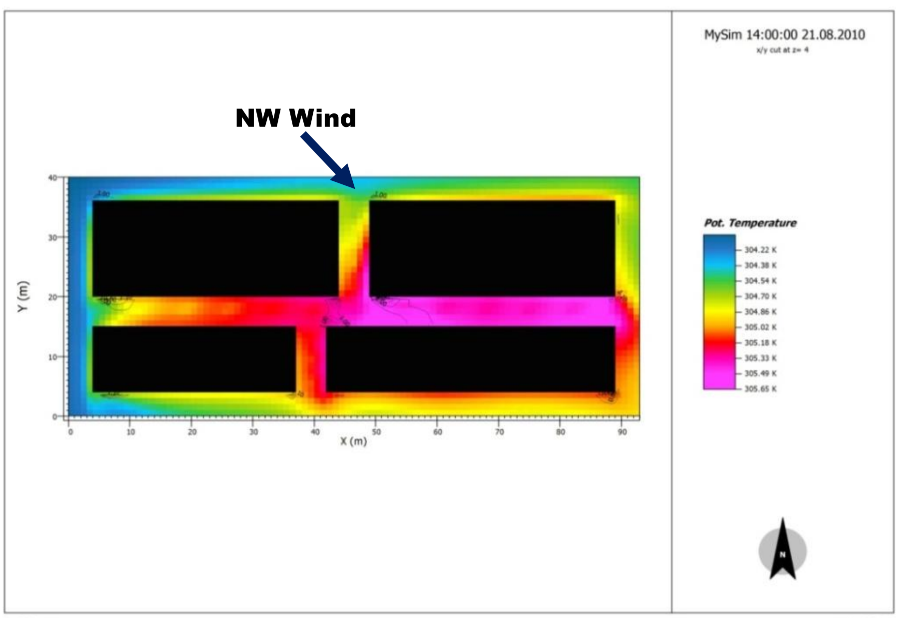



**Figure 5.2. The thermal distribution of the EW orientation at 14.00 on the 21st of August indicating the NW wind.**

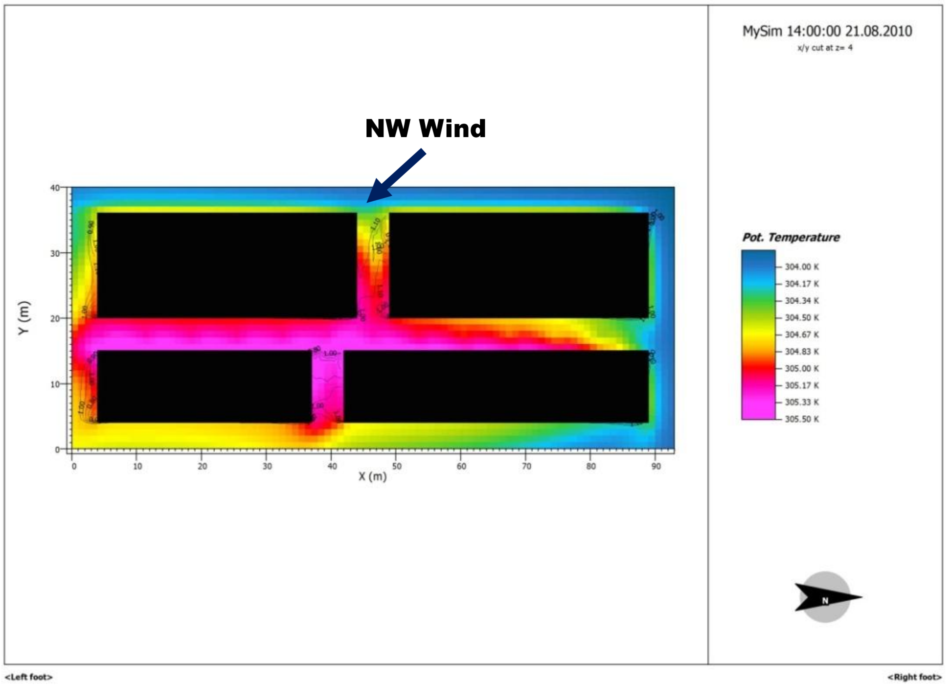



**Figure 5.3. The thermal distribution of the NS orientation at 14.00 on the 21st of August indicating the NW wind.**

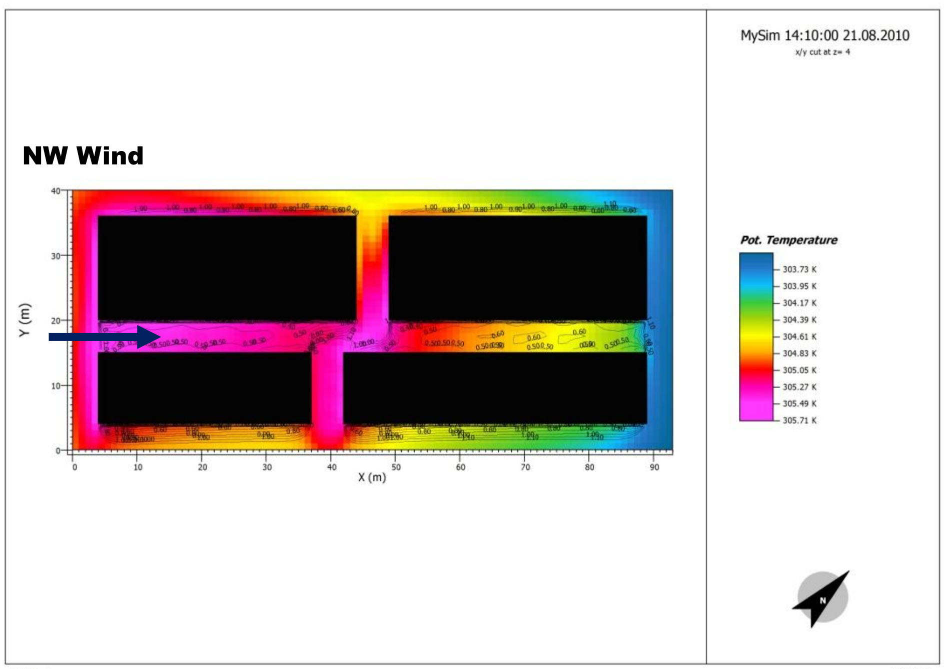



**Figure 5.4. The thermal distribution of the SE-NW orientation at 14.00 on the 21st of August indicating the NW wind.**

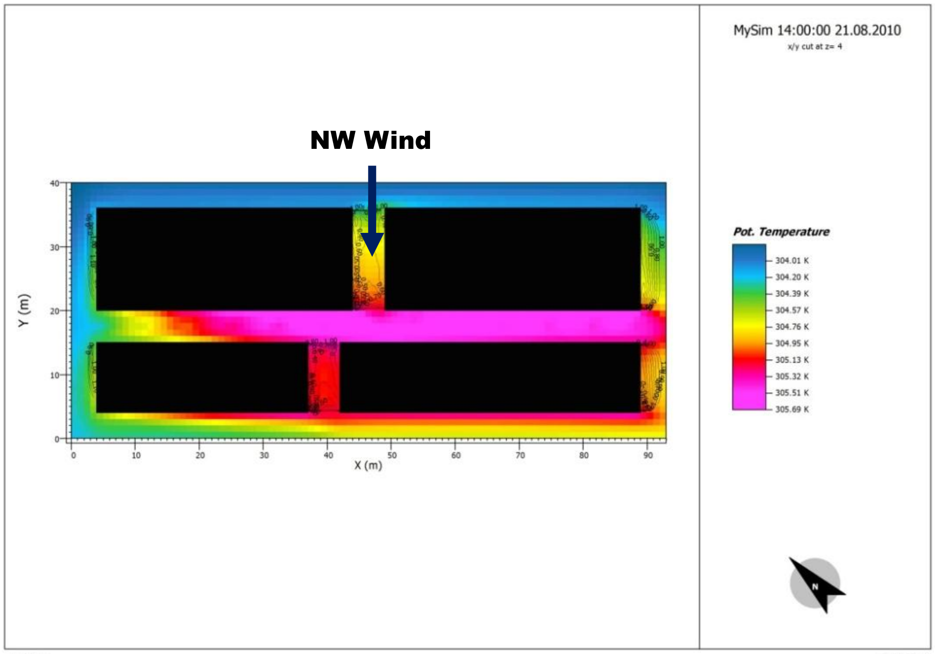



**Figure 5.5. The thermal distribution of the SW-NE orientation at 14.00 on the 21st of August indicating the NW wind.**

Wind recorded a more significant differences than the temperature variations of the four orientations shown in Figure 4.8. the SW-NE orientation considered as the lowest temperatures had the lowest average wind speed values followed by the EW, NS and SE-NW orientation. The sequnce of the wind speed values contribute to the independence of the temperature values on the wind speed values. Furthermore, wind is not considered to be a cooling factor in such case. Moreover, the SE-NW orientation is parallel to the prevaling wind that blows from the NW direction and yet recorded the second highest temperature values.

Observing carefully the gradient maps represented above, the wind factor has proved to have no cooling effect on the spaces yet has a 'spreading effect'. According to Robitu et al. (2006) the wind is considered a cooling factor if the wind temperature was reduced before penetrating the space. Hence it was concluded that if wind passes through a hot area which would increase its temperature then it would have a warming effect which can clearly be seen in Figure 5.4. The cooling effect of wind is applicable for the SW-NE, NS and EW orientation shown in Figures 5.2, 5.3 and 5.5 as that effect minimizes the heated area and the heat intensity within. Therefor wind is considered to be very much dependant on the orientation however a visual analysis to the temperautre distribution has to be conducted to prevent creating a warming effect. In this case, the wind aspect had also contributed to make the SW-NE orientation record the lowest average temperatures .

### 5.2.2 Effect of Geometry

The H:W ratio is the geometry parameter investigated in the current study ranging between three configurations with the same height of 8m yet with varying width of 16m, 4m and 2m thus varying ratios of 0.5, 2 and 4 consecutively. Unexpectedly, this parameter revealed a slight variation between the three configurations having the highest ratio of 4 to record the lowest average temperature values. The sequence revealed by the results attained seemed to be logic and justified.

Hoffman and Bar (2003), Toudert and Mayer (2006), Mazouz and Masmoudi (2004) and Johansson (2006) supported the current inverse relationship between the H:W ratio and the temperature. Wide spaces receive more solar penetration thus more solar gain while deep ones is sheltered from the solar access depending on the ratio. The H:W aspect ratios reduces the maximum temperature levels during the peak thermal stress period equivalent to the maximum temperature thus reduces the average temperature accordingly. As the ratio of the space exceeds 2, the temperature variation is reduced compared to the spaces with ratios below 2 which are considered to form a balance between the diurnal heat gain and the nocturnal heat loss cycle. The ratio 2 simulations had the moderate maximum and average temperature values between the three configurations yet recorded the lowest minimum temperature which is during the early morning due to the night heat radiation release.

The latter phenomenon is well documented and has the same behavior in several bioclimatic parameters. The denser the buildings or vegetation are the more difficult that space struggles to release its heat into the atmosphere during the night. Heat radiated to the space is absorbed by other objects in narrow spaces while the wide spaces ability to lose the heat gained during the day is easier yet that amount of heat is to be considered as shown in Figure 5.6. Furthermore, wide spaces that absorb high amount of heat during the day would take longer periods to release it during the night contributing to higher temperature values versus narrow spaces that received only few amounts of heat waves during the day even if the nocturnal heat loss is tougher than the previous. Therefore, Toudert and Mayer (2006) and Hoffman and Bar (2003) argued that average ratios of 2 creates an acceptable balance between both day and night environmental requirements which is supported by the results presented in this paper. The difference between the improvement of a ratio of 2 and ratio of 4 was very small since a higher ratio to a great extent has a smaller period of thermal comfort levels which is mainly during the daily peak thermal stress. Extremely tight spaces provide smaller standard deviation levels between the daily temperatures in which would provoke the space.

The wind speed daily values represented in Figure 4.18 shows the separation between the ratios below 2 and the ones above. It is obvious that the wider the spaces are the more wind it allows inside the space. The phenomenon discussed previously, that wind has a ‘spreading effect’ rather than a ‘cooling effect’ also seems to be applicable in the geometry simulation results shown in Figures 5.7, 5.8 & 5.9. The 0.5 ratio represented in Figure 5.9 shows more contours within the space that indicates the turbulence occurred due to the wind speed slightly extending the cooled area on the left side versus the other two ratios. Moreover, the highest ratio of 4 that recorded the lowest temperature values revealed the lowest average wind speed values similar to the orientation wind speed and temperature behavior.

Tighter spaces revealed to provide more shade which in turn reduces the amount of surfaces exposed to solar gain thus enhances the air temperature more than wide spaces. Knowing the solar path within the space is quite important to be able to achieve the suitable ratio which notifies the relation between the orientation and the space geometry. A narrow space is considered to improve the air temperature of the space more than a wide one based upon the same orientation. Understanding the behavior of the temperature and wind in accordance to the reasons for the solar gains is the guide. The more shaded surfaces are created through the geometry the better the microclimate can be.

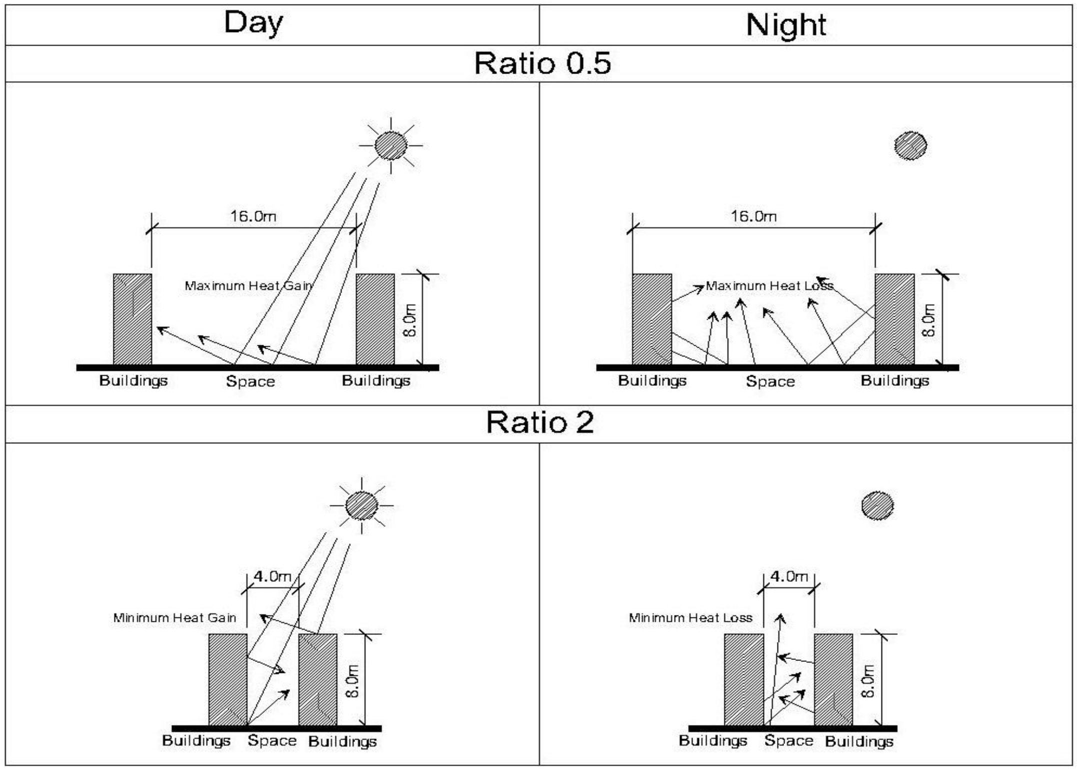



**Figure 5.6. The process of diurnal heat gain and nocturnal heat loss based upon two of the tested H:W ratios.**

**Source: Nihal AL Sabbagh**

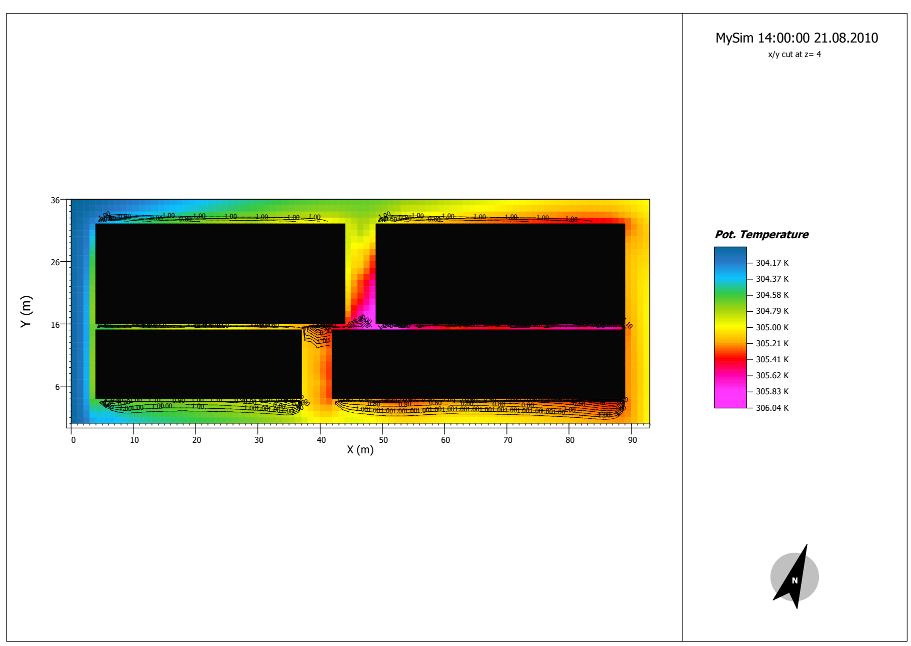



**Figure 5.7. The thermal distribution of the 4 H:W ratio at 14.00 on the 21st of August.**

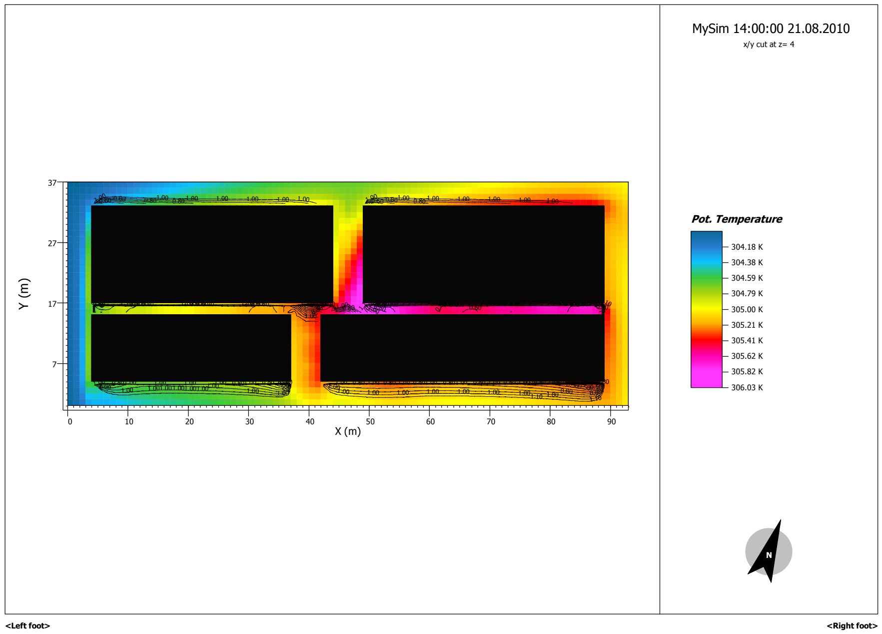



**Figure 5.8. The thermal distribution of the 2 H:W ratio at 14.00 on the 21st of August.**

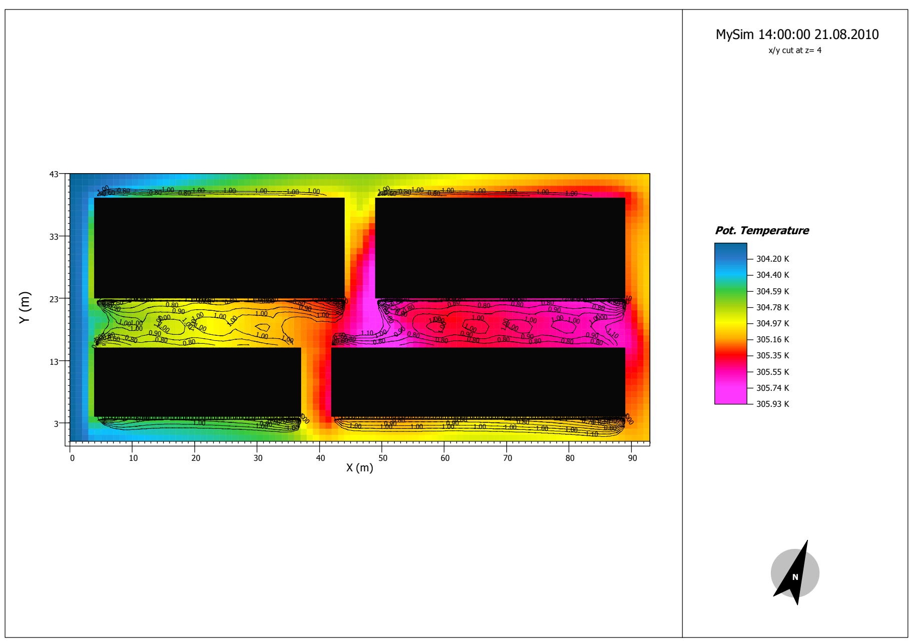



**Figure 5.9. The thermal distribution of the 0.5 H:W ratio at 14.00 on the 21st of August.**

### 5.2.3 Effect of Vegetation

Six landscape strategies were simulated to test the effect of vegetation on the outdoor air temperature. The current study investigated the cooling effect obtained by the manipulation of grass and trees as vegetation parameters in respect to the concept of diurnal gain and nocturnal loss presented in the geometry discussion previously. Trees should be distributed within the site to enhance ventilation especially in the current climate. It is considered essential to test the effect of vegetation planting strategy within the context required to enhance where as the climatic requirements for a hot dry climate differs from that of a hot arid one. In the hot arid climate, the case of Dubai, air infiltration within the site is required and planting recommendations specifies the prevention of dense vegetation that provokes ventilation. The several strategies proposed do not incorporate dense distribution of trees and when groups of trees were implemented, large spacing between them was given.

It was found that the cooling effect obtained by vegetation depends on the surrounding temperature of the site investigated called the ‘background effect’ were the cooling effect increases as the surrounding temperature increases (Hoffman and Bar, 2000). The current landscape proposals investigations are even in terms of ‘background effect’ since all the strategies having the same conditions. Yet such phenomenon indicates the significance of other variables that influence the vegetation parameter. All the simulation models testing vegetation had a SW-NE orientation (which proved to be the best orientation) and a 0.8 H:W ratio. Therefore, if the geometry and orientation characteristics are changed, could lead to a different effect yet with the same sequence. For instance a NS orientation used by Bar et al. (2009) for various vegetation strategies revealed a cooling effect of 2K versus 0.7 K under a SW-NE orientation for plants and grass implementation. An observation of the Figures 5.10 to 5.14 indicates that there is a wide variation between the temperature distributions in the space though the total average values are small.

Masmoudi and Mazouz (2004), Robitu et al (2006), Hoffman and Bar (2000), Bar et al (2009) and many other studies assured the contribution of plants to enhance the air temperature yet with wide variation of results. The conditions of each study were different yet support the current findings that different strategies have a cooling effect but with different levels. As the case with the two investigated variables the differences obtained between all landscape strategies were not significant yet the vegetation proved to be the most effective variable of all with an improvement of 0.6 K of the average temperature and 0.7 K of the maximum temperature during the peak thermal stress period. The maximum temperature difference was larger than the average difference which confirms that the effect of vegetation increases during the hottest time of the day opposite to the orientation behavior and in compliance with the geometry during the same period. Robitu et al. (2006) added that vegetation enhanced the levels of thermal comfort due to its ability not only to enhance the air temperature but also humidity, air velocity and a lot of complex outdoor parameters. The average temperature results comparing between the six landscapes strategies shown in Figure 4.21 makes the strategy containing both grass and trees to record the lowest values contributing to a better passive cooling effect.

The vegetation incorporates two mechanisms responsible for the cooling effect which are the evaporo-transpiration and the shade provided by plants. The shade is discussed earlier to reduce the amount of heat absorbed thus radiated by the surfaces in which reduces the surface temperatures. The other advantage of vegetation is mainly two parts, first is based upon the soil surrounding a tree considering the irrigation process contributing to evaporative cooling or grass and second is the characteristic of the plants natural life cycle called transpiration. Plants converts the energy in the air into food and the water circulation within the leaves and stem is also evaporated to air providing a cooling effect. Grass incorporates the second mechanism which is the evaporative cooling effect while trees revealed to be more effective than grass in the temperature reduction since they provide shade along with the evaporative cooling effect. The results differences between the no grass shown in Figure 5.14 and the continuous grass shown in Figure 5.9 scenario was 0.3 K which was relatively higher than the difference between the no tree shown in Figure 5.15 and tree group’s scenario shown in Figure 5.13 was 0.5 K. Comparing those figures carefully it’s clear that the wind (indicated by contours) is much more affected by the different strategies than the temperature especially when trees are incorporated. The groups of trees recorded a slightly higher average and maximum temperatures than the central continuous band of trees. The groups of trees interrupted the wind flow vastly as shown in Figure 5.13 more than the central band shown in Figure 5.12 in which obviously blocked the cooler wind breeze coming from the NW direction from flowing within the space represented clearly on the space contour in Figures 5.12 & 5.13.

The wind speed behavior is very much variance between the different strategies where trees have a dominant effect on wind. The grass proposals yet revealed to differ from each other which are due to the friction caused between the ground surface and the wind. The friction between the grass and the wind reduced its speed depending on the amount of grass applied. This phenomenon requires to be considered when sustainable landscape is required especially in a hot arid climate where wind flow if favorite. The wind speed reduced in the continuous grass scenario still recorded lower temperature values than the grass pieces and no grass scenarios which bring us back to the concept discussed previously where wind is not considered to have an ultimate cooling effect clearly represented in Figure 5.14 comparing between the left and right side of the image in consideration to the wind direction and solar path.

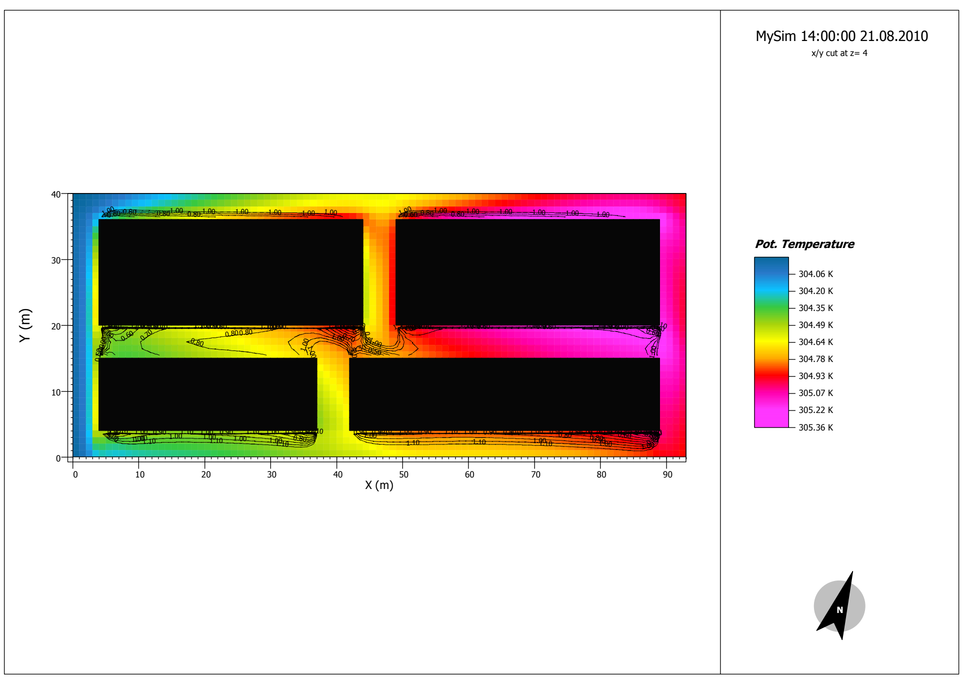



**Figure 5.10. The thermal distribution of the vegetation strategy containing continuous grass at 14.00 on the 21st of August.**

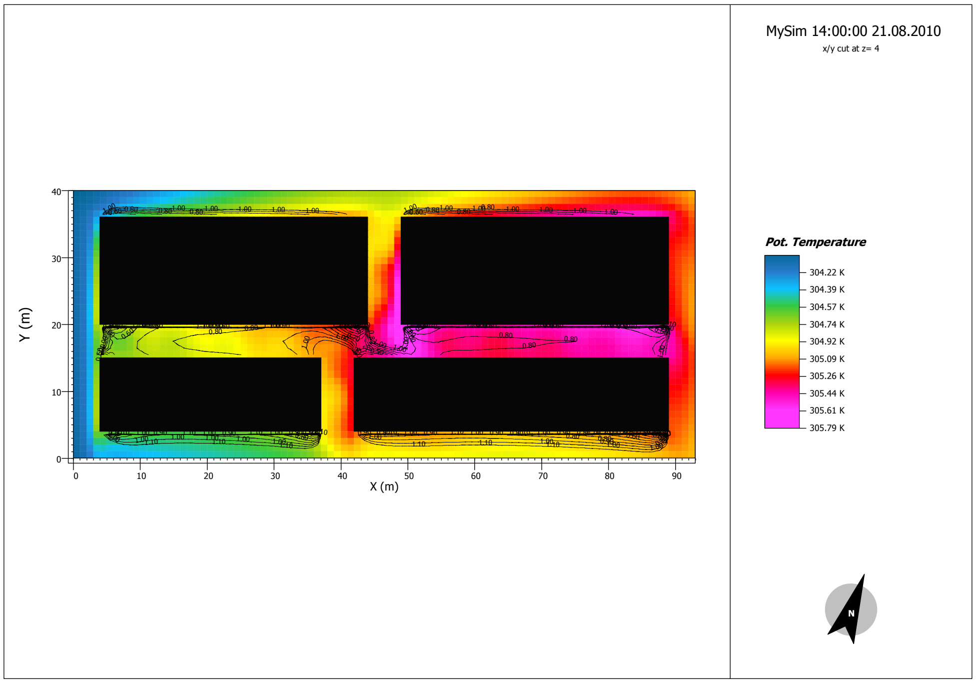



**Figure 5.11. The thermal distribution of the vegetation strategy containing pieces of grass at 14.00 on the 21st of August.**

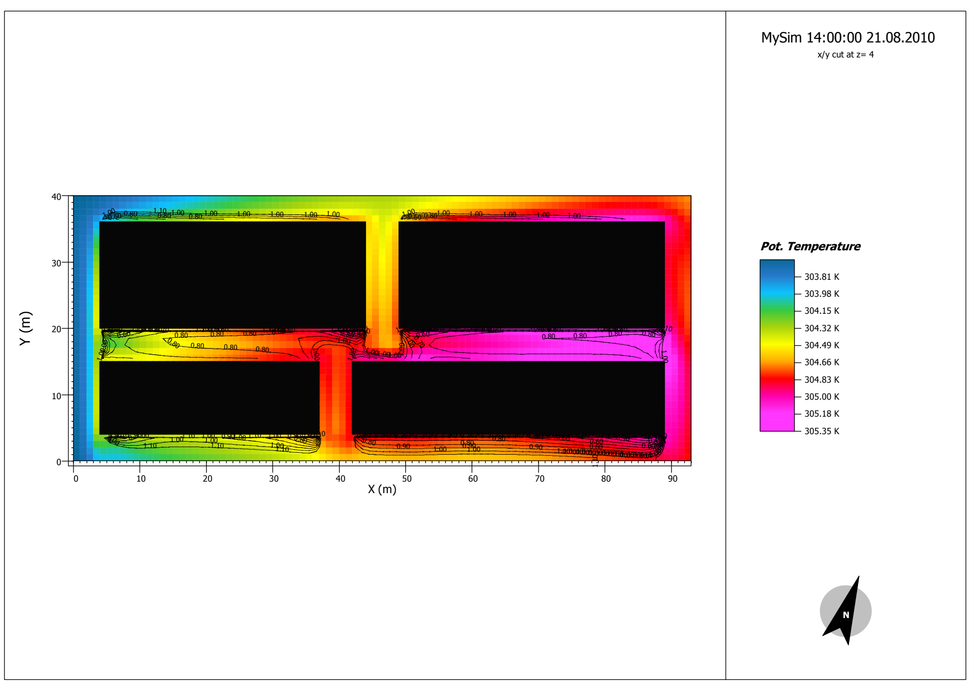



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**Figure 5.12. The thermal distribution of the vegetation strategy containing continuous trees at 14.00 on the 21st of August.**

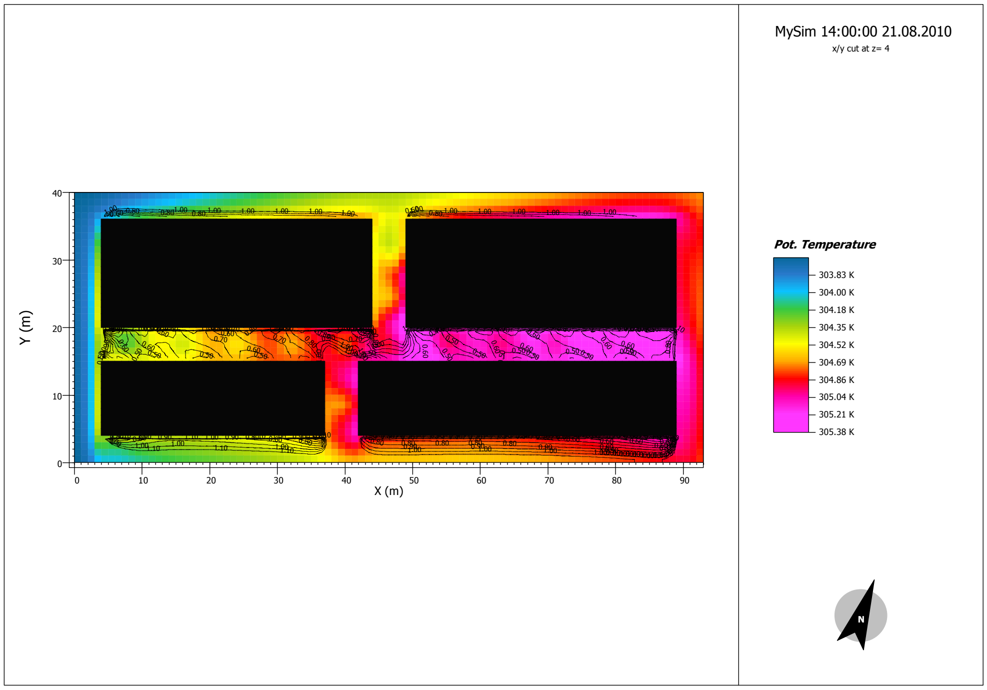


**Figure 5.13. The thermal distribution of the vegetation strategy containing trees groups at 14.00 on the 21st of August.**

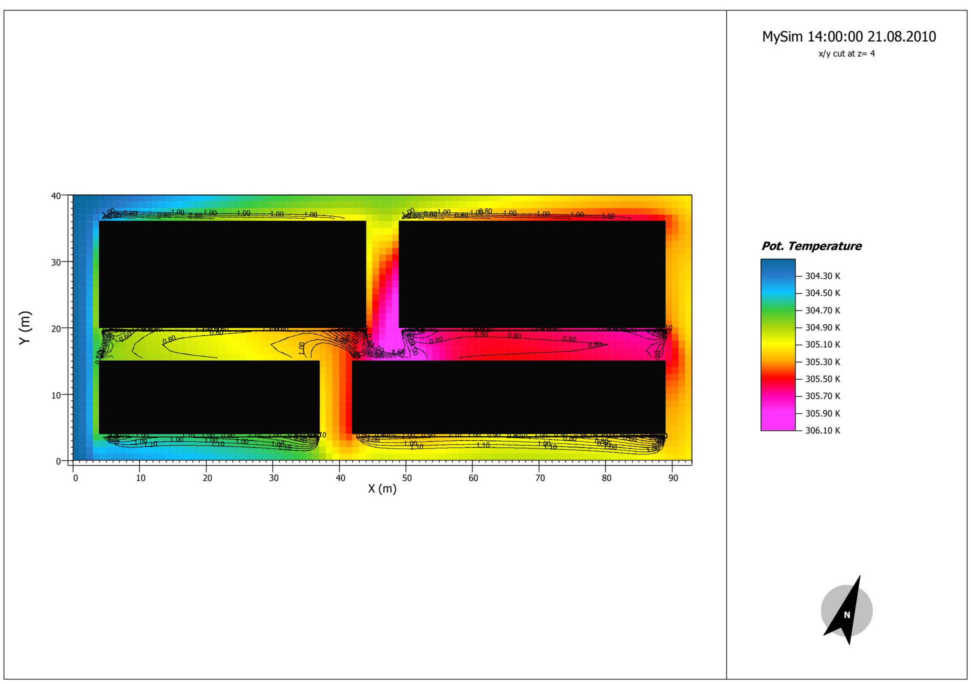


**Figure 5.14. The thermal distribution of the vegetation strategy containing no trees at 14.00 on the 21st of August.**

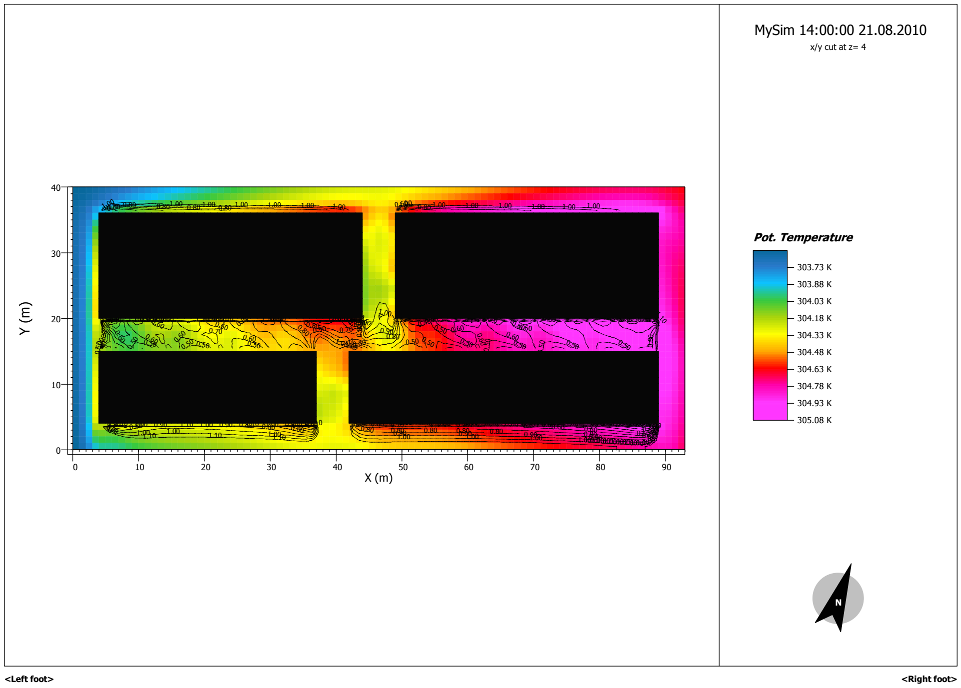


**Figure 5.15. The thermal distribution of the vegetation strategy containing continuous grass and groups of trees at 14.00 on the 21st of August.**

### 5.2.4 Summary of the Independent Variables Effect

The selection of the most suitable variable that was incorporated in the enhanced scenario was based upon the lowest average temperature. The variable that recorded the lowest average temperature was not necessarily the one to record the lowest maximum temperature. The maximum temperature values obtained was observed carefully since they influence the behavior of each parameter during the daily peak thermal stress. Simulations that tested the orientation, geometry and vegetation had different values of standard deviation STDV between the average and maximum temperatures as shown in Figures 5.16, 5.17 & 5.18. Selection of the best parameter if was based upon the least value of the maximum temperature would most probably result in different values in the enhanced scenario since each variable behaved differently under various environmental conditions.

The orientation revealed the highest value of STDV followed by the geometry and vegetation consecutively which does not necessarily be the variable with the maximum cooling effect whereas the vegetation had the most cooling effect between the three parameters followed by the orientation. Masmoudi and Mazouz (2004) tested the three independent variable investigated but under different conditions, supported the cooling sequence granted in this study. The effect of the different variable has to be investigated in relevance to one another. Furthermore, each aspect of the site is considered to have a behavior under the conditions of the other variables where if changed that behavior does not necessarily be predicted. In this paper, when one variable was tested the other variables were fixed to be able to evaluate the results consistently. Yet it was observed that the results attained from the geometry under a SW-NW orientation would not be the same for an EW orientation even from an improvement percentage point of view. The sequence of variables in terms of enhancing the air temperature is the only aspect predicted to remain constant yet is not definite.

Generally shading proved to be very efficient in reducing the air temperature during the daily peak thermal stress particularly contributing to lower average daily temperatures. Yet excessive shading is not recommended since it reduces the heat radiation losses process leading to higher temperatures (Hwang, 2010). It was observed that dense vegetation is not preferable and very high H:W space ratios is not optimum.

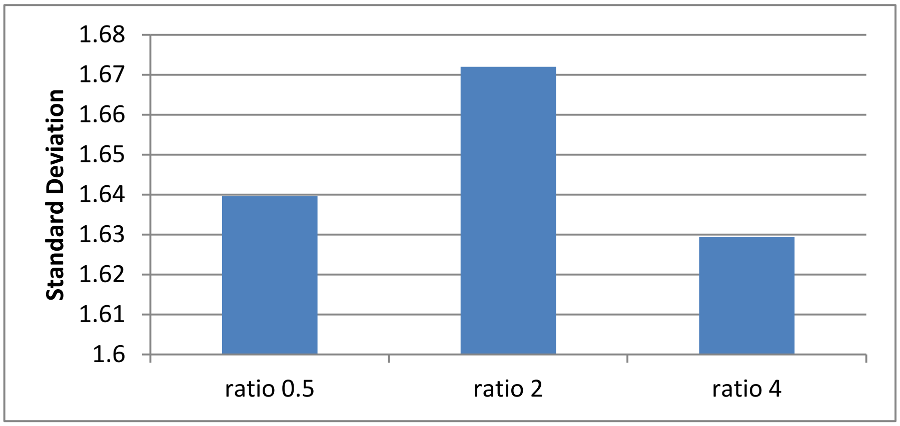


Figure 5.16. The standard deviation between the average and maximum temperatures for the tested H:W ratios.

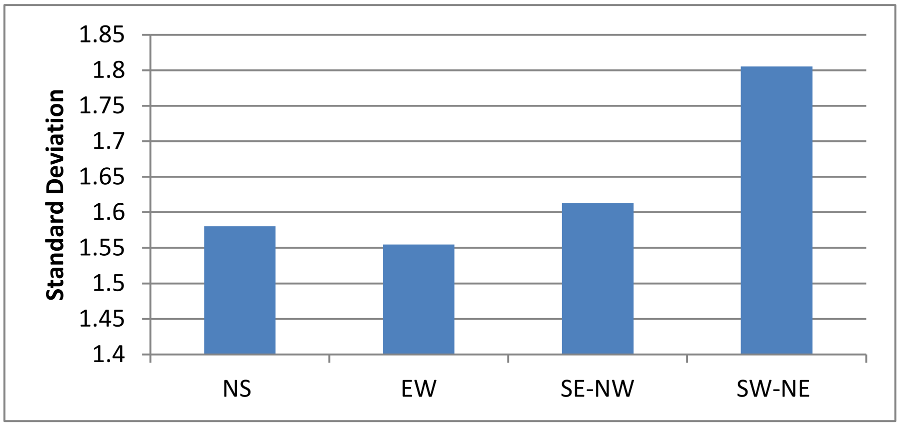


Figure 5.17. The standard deviation between the average and maximum temperatures for the tested orientations.

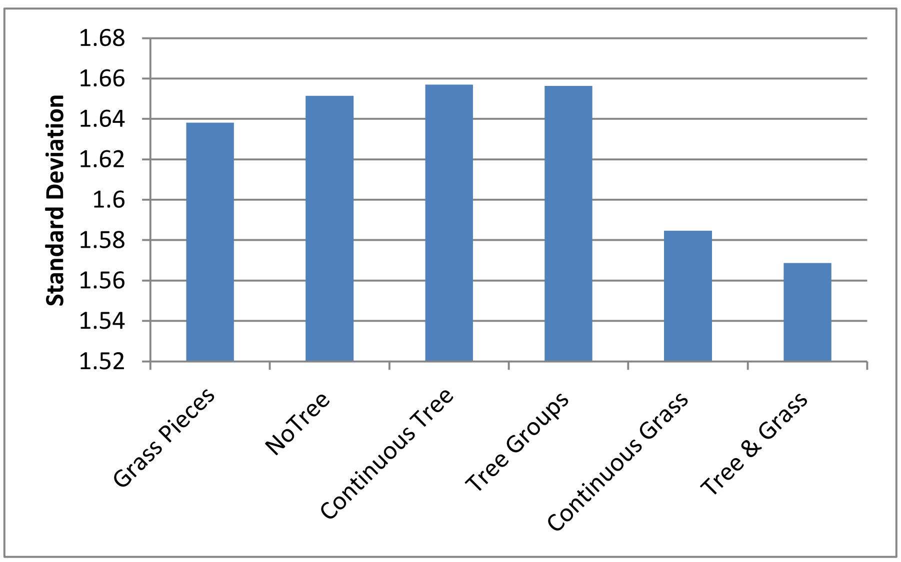


Figure 5.18. The standard deviation between the average and maximum temperatures for the tested vegetation strategies.

## 5.3 Observations of the Three Scenarios

### 5.3.1 Effect of Temperature

The results of the three scenarios compared together in Chapter 4 showed that the application of the bioclimatic principles suggested, improved the air temperature by 1 K. though this value is considered to be relatively small yet an improvement is verified which required further observations to justify such value.

By looking at the visual thermal maps distribution given by the three scenarios (during summer and during winter) it was clear that temperature variations on the visual maps between the three scenarios are wider than quantitative values attained. The methodology used for the quantitative values explained in Chapter 3 was represented by an average value for the whole area. Furthermore, the temperature values given in the output files for each single grid point in the drawing model were averaged into one number that represented the temperature of the whole site during that specific hour (buildings were deducted and 8m surrounding the buildings was incorporated within the calculations). Such method of calculation was intended to be used and considered to be more realistic in terms of the existing site configuration taking into consideration the minimum 'background effect' explained previously where an outdoor open space is never isolated in reality. Hence, the values attained and compared were the average temperature taken for the entire site every 30 minutes.

The enhanced scenario against the existing scenario will be discussed first then the enhanced scenario against the worst case scenario discussion is then to come notifying the main reasons for the positive and negative effects.

The enhanced scenario slightly improved the outdoor air temperature of the existing condition by 0.5 K during summer and 0.3 K during winter of average and minimum values and slighter maximum values. While the enhanced scenario improved the worst case scenarios outdoor average air temperature by 1.1 K during summer. The efficiency of the bioclimatic principles applied in the enhanced scenarios was maximized during the peak thermal stress periods with the lowest values during summer and the highest during winter. The balance created by the enhanced scenario during that period of the day on the two seasons was considered vital yet its efficiency was relatively reduced during winter evenings considered as the coldest time of the year as shown in Figure 4.34. A bioclimatic space should be designed to suite the summer and winter needs along with the day and night changes within the day. The awareness of such phenomenon was incorporated since the early design of the variables tested such as excluding dense trees within the space or very low H:W ratios. The difference in temperature created by the enhanced scenario seems to be realistic compared to real life where enhancing the outdoor temperature is a very decisive and complicated issue. The application of several environmental variables is essential to obtain a considerable difference. The results and findings in hand highlight the presence of a threshold in the size of the bioclimatic parameters designed. Furthermore, vegetation has proved enough to enhance the outdoor temperature but definitely the results of having a park differs from a front yard garden differs from a flower box with a couple of trees. Not only would the improvement level differ from one scale to the other but the rate of enhancement is multiplied when the scale increases. The cooling effect of vegetation on an outdoor space is reduced gradually from a park to a yard until it reaches a certain scale where that effect becomes insignificant such as the cooling effect of a trees or having plant in your terrace demonstrated in Figure 5.18. Though a slight level of comfort sensation might be obtained but that does not independently contribute to change the outdoor air temperature.

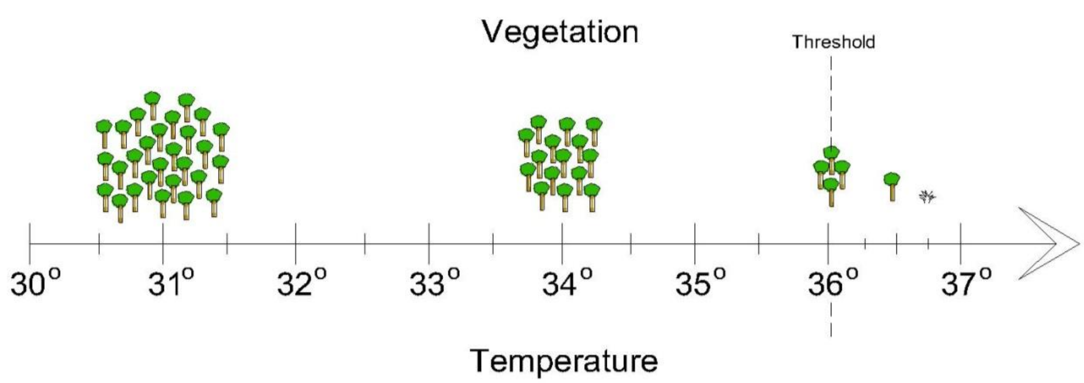


**Figure 5.19. The inversely relationship between the vegetation scale and the temperature indicating a threshold of which below it the temperature reduction becomes insignificant.**

**Source: Nihal AL Sabbagh**

Generally, the temperature behavior of the three scenarios during summer and winter has a logical manner. Where, the worst scenario did not incorporate any of the bioclimatic parameters thus achieved highest temperature during summer and lowest during winter. The existing scenario was in an in between category since it was based upon the mixture between the enhanced and the worst scenario hence recorded an in between values. The enhanced scenario incorporated all the variables revealed to have the largest cooling effect and thus reduced the air temperature than both the previous two scenarios.

It was concluded that the cooling effect of the orientation was 0.7 K, the H:W ratio was 0.6 K and the vegetation was 1 K during the daily peak thermal stress in summer. The enhanced scenario was based upon the incorporation of the three variables yet the total cooling effect obtained was 1.1 K almost equivalent to the vegetation effect only. The current observation supports the previously discussed concept of the ability to enhance the outdoor air temperature. The behavior of the outdoor parameters is quite complex where some variables such as orientation revealed to be less effective during peak thermal stress while others such as geometry and vegetation proved to be more effective during that period. This non uniform pattern is again repeated when observing the effect of each bioclimatic principle dependently and their assembly together.

Finally, the enhancement of the outdoor air temperature is considered to be crucial in which requires further examination. The thermal behaviors of the different scenarios and variables in search for an ecological design are logic in terms of their sequential effect yet the assessment of such impact is unpredictable. The contextual conditions are essential for understanding the thermal behavior where the outcome results depend upon. No single parameter should be tested unless the other factors are incorporated and fixed.

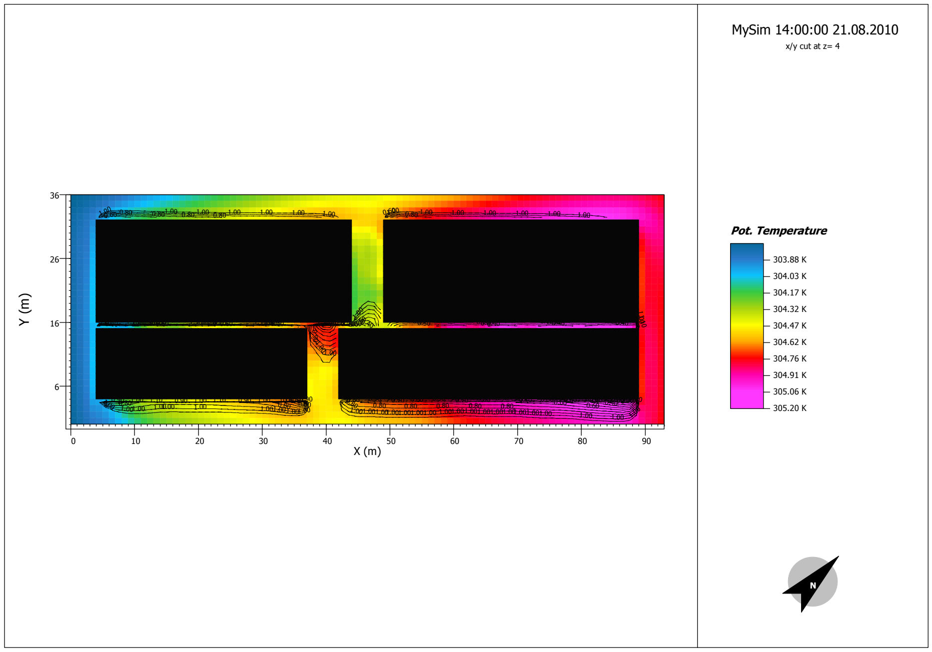

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**Figure 5.20. The thermal distribution of the enhanced scenario at 14.00 on the 21st of August.**

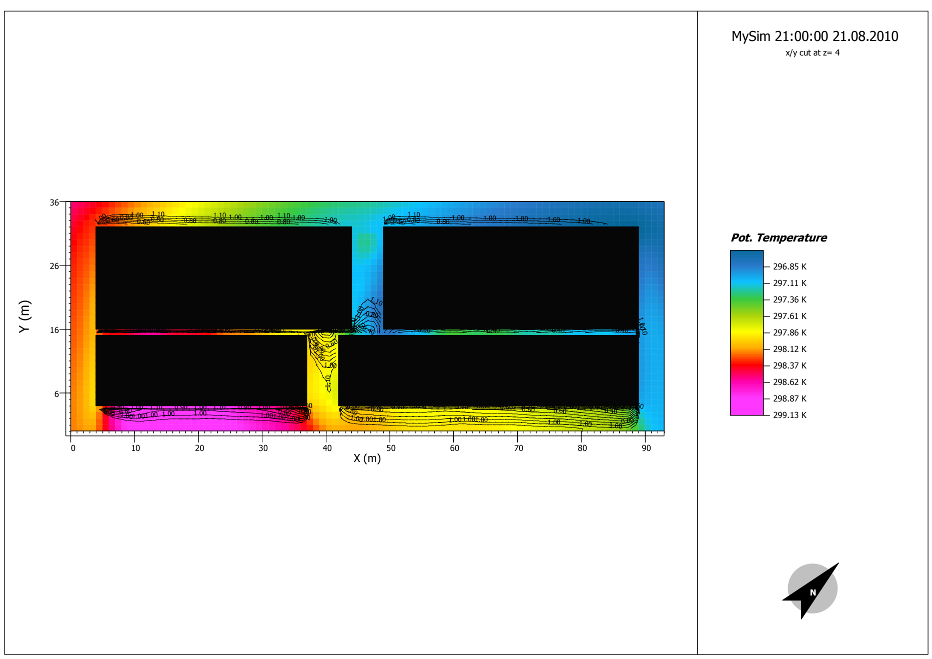

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**Figure 5.21. The thermal distribution of the enhanced scenario at 21.00 on the 21st of August.**

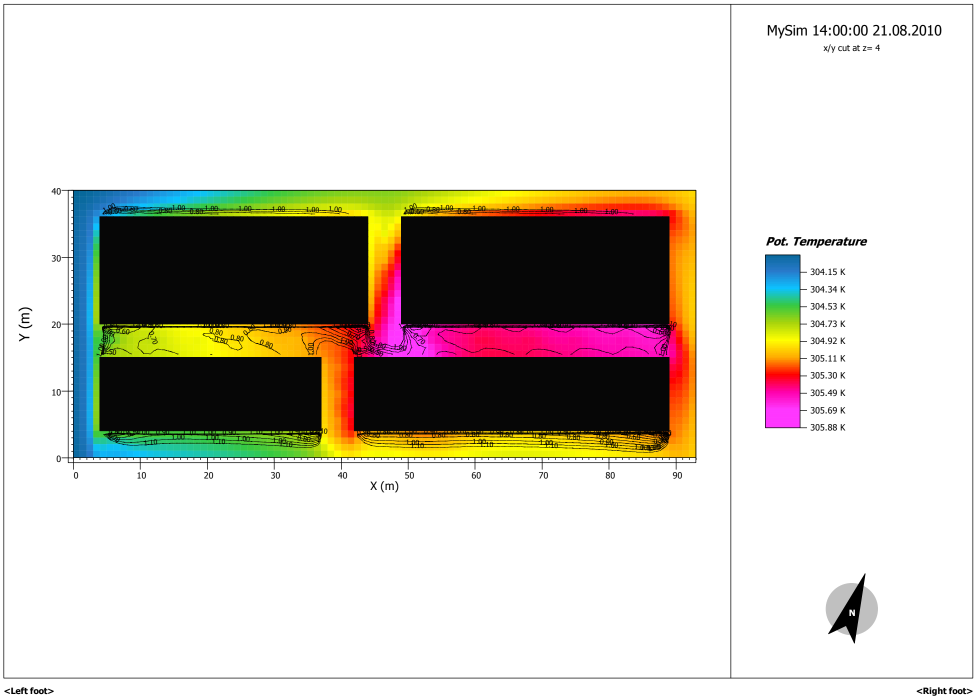


**Figure 5.22. The thermal distribution of the existing scenario at 14.00 on the 21st of August.**

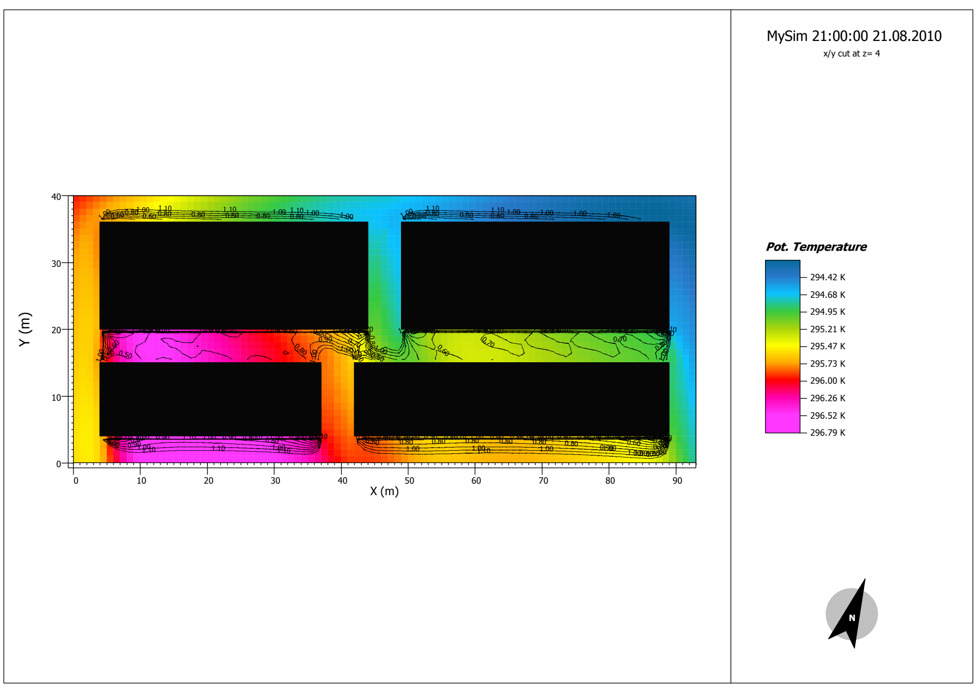


**Figure 5.23. The thermal distribution of the existing scenario at 21.00 on the 21st of August.**

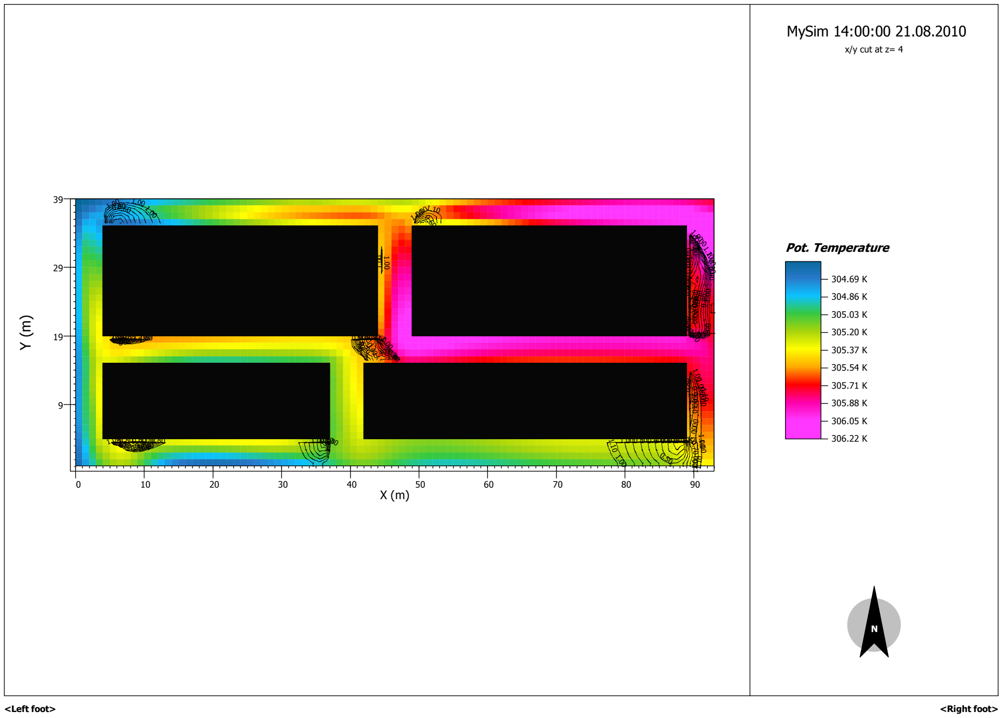


**Figure 5.24. The thermal distribution of the worst case scenario at 14.00 on the 21st of August.**

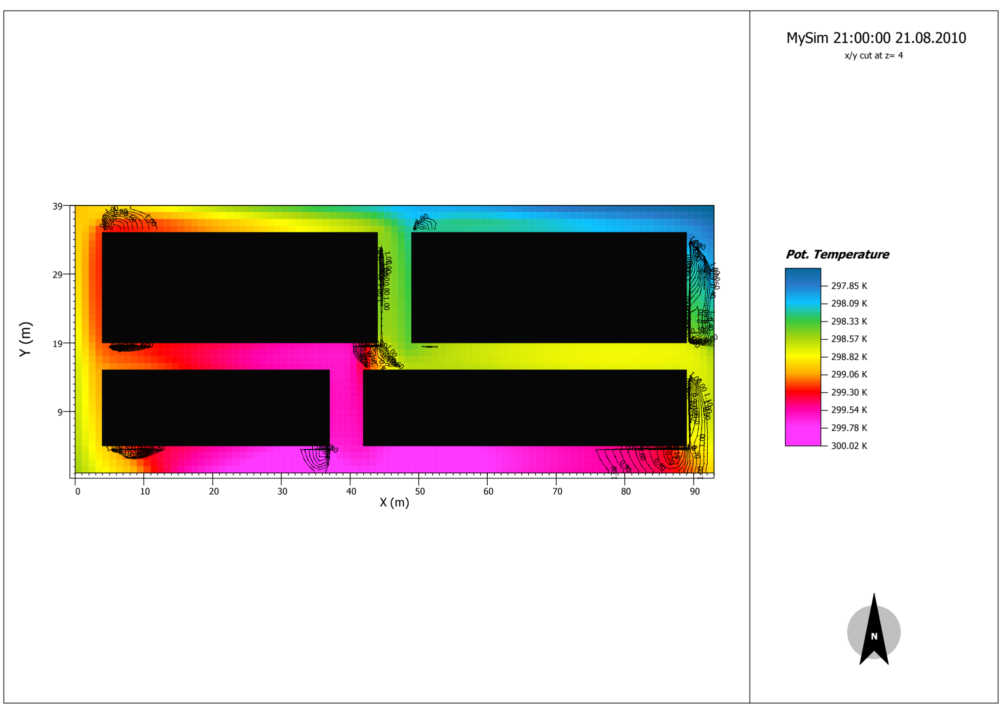


**Figure 5.25. The thermal distribution of the worst case scenario at 21.00 on the 21st of August.**

### 5.3.2 Effect of Wind Flow

The variables manipulated during the various simulations affected the wind speed positively in some cases and negatively in another. A physical body that stands the wind such as trees causes turbulence within the space contributing to positive pressure areas and negative pressure areas and reduction in the wind speed values. Building corners also created the same effect which can be clearly seen on any of the visual thermal maps. Designing a space based upon the positive and negative pressure where you can adjust the cool areas to expand accordingly is a very promising field yet requires further investigations using wind flow based softwares. The other parameter of vegetation; grass also seemed to reduce the wind speed very slightly due to the friction created. Therefore vegetation was considered to have an inverse relation with the wind speed.

Orientation is basically the main variable controlling the wind speed aspect. Wind can be prevented or allowed within the site through proper orientation depending whether wind is preferable or not. In hot arid climates wind is an essential criterion in an environmental design where the wind breeze usually enhances the thermal sensation. Yet, it was concluded that wind has a spreading effect rather than a cooling effect as discussed earlier in which a proper orientation and building distribution is required. Cool areas should be facing the wind to broaden the cooling effect while hot points within the space should be sheltered from the wind to prevent such effect to take place. In the case with the enhanced scenario as shown in Figures 5.20 & 5.21 the wind breeze comes from the NW orientation blocked by the building facing it yet if wind was considered to blow parallel to the space a better reduction of temperature would have been possible since the SW area has a lower temperature values during the peak thermal stress. Wind can be oriented and maneuvered through buildings, wind tunnels and vegetation. The awareness of the wind behavior during the early urban design phase would definitely lead to achieve higher levels of comfort.

The worst scenario recorded much higher values of wind speed since the model was vacant of trees and the space is wider with low H:W ratio thus enhances the wind flow within with almost no turbulence caused as shown in Figure 5.24 & 5.25. The existing scenario had a central value between the worst case and the enhanced scenario creating more wind turbulence due to the central band of trees shown in Figure 5.22 & 5.23. The wind speed is somehow stable during the day and night as shown in Figure 4.35.

## 5.4 Validation of Findings

Earlier studies investigating the same parameters used several methodologies including field measurements, simulation and experiments. The results obtained earlier supported the current findings in terms of effect and sequence and not values in which validates the results attained. All earlier validated studies testing the same variables revealed to have a wide range of differences between the outcome findings yet they mostly agreed upon the same concepts. The variations obtained between the earlier studies and between those studies and the current investigation will always be valid between a study and another where each examination has its own conditions. Validation for this study is presented through earlier published studies which assure the validation their results in respect to the scale, date, simulation duration and measurement criteria of each investigation. Few studies where mentioned since Chapter 2 has more details of all studies reviewed.

### 5.4.1 Cooling Effect of SW-NE Orientation

Masmoudi and Mazouz (2004) and Mayer (2006) agreed that the SW-NE is a good compromise for passive design revealing the coolest effect mentioning that the EW recorded the highest temperature values. The results support the current findings.

### 5.4.2 Cooling Effect of H:W Ratio of 4

Mayer (2006) recorded the difference between the 0.5 ratio and 2 of about 0.2 K while that between the 2 and 3 of that 0.1 K. the study assured that higher ratios have lower temperature values. The very small difference validates the results attained in the current study between the three geometries.

### 5.4.3 Cooling Effect of Vegetation

It is noted that all the earlier studies investigating the impact of vegetation on the air temperature agreed that vegetation has a large cooling effect relative to the passive cooling strategies. The cooling values were different between all studies yet were within the same range. In the current paper vegetation seemed to be the coolest parameter of the tested variables in which complies with the earlier findings

Bar et al (2009) used an experimental method to test the impact of vegetation on air temperature. The improvement vegetation had on a similar size and scale of an outdoor space through six different landscape strategies was found to be 2K in which the current cooling effect value was 1.1 K. The duration and date of the test was not mentioned.

Wong et al. (2007) luckily used the same tool as the current study which is ENVI-met supported the results using field measurement yet the scale of application was much larger than the current study. The field measurement supported his results revealed that dense vegetation on a large scale enhanced the air temperature by 3 K. the results seems to be supporting the current findings since the scale used in this study is much bigger in which definitely has a greater cooling effect.

Bar and Hoffman (2000) supported the cooling effect of greenery to be of average 2.8 K depending on the shading coverage and the background effect of the site.

Masmoudi and Mazouz (2004) mentioned the difference between an empty space and that of three central bands of trees was 1.7 K in which is similar to the value attained with respect to the size and date of simulation.

### 5.4.4 Spreading Effect of Wind

Robitu et al. (2006) explained the behavior of wind found in the current study in which wind has a spreading effect rather than a cooling effect depending on its temperature.

# CHAPTER SIX: CONCLUSION AND RECCOMENDATIONS

## 6.1 Conclusion

The existence of usable open spaces remains vital for the existence of sustainable cities. In Dubai representing a hot arid climate life in the outdoor open spaces became part of the city's character during the good weather conditions especially in winter. The needs to achieve pleasantly used spaces for longer periods of the year helped motivated the current study and present a set of outdoor climatic guidelines that improve their air temperature.

In this study the impact of selected bioclimatic parameters on the air temperature was investigated extensively to enhance small outdoor spaces. Initially, a wide number of parameters were tested to elect the most effective ones in terms of passive cooling. The methodology used for investigation was based upon a set of fixed variable such as flat building facades and flat roofs to prevent any confounding results. The extreme summer conditions ($21^{st}$ of August) was the target of the variables such as orientation, geometry and vegetation yet a yearly balance was considered essential as well (between summer on the $21^{st}$ of August and winter on the $21^{st}$ of January). The empirical findings of the simulations done demonstrated the temperature and wind speed behaviors were several patterns 'phenomena' were extracted and justified.

The coolest orientation that recorded the lowest average temperature values which achieves longer periods of improvement revealed to be the SW-NE orientation followed by the NS, SE-NW and the EW consecutively. The results were due to three reasons; the shade provided in the space by each orientation, the temperature of the area facing the prevailing wind, and last the South facades position in relevance to the sun angle in each orientation. The SW-NE orientation compromised a balance between all reasons contributing to the lowest values of temperature.

The coolest geometry was the one with the highest aspect ratio of 4 where the H:W ratio reveled to be inversely proportional to the temperature. A slight difference was observed between the ratio of 2 and 4 versus the difference between the ratios 0.5 and 2. This was due to the difficulty tight spaces face to radiate their heat to the environment and thus the inverse relation mentioned has a threshold where the temperature starts increasing again.

The coolest vegetation strategy reveled to be the one with grass and trees were trees provided shade and evaporative cooling while grass had the advantage of reducing the surface radiation and adding an evaporative effect. Landscape strategies are much wider to be tested in one study yet the strategies proposed were based on earlier recommendations.

Generally, it was concluded that in extremely hot environments such as the case of Dubai, achieving the thermal comfort levels of temperature in outdoor spaces revealed to be impossible during summer yet a slight improvement is achievable. The application of proper orientation of a SW-NE, a high space ratio of 4, groups of trees and grass considered as the ‘bioclimatic application’ enhanced the air temperature with a value of 1.1 K. This value proved to be acceptable when dealing with the outdoor environment where significant changes were not possible. However, the results obtained are promising for passive cooling techniques of the outdoor environment. Several findings worth mentioning were attained demonstrated in the Table 6.1 below;

**Table 6.1 Summary of findings and phenomena extracted demonstrating their use for urban designers**

| Results | Observations | Implication |
|---|---|---|
| Orientation improved the outdoor air temperature by 0.6 K, while geometry improved it By 0.6 K and vegetation by 1 K during the hottest time of the day according to the maximum values yet the bioclimatic scenario recorded a total improvement value of 0.9 K based upon the same parameters. | This means that the thermal improvement of passive cooling techniques is not based upon the amount of parameters applied rather than other factors such as their composition and space morphology. The behavior of several outdoor parameters together is unpredictable to a certain extent. | Improvements done to the outdoor environment cannot be based upon suggestions but have to be tested in a quantitatively. Examination of the preliminary urban designs through simulations would be considered time and energy saving were the bioclimatic parameters would be prioritized based upon their environmental impact. |
| During peak thermal stress period represented by maximum temperature values the difference between the orientations variables decreased. | Benefit of proper orientation SW-NE on the air temperature is less efficient during the hottest time of the day due to the solar path. | Such parameter would be prioritized in an environmental space design when the function of the space requires thermal comfort achievement along the day rather than midday. |

| | | |
|---|---|---|
| During peak thermal stress period represented by maximum temperature values the difference between the geometries and vegetation variables increase. | Benefit of proper geometries and vegetation on the air temperature is more efficient during the hottest time of the day due to the solar path cycle. | Such parameter would be prioritized in an environmental space design when the function of the space requires thermal comfort achievement during that time of the day. |
| The NW-SE orientation where the space is parallel to the wind recorded the higher temperature than the SW-NE and NS orientations where the buildings prevent the wind from flowing through the space. | Wind does not have a cooling effect but has a spreading effect. If wind passes through a cooler area thus its temperature decreases and the same happens when it passes through hot spots spreading the warm effect in the space | Wind should be utilized as a passive cooling technique to cool the space and reduce its temperature. If the orientation creates a warm spreading effect thus wind should be prevented or reoriented. |
| Difference between the thermal values of the ratios 2 and 4 are much smaller compared those between 0.5 and 2. | Very tight spaces have shorter periods of thermal comfort since the heat radiation loss is more difficult. | A balance between the H:W ratio of the space should be achieved with a range of 2. Minimize the length of tighter spaces. |
| Two spaces of the same H:W ratio 2 recorded significantly different values and thermal behaviors where one was 20:10 and 16:8 m. | Spaces with the same ratio but with different values have different behaviors where a space 70m wide would definitely differ from a 5m wide space even if the same ratio is addressed. | Minimum and maximum width of space needs to be considered based upon the shading coverage achieved. An intimate scale is always preferable since more shading is provided. |

## 6.2 Climatic Design Guidelines

Dubai's urban planners and the public has to bear in mind that the application of climatic guidelines within the urban design would have numerous economical and social benefits on their lives such as energy consumption and health benefits based upon the increase of outdoor usage. Environmental design guidelines suggested for the outdoor urban spaces in hot arid climates should be utilized during initial design stages and before detailed design is to take place. The environmental guidelines presented below are based upon understanding of the behaviors of the outdoor parameters through the current investigation. Suggestion of all the outdoor parameters is quite difficult to propose yet some variables were understood during the current investigation which will also take place.

- ✓ A bioclimatic design should achieve a balance between diurnal and nocturnal patterns on a yearly basis accommodating the needs of various seasonal changes.
- ✓ Pay more attentions to the natural elements inserted in a space that contributes directly to the environment such as trees, grass, orientation, building setting, space enclosure. The design of these elements will either have a positive or negative impact on the outdoor temperature.
- ✓ Variety of shading levels and their distributions within the space to get maximum benefit of space during summer and winter which have opposite needs. There is a need to provide the space users with a choice depending upon other parameters that play role in the thermal sensation levels.
- ✓ When grass is applied shading strategies should be implemented (by trees or shading mesh that is not continuous to prevent heating effect) to reduce the high levels of water consumption of grass (Bar et el., 2009).
- ✓ Trees utilized should have high trunk with wide canopy to provide maximum shade with minimum wind blockage and shrubs is not preferable since they block the wind and increase the humidity level (Givoni, 1991) but can be utilized for wind orientation along for aesthetic purposes.

- ✓ Trees distributed in groups of linear forms should be oriented parallel to the wind direction unless wind is not preferable into the space due to its high temperature thus wind breakers is recommended (through trees, buildings or physical objects).
- ✓ Maximize the passive cooling effect through wind utilization. Extensive passive cooling techniques should be added to the space facing the wind direction before wind goes through the space to enhance cool breeze by the spreading effect caused through the air flow.
- ✓ Reduce the usage of materials that absorb solar energy to minimize the solar heat gain. Grass is considered to provide several benefits in this matter yet a balance of water consumption is to be considered through efficient irrigation systems.
- ✓ A deep understanding to the mechanism of the bioclimatic parameters before selection and application since their effect is variable depending upon the testing conditions where a balance between all the variables incorporated need to be achieved.
- ✓ Identifying the hotspots within the space to be able to select the most efficient technique suitable for solving that problem before the environmental amendments is to take place.
- ✓ Enhancing one outdoor space would contribute to adjacent spaces enhancement based upon the ‘background effect’ phenomenon.

## 6.3 Recommendations for Future Investigations

By commencing this investigation a direction for future recommendations to fill in the gap of knowledge is done. The current findings presented in the previous Chapters were based upon specified criteria limited by the resources available. The limited time frame and testing tools mainly controlled a lot of circumstances in the formation of the test matrix of the variables examination.  Some of the parameters that were selected for this study were too broad that required further investigation such as vegetation yet was not possible and therefore will be mentioned below for future works. Some of the results and findings discussed previously triggered a lot of questions that also needs remedial actions. The set of recommendations below are suggestions for future works which would complete the knowledge presented in this paper;

- Upgrading a wide database for knowledge through research and various examination methods of various parameters regarding our environmental design to help achieve ecological cities and thus minimizing our footprint on earth.
- The independent parameters (orientation, wind and vegetation) were tested during 10 hours on August noting the diurnal patterns in which nocturnal patterns requires to be further investigated to verify the coolest parameters selected.
- Investigation of the independent variables during winter season.
- The scenarios presented tested the extreme weather conditions during both summer and winter justifying that if improvement was guaranteed during that period then higher levels of enhancement would be achieved during the year which requires further examination.
- Geometry investigation in accordance to the same composition from a SKV parameters rather than air temperature.
- Comparison of ENVI-met results with field measurements to solve the problem of validation through earlier researches.
- Field measurements done in earlier studies were always based upon point measurements versus average value for the whole space commonly used through computer simulations though some softwares are capable of doing that. Future studies should be utilizing such method based to verify the same results.
- Investigate larger sizes of spaces for the same parameters to identify the threshold mentioned for the efficiency of the bioclimatic principles based on the size.
- The test matrix presented in Chapter 3 can be breakdown into more variables with different manipulations leading to more phenomena’s about the outdoor parameters.
- Incorporating the possibility of utilizing wind speed aspect through proper design in accordance with the investigated scenarios.
- Develop more number of softwares that are simple for outdoor investigation with wide libraries and materials effect is needed. Where incorporation of the fixed

variables such as building facades projections, colonnades or shading devices and its impact on the outdoor space.

- Investigate the enhanced and worst scenarios effect on the indoor cooling loads and the thermal performances of the buildings during summer and winter would add a financial value to the work.
- The bioclimatic parameters concluded could be investigated on other spaces within the same location in the DKV especially the central space of focus.
- Testing adjacent outdoor spaces in the DKV site along with the current area to investigate the ‘background effect’ defining its exact cooling impact.

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# APPENDICES

**Appendix A**

Numerical data obtained from the simulations testing the Orientation, Geometry and vegetation variables along with graphical representations of the daily wind and temperatures patterns with 30 minutes saving intervals.

**Table A.1 Daily temperatures and wind speed values for EW orientation based on simulation results**

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 297.2444293 | 1.43567822 |
| **8:30** | 298.0498312 | 1.421924528 |
| **9:00** | 298.9293308 | 1.412626155 |
| **9:30** | 300.3717309 | 1.404425634 |
| **10:00** | 301.6789738 | 1.396870527 |
| **10:30** | 302.7222617 | 1.393018803 |
| **11:00** | 303.3751381 | 1.394118478 |
| **11:30** | 303.8862108 | 1.399046845 |
| **12:00** | 304.3423193 | 1.407117241 |
| **12:30** | 304.6765331 | 1.416688549 |
| **13:00** | 304.9001518 | 1.427172804 |
| **13:30** | 305.0118979 | 1.4373311 |
| **14:00** | 305.0704274 | 1.445587638 |
| **14:30** | 305.087961 | 1.452348536 |
| **15:00** | 304.9801347 | 1.457241379 |
| **15:30** | 304.7232565 | 1.459686858 |
| **16:00** | 304.4134615 | 1.46000475 |
| **16:30** | 303.9573342 | 1.456724593 |
| **17:00** | 303.321364 | 1.444615355 |
| **17:30** | 302.4770174 | 1.428161158 |
| **18:00** | 301.4557856 | 1.418936645 |
| **Average** | 302.889 | 1.427 |
| **Maximum** | 305.088 | 1.460 |
| **Minimum** | 297.244 | 1.393 |

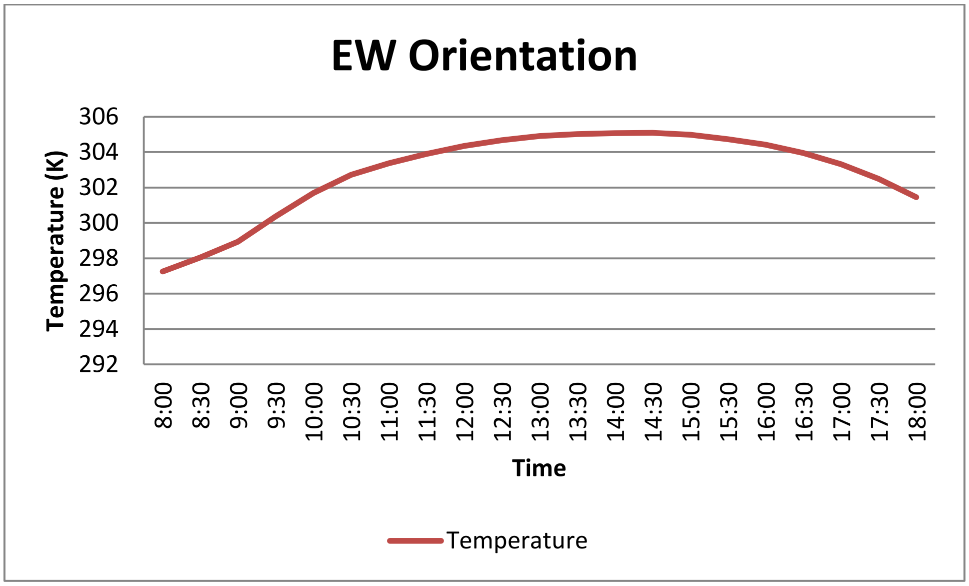


**Figure A.1 Daily temperature pattern for EW orientation based on results every 30 minutes**

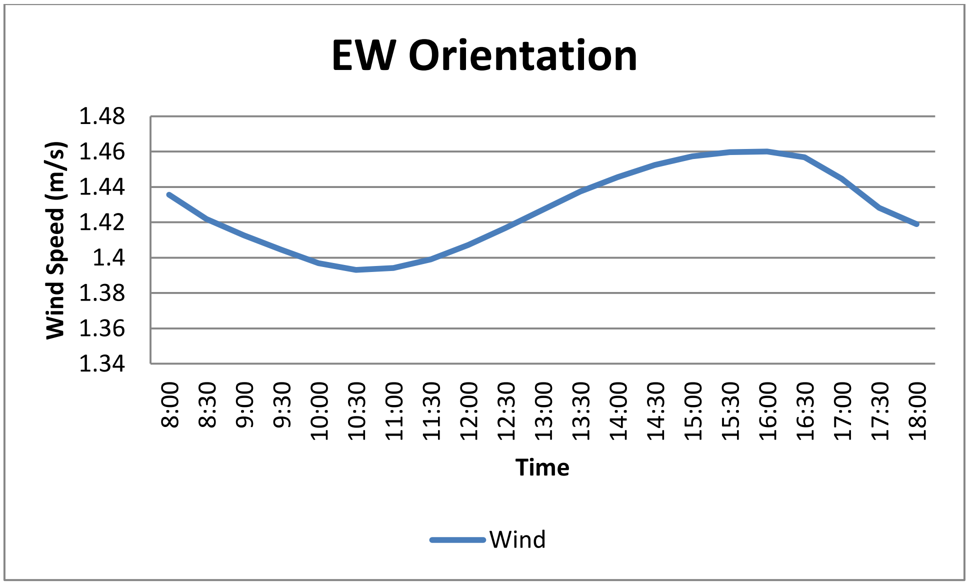


**Figure A.2 Daily wind speed pattern for EW orientation based on results every 30 minutes**

Table A.2 Daily temperatures and wind speed values for NS orientation based on simulation results

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 297.0638889 | 1.635971958 |
| **8:30** | 297.775772 | 1.620322967 |
| **9:00** | 298.5399232 | 1.60639948 |
| **9:30** | 299.9390029 | 1.593485751 |
| **10:00** | 301.2303185 | 1.580770202 |
| **10:30** | 302.4033588 | 1.569588159 |
| **11:00** | 303.0708044 | 1.564593689 |
| **11:30** | 303.5869661 | 1.565539427 |
| **12:00** | 304.1836373 | 1.571934873 |
| **12:30** | 304.5409757 | 1.581697398 |
| **13:00** | 304.7954258 | 1.593017502 |
| **13:30** | 304.8153956 | 1.604886207 |
| **14:00** | 304.8165232 | 1.615271633 |
| **14:30** | 304.811164 | 1.622906701 |
| **15:00** | 304.7001233 | 1.627629408 |
| **15:30** | 304.328054 | 1.628014834 |
| **16:00** | 304.0198542 | 1.622891737 |
| **16:30** | 303.5181296 | 1.610550423 |
| **17:00** | 302.8679964 | 1.585145608 |
| **17:30** | 302.051644 | 1.560218998 |
| **18:00** | 301.1543672 | 1.539382108 |
| **Average** | 302.582 | 1.595 |
| **Maximum** | 304.817 | 1.636 |
| **Minimum** | 297.064 | 1.539 |

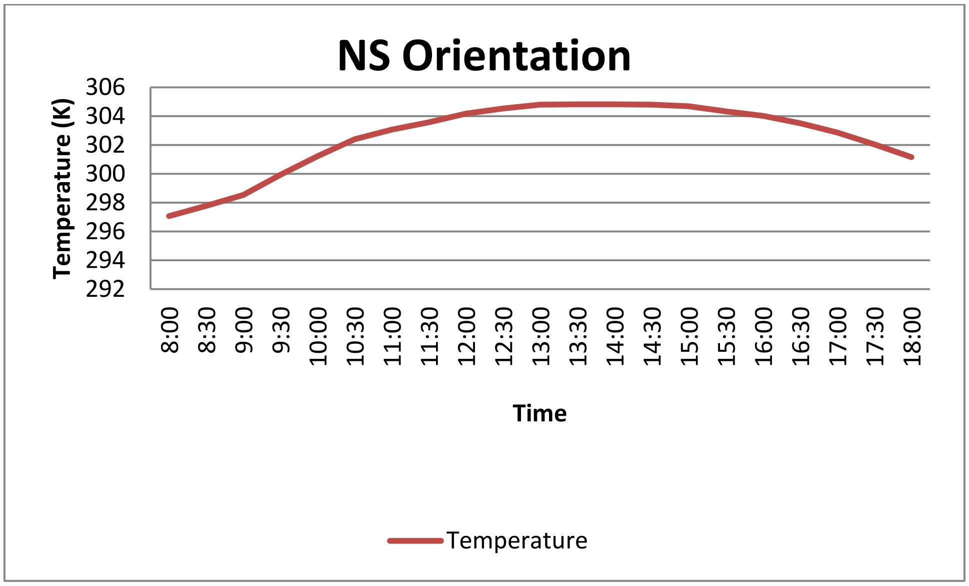


**Figure A.3 Daily temperature pattern for NS orientation based on results every 30 minutes**

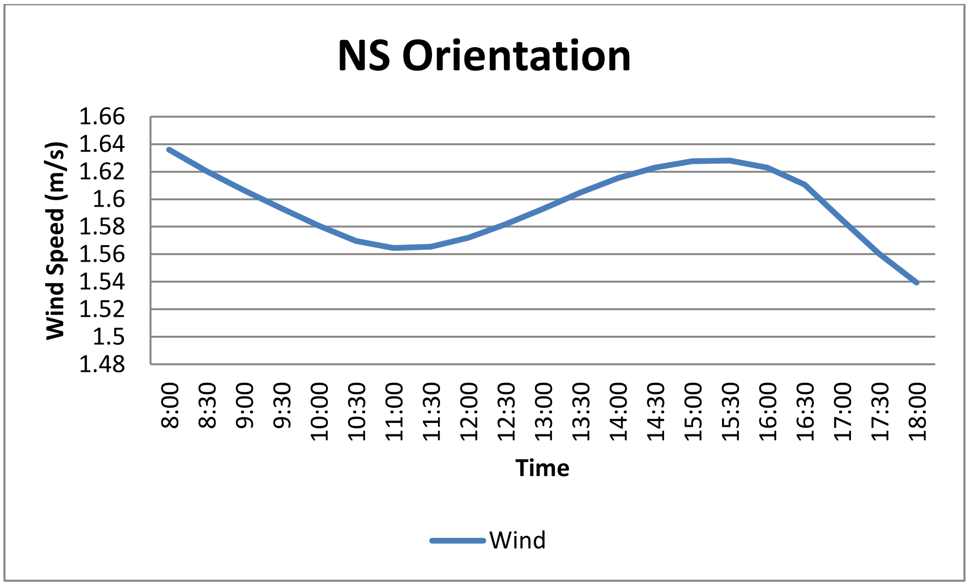


**Figure A.4 Daily wind speed pattern for NS orientation based on results every 30 minutes**

**Table A.3 Daily temperatures and wind speed values for SE-NW orientation based on simulation results**

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 297.0638889 | 1.635971958 |
| **8:30** | 297.8987678 | 1.696408979 |
| **9:00** | 298.8582657 | 1.683653351 |
| **9:30** | 300.276888 | 1.671743136 |
| **10:00** | 301.5699254 | 1.65936337 |
| **10:30** | 302.4540805 | 1.649978595 |
| **11:00** | 303.3431299 | 1.647306831 |
| **11:30** | 303.8771655 | 1.650773975 |
| **12:00** | 304.303201 | 1.658121015 |
| **12:30** | 304.6830642 | 1.667609174 |
| **13:00** | 304.7721672 | 1.677849772 |
| **13:30** | 304.8691507 | 1.687651659 |
| **14:00** | 304.9438221 | 1.692537452 |
| **14:30** | 304.9042488 | 1.697506441 |
| **15:00** | 304.7952601 | 1.697891152 |
| **15:30** | 304.4396291 | 1.695167599 |
| **16:00** | 304.0388709 | 1.687244697 |
| **16:30** | 303.5788822 | 1.672398439 |
| **17:00** | 302.7646651 | 1.649095511 |
| **17:30** | 301.7950619 | 1.627707352 |
| **18:00** | 300.6856709 | 1.610516981 |
| **Average** | 302.663 | 1.667 |
| **Maximum** | 304.944 | 1.698 |
| **Minimum** | 297.064 | 1.611 |

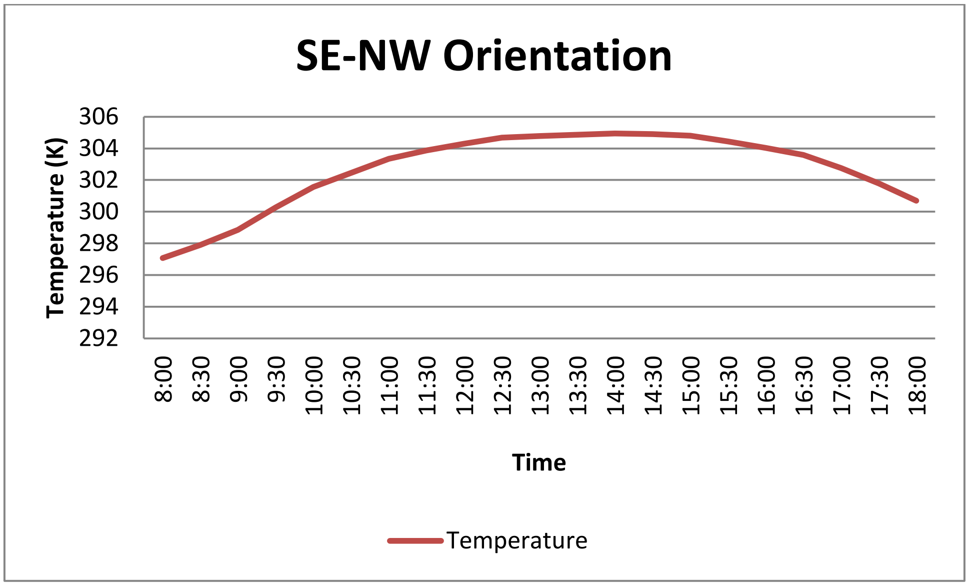


**Figure A. 5 Daily temperature pattern for SE-NW orientation based on results every 30 minutes**

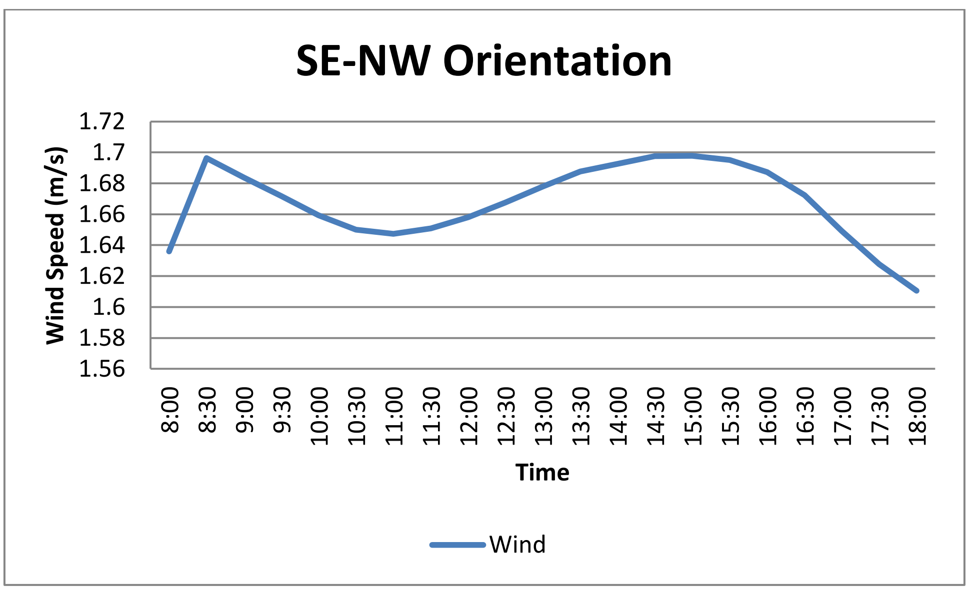


**Figure A.6 Daily wind speed pattern for SE-NW orientation based on results every 30 minutes**

**Table A.4 Daily temperatures and wind speed values for SW-NE orientation based on simulation results**

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 296.7336343 | 1.042831034 |
| **8:30** | 297.8599813 | 1.038813858 |
| **9:00** | 299.0843846 | 1.035476773 |
| **9:30** | 300.7065554 | 1.032699545 |
| **10:00** | 302.1011165 | 1.029851724 |
| **10:30** | 301.3603936 | 1.046280742 |
| **11:00** | 302.7684509 | 1.0416635 |
| **11:30** | 303.6232584 | 1.04820566 |
| **12:00** | 303.6232584 | 1.04820566 |
| **12:30** | 304.6710532 | 1.082086988 |
| **13:00** | 304.8208316 | 1.101829408 |
| **13:30** | 304.9005304 | 1.120397918 |
| **14:00** | 304.9163283 | 1.134715745 |
| **14:30** | 304.6571816 | 1.14334216 |
| **15:00** | 304.4370178 | 1.146312167 |
| **15:30** | 304.0822364 | 1.145132531 |
| **16:00** | 303.5964438 | 1.133872088 |
| **16:30** | 303.0315152 | 1.11268972 |
| **17:00** | 302.0668372 | 1.086026545 |
| **17:30** | 300.9098759 | 1.064543787 |
| **18:00** | 299.680012 | 1.049664476 |
| **Average** | 302.363 | 1.080 |
| **Maximum** | 304.916 | 1.146 |
| **Minimum** | 296.734 | 1.030 |

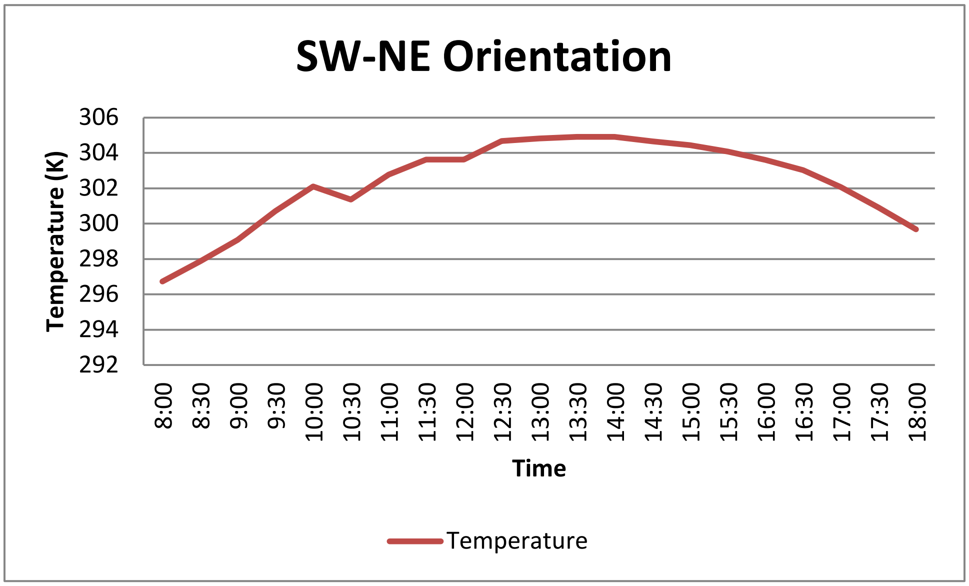


**Figure A.7 Daily wind speed pattern for SW-NE orientation based on results every 30 minutes**

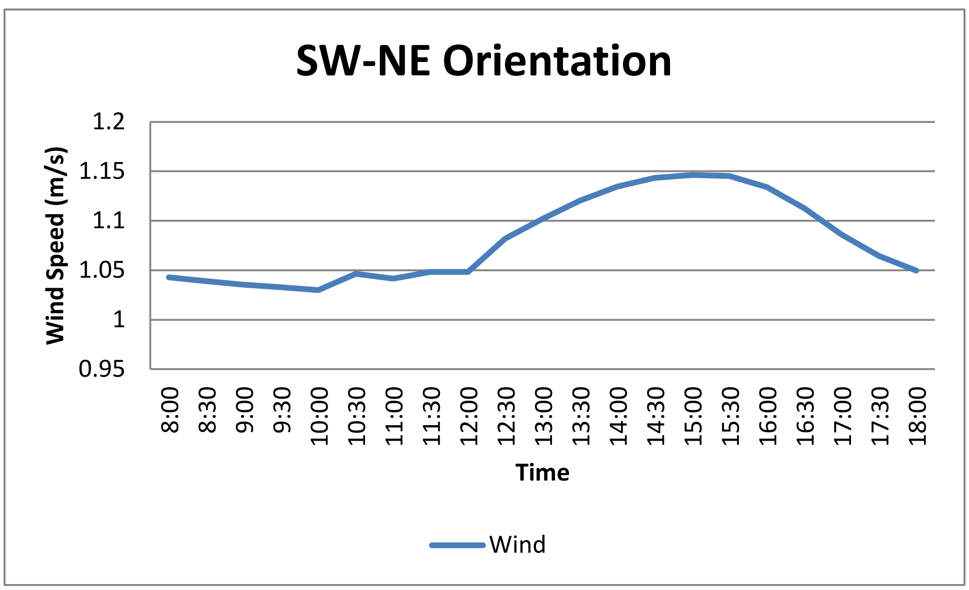


**Figure A.8 Daily wind speed pattern for SW-NE orientation based on results every 30 minutes**

Table A.5 Daily temperatures and wind speed values for H:W ratio of 0.5 based on simulation results

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 297.1033214 | 1.140634857 |
| **8:30** | 298.0990532 | 1.137028634 |
| **9:00** | 299.1745914 | 1.134084031 |
| **9:30** | 300.6531643 | 1.131549725 |
| **10:00** | 301.9009368 | 1.129471971 |
| **10:30** | 302.7871091 | 1.131417786 |
| **11:00** | 303.4425642 | 1.138481718 |
| **11:30** | 303.9841777 | 1.149379736 |
| **12:00** | 304.3764664 | 1.162584306 |
| **12:30** | 304.8092187 | 1.176513767 |
| **13:00** | 305.0456475 | 1.190902478 |
| **13:30** | 305.1335213 | 1.203601707 |
| **14:00** | 305.209 | 1.213729295 |
| **14:30** | 305.2011223 | 1.220831278 |
| **15:00** | 305.0382284 | 1.22538728 |
| **15:30** | 304.7937975 | 1.227008921 |
| **16:00** | 304.3338024 | 1.225100275 |
| **16:30** | 303.8014365 | 1.21699185 |
| **17:00** | 302.9876539 | 1.200856333 |
| **17:30** | 301.9940008 | 1.182755672 |
| **18:00** | 300.8267915 | 1.167914482 |
| **Average** | 302.890 | 1.176 |
| **Maximum** | 305.209 | 1.227 |
| **Minimum** | 297.103 | 1.129 |

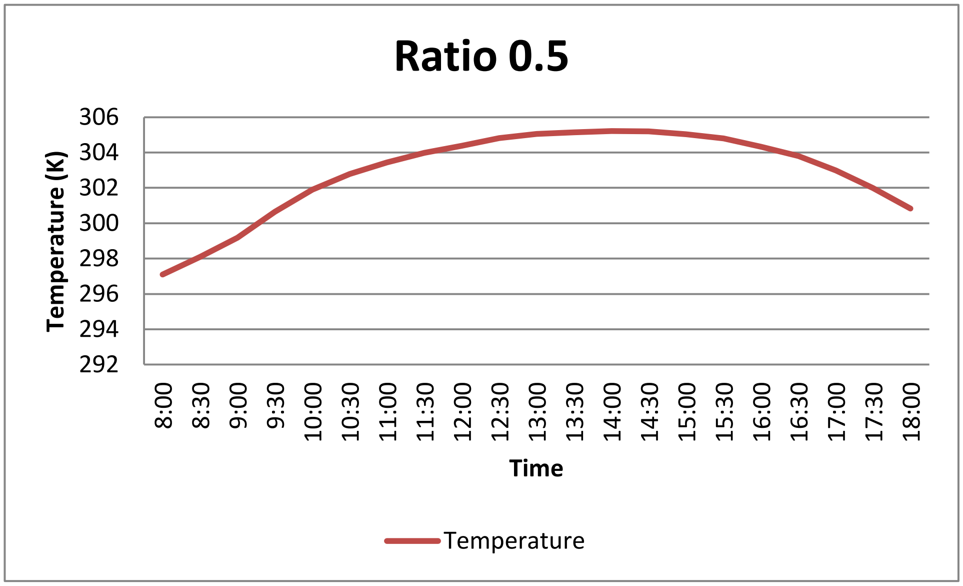


**Figure A.9 Daily temperature pattern for 0.5 ratio based on results every 30 minutes**

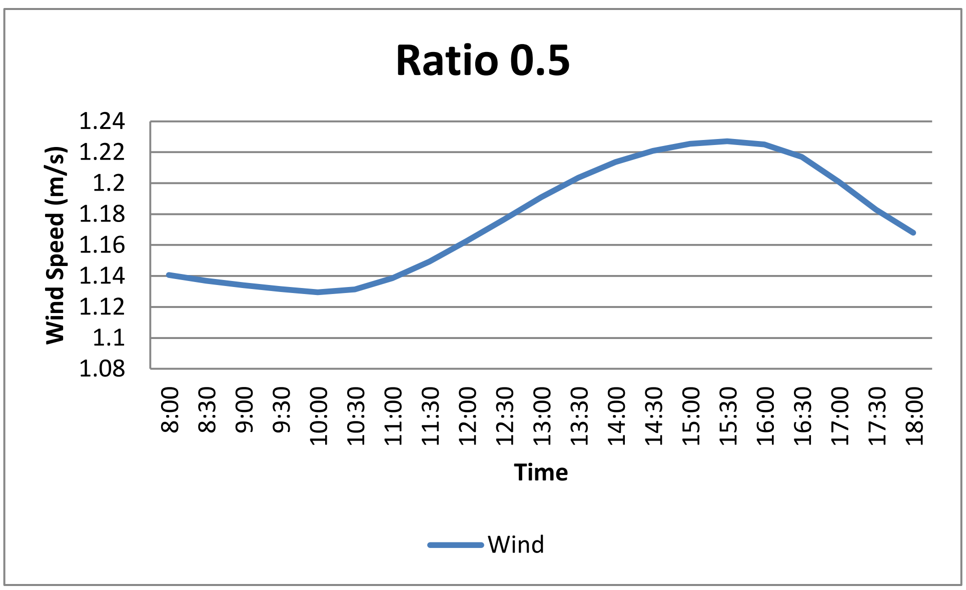


**Figure A.10 Daily wind speed pattern for 0.5 ratio based on results every 30 minutes**

Table A.6 Daily temperatures and wind speed values for H:W ratio of 2 based on simulation results

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 296.9725186 | 1.196182989 |
| **8:30** | 297.9991683 | 1.191713831 |
| **9:00** | 299.095513 | 1.188069157 |
| **9:30** | 300.5877593 | 1.184931081 |
| **10:00** | 301.8482141 | 1.182242528 |
| **10:30** | 302.7254347 | 1.183921622 |
| **11:00** | 303.364496 | 1.191197138 |
| **11:30** | 303.9219462 | 1.202896502 |
| **12:00** | 304.299386 | 1.217352385 |
| **12:30** | 304.7868856 | 1.232815103 |
| **13:00** | 305.0325929 | 1.248989348 |
| **13:30** | 305.0846163 | 1.263401749 |
| **14:00** | 305.1362328 | 1.274816455 |
| **14:30** | 305.1123706 | 1.282821781 |
| **15:00** | 304.9101082 | 1.288247218 |
| **15:30** | 304.6425547 | 1.290119078 |
| **16:00** | 304.1302425 | 1.287650079 |
| **16:30** | 303.565339 | 1.277649921 |
| **17:00** | 302.7311367 | 1.258472099 |
| **17:30** | 301.7168981 | 1.237966296 |
| **18:00** | 300.5415615 | 1.221633545 |
| **Average** | 302.772 | 1.233 |
| **Maximum** | 305.136 | 1.290 |
| **Minimum** | 296.973 | 1.182 |

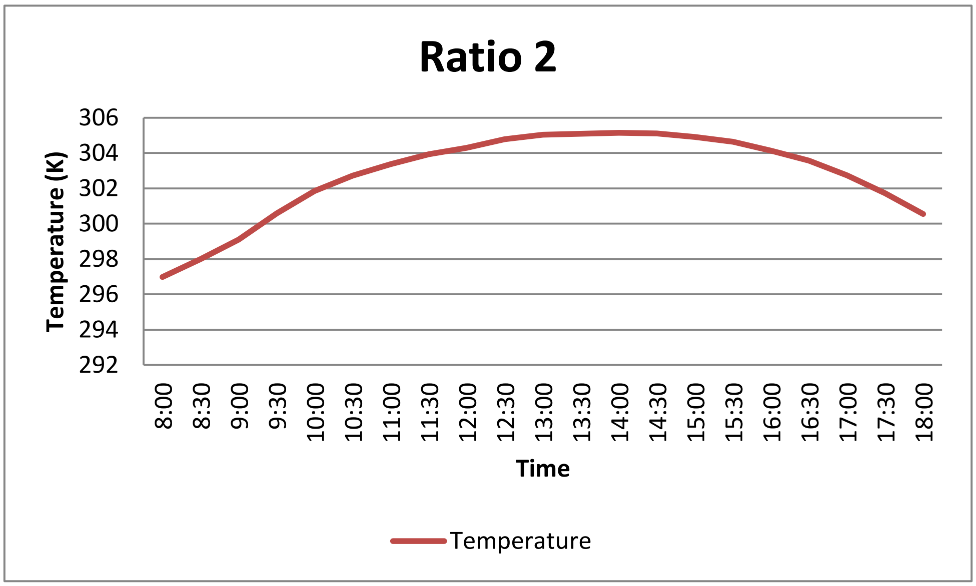


**Figure A.11 Daily temperature pattern for 2 ratio based on results every 30 minutes**

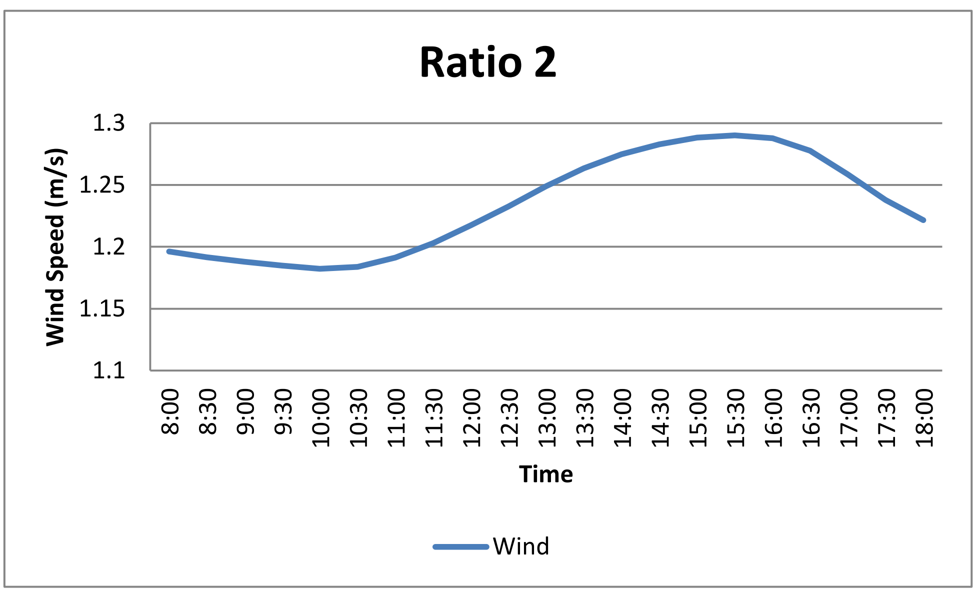


**Figure A.12 Daily wind speed pattern for 2 ratio based on results every 30 minutes**

Table A.7 Daily temperatures and wind speed values for H:W ratio of 4 based on simulation results

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 297.0482163 | 1.190448345 |
| **8:30** | 297.9791565 | 1.186934397 |
| **9:00** | 298.9934979 | 1.184072104 |
| **9:30** | 300.4160401 | 1.181646927 |
| **10:00** | 301.6696307 | 1.17991643 |
| **10:30** | 302.5438818 | 1.182589716 |
| **11:00** | 303.1793004 | 1.190747754 |
| **11:30** | 303.7485739 | 1.203182033 |
| **12:00** | 304.1390262 | 1.218108629 |
| **12:30** | 304.6115262 | 1.233966548 |
| **13:00** | 304.8622324 | 1.250319385 |
| **13:30** | 304.9299427 | 1.264729196 |
| **14:00** | 304.9941726 | 1.275838534 |
| **14:30** | 304.9840671 | 1.283941371 |
| **15:00** | 304.804313 | 1.289008983 |
| **15:30** | 304.5792819 | 1.290800827 |
| **16:00** | 304.1086332 | 1.287973286 |
| **16:30** | 303.5657675 | 1.278309338 |
| **17:00** | 302.7812502 | 1.259694917 |
| **17:30** | 301.8358397 | 1.23973617 |
| **18:00** | 300.7149882 | 1.224091135 |
| **Average** | 302.690 | 1.233 |
| **Maximum** | 304.994 | 1.291 |

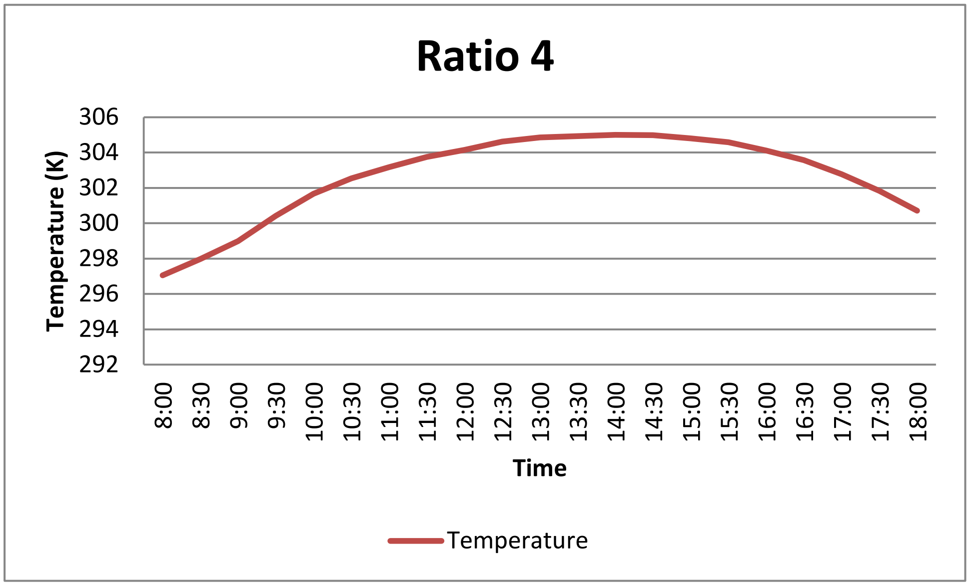


**Figure A.13 Daily temperature pattern for 2 ratio based on results every 30 minutes**

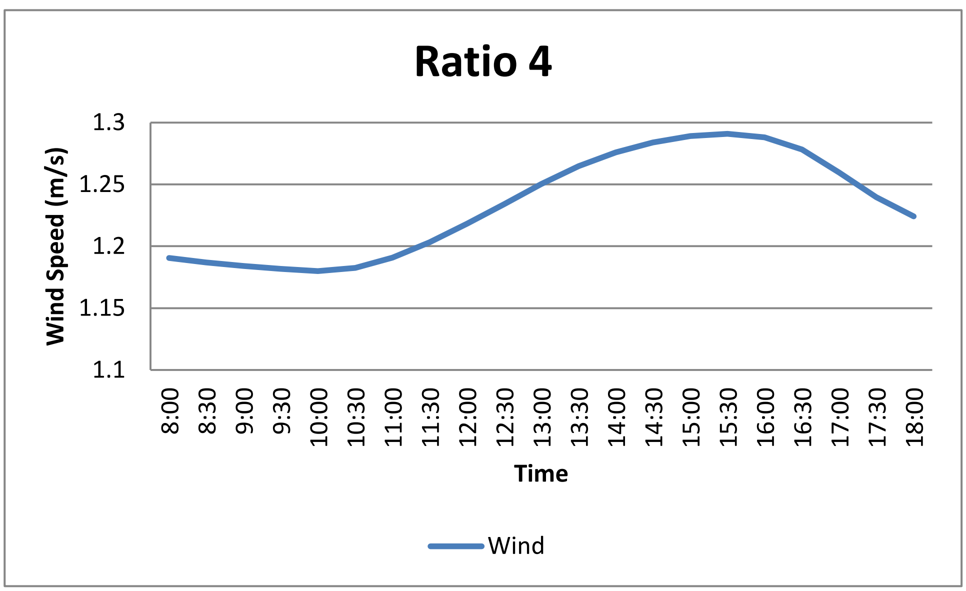


**Figure A.14 Daily wind speed pattern for 2 ratio based on results every 30 minutes**

Table A.8 Daily temperatures and wind speed values for grass pieces vegetation strategy

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 297.0732899 | 1.164512362 |
| **8:30** | 298.0720861 | 1.160606441 |
| **9:00** | 299.1455038 | 1.157623813 |
| **9:30** | 300.6232381 | 1.155213012 |
| **10:00** | 301.8583138 | 1.153587638 |
| **10:30** | 302.7385783 | 1.160255646 |
| **11:00** | 303.3711254 | 1.163139818 |
| **11:30** | 303.9144601 | 1.174127131 |
| **12:00** | 304.2794285 | 1.187418543 |
| **12:30** | 304.7316206 | 1.197484833 |
| **13:00** | 304.9771021 | 1.215570657 |
| **13:30** | 305.0575716 | 1.228361418 |
| **14:00** | 304.8894149 | 1.229985743 |
| **14:30** | 305.1263897 | 1.235678899 |
| **15:00** | 304.9655934 | 1.249503318 |
| **15:30** | 304.7260537 | 1.251441379 |
| **16:00** | 304.2582921 | 1.250165843 |
| **16:30** | 303.7059824 | 1.243630124 |
| **17:00** | 302.8878412 | 1.230809694 |
| **17:30** | 301.8882316 | 1.216240403 |
| **18:00** | 300.7143899 | 1.203397658 |
| **Average** | 302.810 | 1.201 |
| **Maximum** | 305.126 | 1.251 |
| **Minimum** | 297.073 | 1.154 |

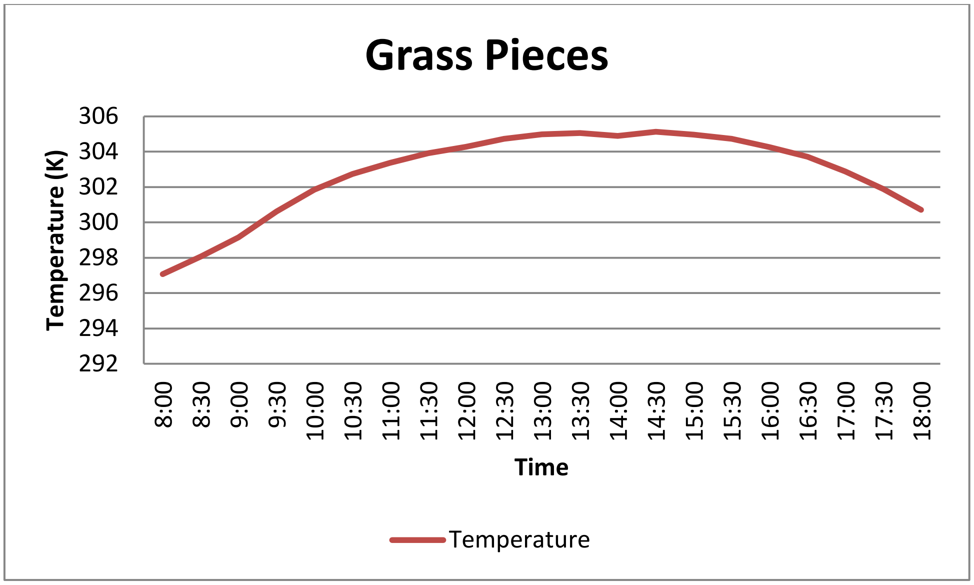


**Figure A.15 Daily temperature pattern for grass pieces vegetation strategy based on results every 30 minutes**

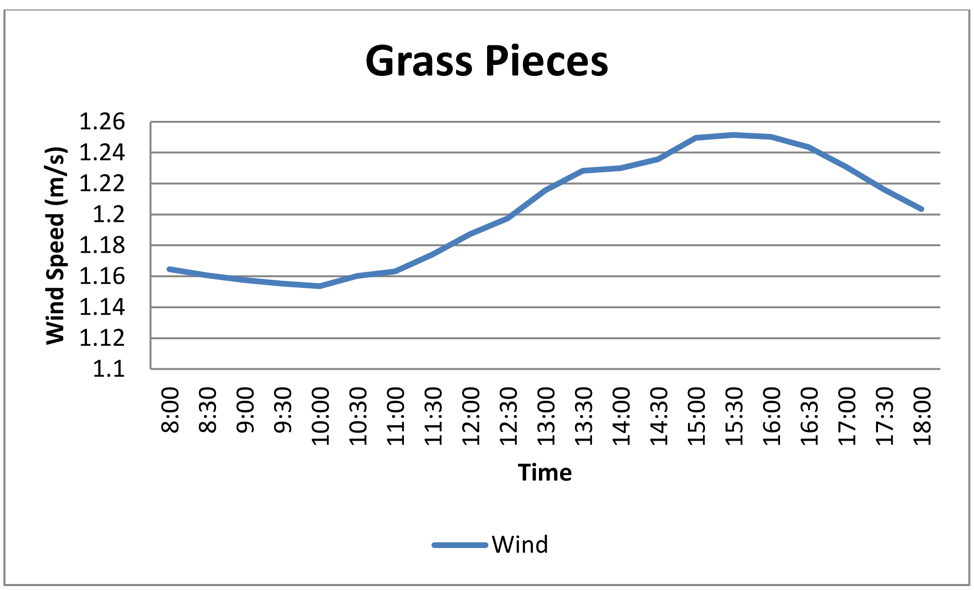


**Figure A.16 Daily wind speed pattern for grass pieces vegetation strategy based on results every 30 minutes**

**Table A.9 Daily temperatures and wind speed values for no tree vegetation strategy**

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 297.1132522 | 1.185942876 |
| **8:30** | 298.1256577 | 1.182482628 |
| **9:00** | 299.2122507 | 1.179853936 |
| **9:30** | 300.7019448 | 1.17768907 |
| **10:00** | 301.9408823 | 1.17624769 |
| **10:30** | 302.8309709 | 1.178863175 |
| **11:00** | 303.4677865 | 1.186355303 |
| **11:30** | 303.9847658 | 1.197621535 |
| **12:00** | 304.3856454 | 1.211206116 |
| **12:30** | 304.842818 | 1.225312167 |
| **13:00** | 305.0922432 | 1.240053351 |
| **13:30** | 305.1808098 | 1.253086337 |
| **14:00** | 305.2617813 | 1.262954977 |
| **14:30** | 305.2637774 | 1.270318022 |
| **15:00** | 305.1065388 | 1.275297072 |
| **15:30** | 304.8668239 | 1.277772674 |
| **16:00** | 304.4029331 | 1.277094209 |
| **16:30** | 303.8513158 | 1.271223422 |
| **17:00** | 303.0256046 | 1.259680481 |
| **17:30** | 302.0133093 | 1.245921535 |
| **18:00** | 300.8219737 | 1.233176838 |
| **Average** | 302.928 | 1.227 |
| **Maximum** | 305.264 | 1.278 |
| **Minimum** | 297.113 | 1.176 |

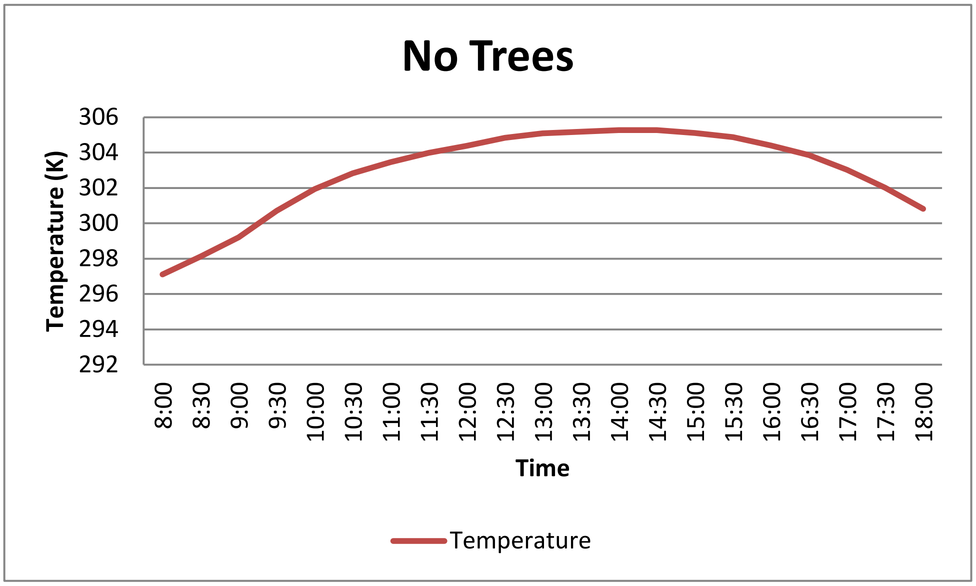


**Figure A.17 Daily temperature pattern for no trees vegetation strategy based on results every 30 minutes**

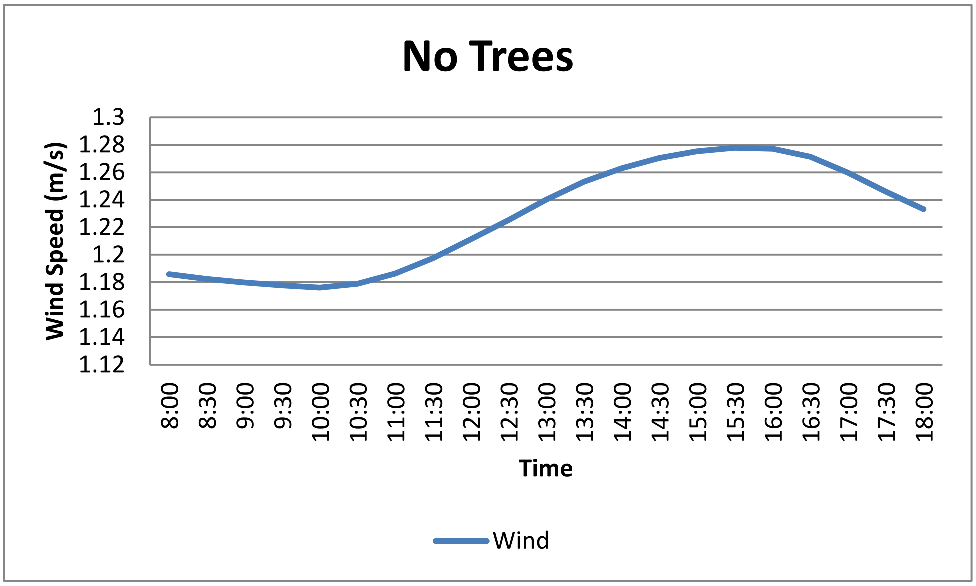


**Figure A.18 Daily wind speed pattern for no trees vegetation strategy based on results every 30 minutes**

**Table A.10 Daily temperatures and wind speed values for continuous trees vegetation strategy**

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 296.9014133 | 1.131664151 |
| **8:30** | 297.8479265 | 1.127342746 |
| **9:00** | 298.8549714 | 1.124032271 |
| **9:30** | 300.2307247 | 1.121411906 |
| **10:00** | 301.4737342 | 1.118970592 |
| **10:30** | 302.3223079 | 1.118373975 |
| **11:00** | 302.969066 | 1.122846467 |
| **11:30** | 303.5593306 | 1.129814769 |
| **12:00** | 303.9990222 | 1.140916981 |
| **12:30** | 304.4499203 | 1.154019193 |
| **13:00** | 304.6499016 | 1.167842941 |
| **13:30** | 304.7143193 | 1.180954587 |
| **14:00** | 304.7861375 | 1.192986077 |
| **14:30** | 304.7466818 | 1.202719519 |
| **15:00** | 304.5509761 | 1.209476383 |
| **15:30** | 304.2110966 | 1.212483669 |
| **16:00** | 303.7203934 | 1.21043136 |
| **16:30** | 303.1687694 | 1.200180026 |
| **17:00** | 302.365734 | 1.185632466 |
| **17:30** | 301.4284558 | 1.172729863 |
| **18:00** | 300.3491529 | 1.162897918 |
| **Average** | 302.443 | 1.161 |
| **Maximum** | 304.786 | 1.212 |
| **Minimum** | 296.901 | 1.118 |

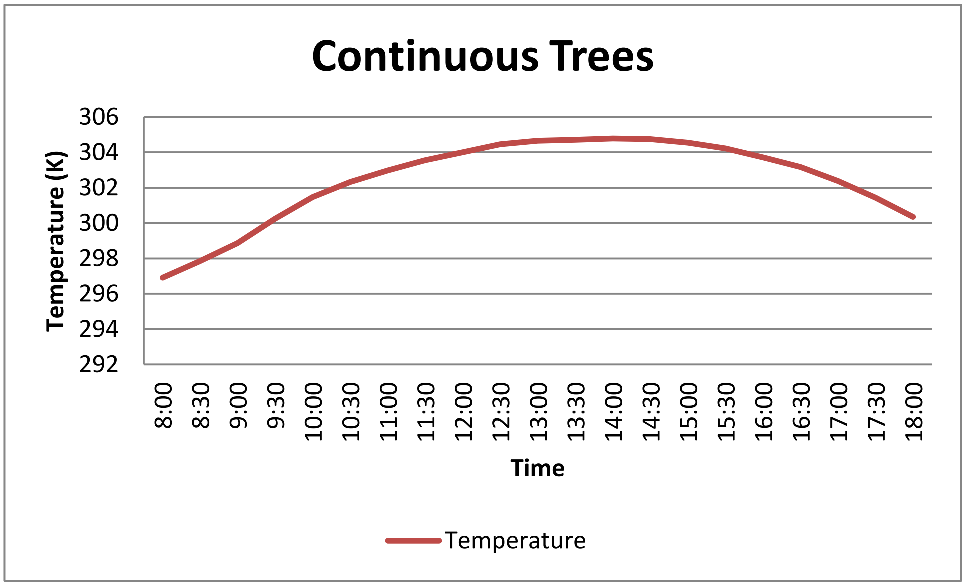


**Figure A.19 Daily temperature pattern for continuous trees vegetation strategy based on results every 30 minutes**

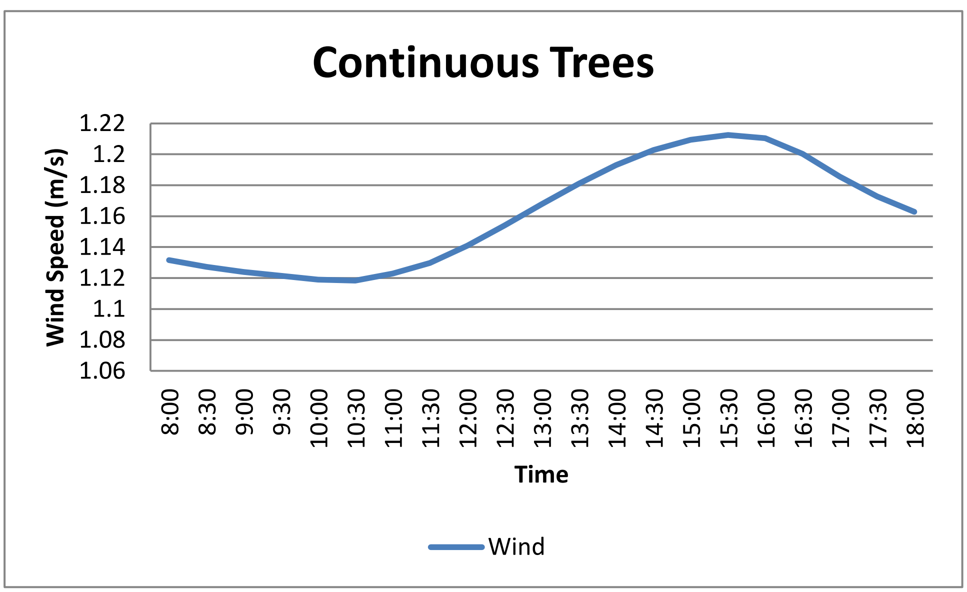


**Figure A.20 Daily wind speed pattern for continuous trees vegetation strategy based on results every 30 minutes**

Table A.11 Daily temperatures and wind speed values for tree groups vegetation strategy

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 296.8812697 | 1.089000846 |
| **8:30** | 297.8298669 | 1.084364411 |
| **9:00** | 298.8566899 | 1.080695576 |
| **9:30** | 300.2781325 | 1.077708783 |
| **10:00** | 301.5673734 | 1.074913598 |
| **10:30** | 302.4522457 | 1.074535133 |
| **11:00** | 303.0928036 | 1.078628367 |
| **11:30** | 303.64317 | 1.08685244 |
| **12:00** | 304.0605651 | 1.098087183 |
| **12:30** | 304.5173987 | 1.111060117 |
| **13:00** | 304.7179018 | 1.124391477 |
| **13:30** | 304.7717009 | 1.136833312 |
| **14:00** | 304.8225811 | 1.147922381 |
| **14:30** | 304.7648361 | 1.156449252 |
| **15:00** | 304.5399426 | 1.161885882 |
| **15:30** | 304.2216807 | 1.163708003 |
| **16:00** | 303.7112304 | 1.16042108 |
| **16:30** | 303.1708398 | 1.148966884 |
| **17:00** | 302.3767396 | 1.134003253 |
| **17:30** | 301.4483887 | 1.1209838 |
| **18:00** | 300.3568134 | 1.11080501 |
| **Average** | 302.480 | 1.115 |
| **Maximum** | 304.823 | 1.164 |
| **Minimum** | 296.881 | 1.075 |

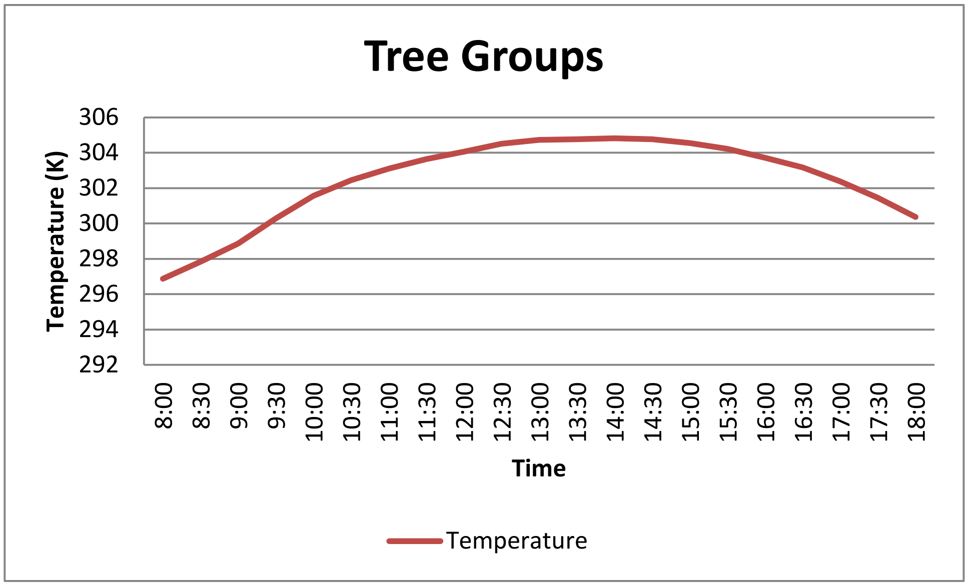


**Figure A.21 Daily temperature pattern for tree groups vegetation strategy based on results every 30 minutes**

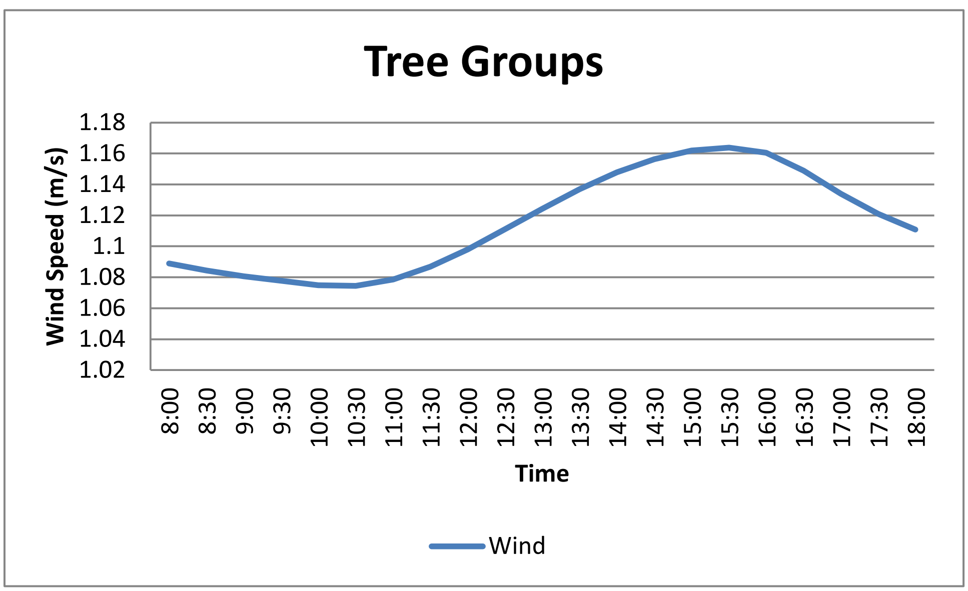


**Figure A.22 Daily wind speed pattern for tree groups vegetation strategy based on results every 30 minutes**

**Table A.12 Daily temperatures and wind speed values for continuous grass vegetation strategy**

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 297.0073536 | 1.138454557 |
| **8:30** | 297.9767815 | 1.133637801 |
| **9:00** | 299.0266317 | 1.130591152 |
| **9:30** | 300.4815805 | 1.128237345 |
| **10:00** | 301.7157275 | 1.126696487 |
| **10:30** | 302.5794966 | 1.129018608 |
| **11:00** | 303.2008977 | 1.13617378 |
| **11:30** | 303.7271472 | 1.147116786 |
| **12:00** | 304.0749656 | 1.160296812 |
| **12:30** | 304.4976896 | 1.17356757 |
| **13:00** | 304.7159813 | 1.188639102 |
| **13:30** | 304.7871107 | 1.201497072 |
| **14:00** | 304.8485081 | 1.210770527 |
| **14:30** | 304.8362743 | 1.217136435 |
| **15:00** | 304.6713501 | 1.220784255 |
| **15:30** | 304.4349925 | 1.2215473 |
| **16:00** | 303.972912 | 1.219059206 |
| **16:30** | 303.4291726 | 1.21092635 |
| **17:00** | 302.620725 | 1.198369616 |
| **17:30** | 301.6441041 | 1.185058816 |
| **18:00** | 300.5070519 | 1.17333123 |
| **Average** | 302.607 | 1.174 |
| **Maximum** | 304.849 | 1.222 |
| **Minimum** | 297.007 | 1.127 |

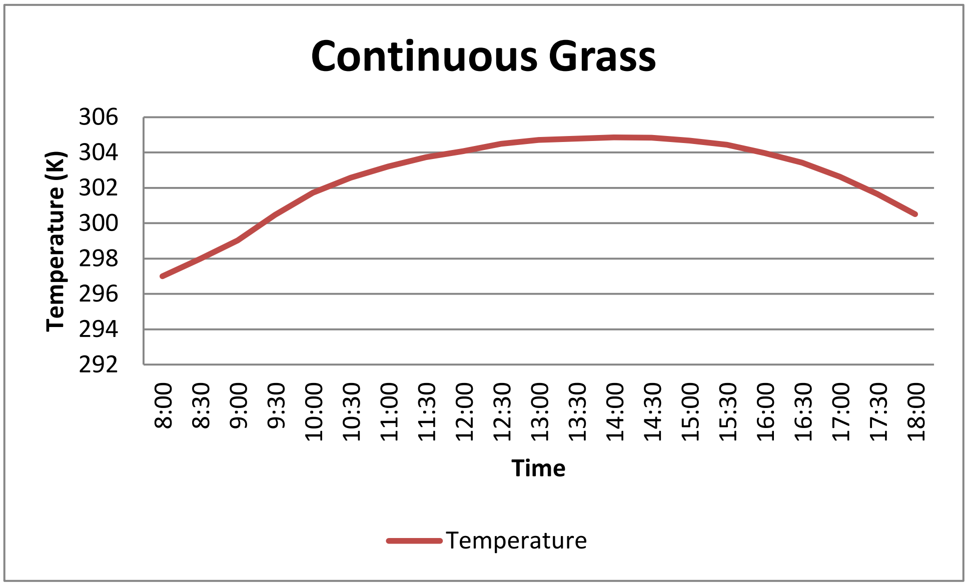


**Figure A.23 Daily temperature pattern for continuous grass vegetation strategy based on results every 30 minutes**

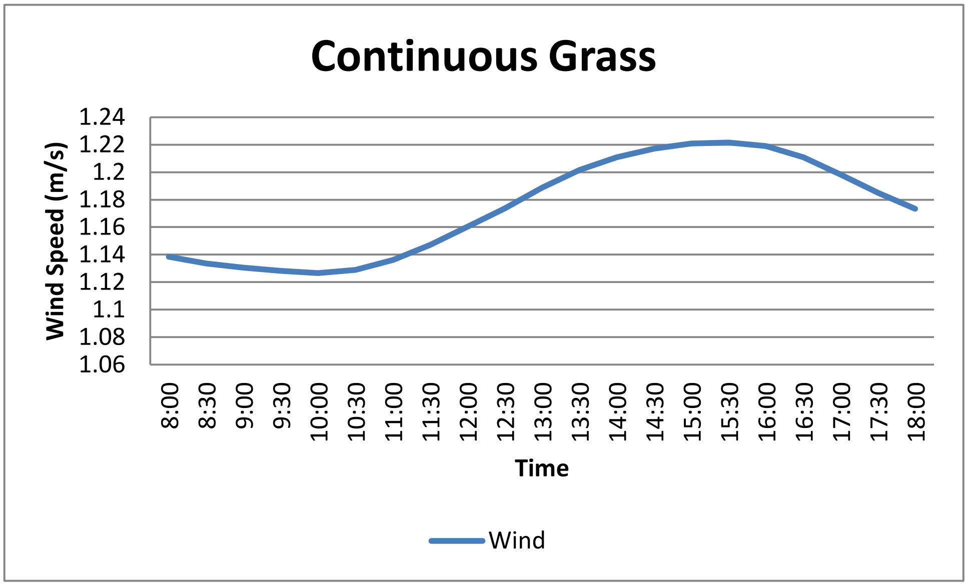


**Figure A.24 Daily wind speed pattern for continuous grass vegetation strategy based on results every 30 minutes**

**Table A.13 Daily temperatures and wind speed values for continuous grass and tree groups vegetation strategy**

| Time | Temperature | Wind |
|---|---|---|
| **8:00** | 296.8382362 | 1.054901627 |
| **8:30** | 297.7738278 | 1.049794665 |
| **9:00** | 298.7862177 | 1.04578998 |
| **9:30** | 300.1873714 | 1.042566103 |
| **10:00** | 301.4649895 | 1.039739232 |
| **10:30** | 302.9575298 | 1.03927404 |
| **11:00** | 303.2947586 | 1.043120104 |
| **11:30** | 303.4828634 | 1.05107853 |
| **12:00** | 303.8817591 | 1.05587687 |
| **12:30** | 304.3060516 | 1.061830644 |
| **13:00** | 304.4938489 | 1.086795901 |
| **13:30** | 304.5380066 | 1.09847853 |
| **14:00** | 304.5716867 | 1.108980286 |
| **14:30** | 304.5018312 | 1.117134353 |
| **15:00** | 304.2761666 | 1.12201542 |
| **15:30** | 303.9677213 | 1.123016916 |
| **16:00** | 303.482708 | 1.11863676 |
| **16:30** | 302.9568277 | 1.106335654 |
| **17:00** | 302.1827301 | 1.091559922 |
| **17:30** | 301.2719258 | 1.079308653 |
| **18:00** | 300.2007285 | 1.070094275 |
| **Average** | 302.353 | 1.076 |
| **Maximum** | 304.572 | 1.123 |
| **Minimum** | 296.838 | 1.039 |

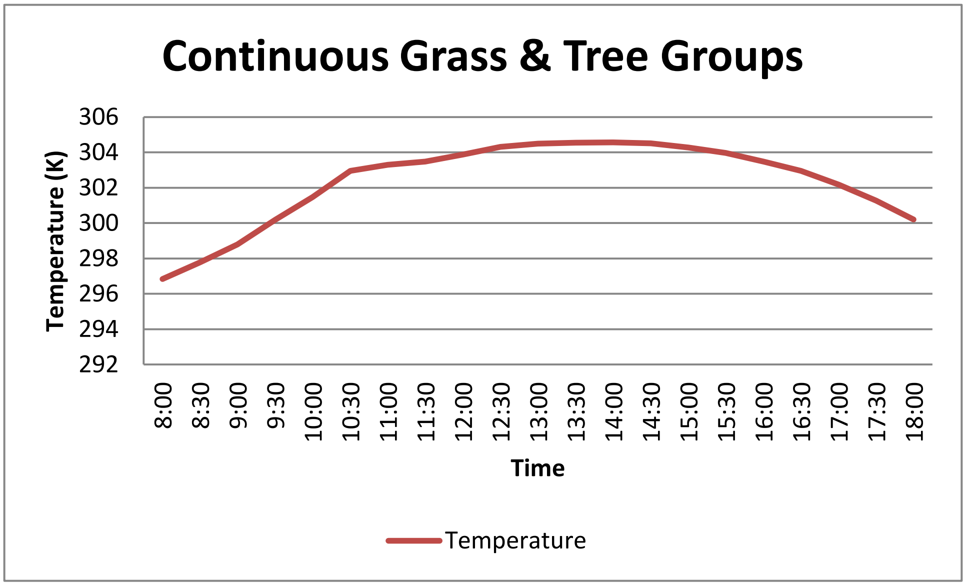


**Figure A.25 Daily temperature pattern for continuous grass and tree groups vegetation strategy based on results every 30 minutes**

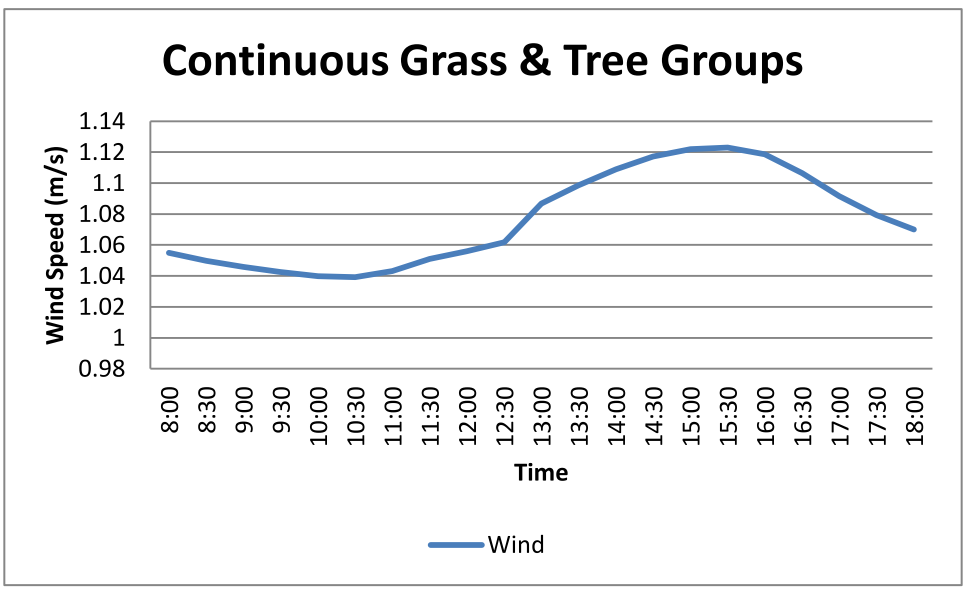


**Figure A.26 Daily wind speed pattern for continuous grass and tree groups vegetation strategy based on results every 30 minutes**

**Appendix B**

Numerical data obtained from the simulations testing the three scenarios named enhanced scenario, existing scenario and the worst case scenario.

**Table B.1 Daily temperatures and wind speed values during summer and winter for the existing scenario**

| Time | Temperature Summer | Temperature Winter | Wind Summer | Wind Winter |
|---|---|---|---|---|
| 8:00 | 297.033902 | 294.9681679 | 1.145211126 | 1.145758751 |
| 8:30 | 298.0279031 | 295.3070477 | 1.141198699 | 1.141717111 |
| 9:00 | 299.0977792 | 295.882346 | 1.138058686 | 1.138165843 |
| 9:30 | 300.5656403 | 296.5680343 | 1.135475732 | 1.135109304 |
| 10:00 | 301.8240029 | 297.3932028 | 1.133211776 | 1.132514834 |
| 10:30 | 302.7032049 | 298.1558602 | 1.134630579 | 1.130405205 |
| 11:00 | 303.3615064 | 298.9603806 | 1.141033442 | 1.129774848 |
| 11:30 | 303.9088479 | 299.9876109 | 1.151367534 | 1.127337671 |
| 12:00 | 304.297736 | 300.7713167 | 1.164369161 | 1.126245283 |
| 12:30 | 304.7486306 | 301.2343057 | 1.17857404 | 1.125173129 |
| 13:00 | 304.9769962 | 301.5353857 | 1.193486597 | 1.12428432 |
| 13:30 | 305.0514696 | 301.7095012 | 1.199784748 | 1.123778985 |
| 14:00 | 305.1227098 | 301.7286255 | 1.217493819 | 1.123504294 |
| 14:30 | 305.1122279 | 301.5995498 | 1.22482056 | 1.123659597 |
| 15:00 | 304.9363976 | 301.3856074 | 1.229904164 | 1.124416981 |
| 15:30 | 304.6874522 | 301.0415032 | 1.231769746 | 1.125143591 |
| 16:00 | 304.2018256 | 300.4957634 | 1.229995836 | 1.125751724 |
| 16:30 | 303.6556427 | 299.812701 | 1.221730839 | 1.126271438 |
| 17:00 | 302.8387996 | 299.0099947 | 1.205454196 | 1.126745153 |
| 17:30 | 301.852653 | 298.1760968 | 1.187813533 | 1.127161158 |
| 18:00 | 300.6829154 | 297.6654252 | 1.173486532 | 1.12743188 |
| 18:30 | 299.6332923 | 297.2840399 | 1.162792258 | 1.127567404 |
| 19:00 | 299.0820415 | 296.9729791 | 1.155093689 | 1.127635133 |
| 19:30 | 298.6604677 | 296.7138426 | 1.155093689 | 1.127659076 |
| 20:00 | 298.3595176 | 296.4947509 | 1.145843787 | 1.127655107 |
| 20:30 | 298.0774934 | 296.3068112 | 1.109832791 | 1.127630384 |
| 21:00 | 297.8556482 | 296.1432881 | 1.108132661 | 1.127597593 |
| 21:30 | 297.6625988 | 295.9991196 | 1.106956083 | 1.127564867 |
| 22:00 | 297.5139077 | 295.8705051 | 1.139196357 | 1.127543331 |
| **Average** | 301.5701107 | 298.4542677 | 1.167648712 | 1.128662207 |
| **Maximum** | 305.1227098 | 301.7286255 | 1.231769746 | 1.145758751 |
| **Minimum** | 297.033902 | 294.9681679 | 1.133211776 | 1.123504294 |

Table B.2 Daily temperatures and wind speed values during summer and winter for the enhanced scenario

| Time | Temperature Summer | Temperature Winter | Wind Summer | Wind Winter |
|---|---|---|---|---|
| 8:00 | 296.5275949 | 294.4272984 | 0.95958885 | 0.960659834 |
| 8:30 | 297.4081233 | 294.8119461 | 0.954029917 | 0.95375374 |
| 9:00 | 298.7940481 | 295.4674069 | 0.949682895 | 0.950562535 |
| 9:30 | 300.3789322 | 296.2610062 | 0.946342936 | 0.946508795 |
| 10:00 | 301.8246227 | 297.1736518 | 0.94324633 | 0.94309633 |
| 10:30 | 302.6775085 | 298.0751701 | 0.94427133 | 0.940863366 |
| 11:00 | 303.4188249 | 298.8998167 | 0.95789355 | 0.938275 |
| 11:30 | 303.862242 | 299.919504 | 0.966548338 | 0.936765997 |
| 12:00 | 304.1786118 | 300.7041959 | 0.983616967 | 0.935753047 |
| 12:30 | 304.5514193 | 301.2149591 | 1.002092798 | 0.934961565 |
| 13:00 | 304.6445741 | 301.6411574 | 1.020347161 | 0.934004363 |
| 13:30 | 304.6986006 | 301.833376 | 1.036238296 | 0.933636357 |
| 14:00 | 304.6917344 | 301.8672274 | 1.047440512 | 0.933712465 |
| 14:30 | 304.4983702 | 301.7280812 | 1.053741066 | 0.933925762 |
| 15:00 | 304.2845683 | 301.5325482 | 1.054942659 | 0.935769114 |
| 15:30 | 303.9653734 | 301.0665136 | 1.051330471 | 0.93778885 |
| 16:00 | 303.5279418 | 300.394319 | 1.0411491 | 0.939440997 |
| 16:30 | 303.0074467 | 299.5915729 | 1.021194598 | 0.940856233 |
| 17:00 | 302.183963 | 298.6622024 | 0.996926177 | 0.942132895 |
| 17:30 | 301.1416134 | 297.7063202 | 0.977040997 | 0.943225693 |
| 18:00 | 299.9456433 | 297.1089521 | 0.962992452 | 0.94398982 |
| 18:30 | 298.8437953 | 296.6877334 | 0.953757548 | 0.944406994 |
| 19:00 | 298.249759 | 296.3558 | 0.947929224 | 0.944544668 |
| 19:30 | 297.8442913 | 296.084051 | 0.944436773 | 0.944481233 |
| 20:00 | 297.5276864 | 296.084051 | 0.942496399 | 0.944481233 |
| 20:30 | 297.2668849 | 295.6624385 | 0.94156385 | 0.944149238 |
| 21:00 | 297.044817 | 295.4943133 | 0.941247022 | 0.94397126 |
| 21:30 | 296.85067 | 295.3466068 | 0.941279086 | 0.94379169 |
| 22:00 | 296.6773334 | 295.2151078 | 0.941495776 | 0.943607548 |
| Average | 301.0523101 | 298.1730113 | 0.980167692 | 0.941831608 |
| Maximum | 304.6986006 | 301.8672274 | 1.054942659 | 0.960659834 |
| Minimum | 296.5275949 | 294.4272984 | 0.941247022 | 0.933636357 |

Table B.3 Daily temperatures and wind speed values during summer and winter for the worst case scenario

| Time | Temperature Summer | Temperature Winter | Wind Summer | Wind Winter |
|---|---|---|---|---|
| 8:00 | 296.5607302 | 294.3424066 | 1.841428947 | 1.841353324 |
| 8:30 | 297.5906965 | 294.6449325 | 1.840751108 | 1.840682064 |
| 9:00 | 298.5673316 | 295.0531693 | 1.841290997 | 1.84120374 |
| 9:30 | 300.2444316 | 295.5301739 | 1.842486288 | 1.842694875 |
| 10:00 | 301.9012057 | 296.0488893 | 1.844455055 | 1.844986704 |
| 10:30 | 303.1484458 | 296.6146675 | 1.850454778 | 1.847954294 |
| 11:00 | 303.8498232 | 297.2571716 | 1.860630748 | 1.851499931 |
| 11:30 | 304.459066 | 298.2670429 | 1.873982756 | 1.855444529 |
| 12:00 | 304.9597447 | 299.3342227 | 1.889641828 | 1.859728186 |
| 12:30 | 305.3523234 | 300.1750936 | 1.906764751 | 1.864299861 |
| 13:00 | 305.5575175 | 300.7493028 | 1.923802562 | 1.86899903 |
| 13:30 | 305.6367852 | 301.0693034 | 1.939582756 | 1.87375831 |
| 14:00 | 305.6759163 | 301.1623668 | 1.953861011 | 1.878791551 |
| 14:30 | 305.5596315 | 301.0656492 | 1.966558795 | 1.884315028 |
| 15:00 | 305.3269357 | 300.8413174 | 1.977561219 | 1.890111565 |
| 15:30 | 304.9901272 | 300.5607407 | 1.986559003 | 1.896071053 |
| 16:00 | 304.6229438 | 300.2000815 | 1.993330679 | 1.902130679 |
| 16:30 | 304.3245004 | 299.7461885 | 1.99738795 | 1.908256648 |
| 17:00 | 303.7827754 | 299.1915895 | 1.996967244 | 1.914437742 |
| 17:30 | 302.9615499 | 298.5662414 | 1.991540859 | 1.920661427 |
| 18:00 | 301.9506102 | 298.1482939 | 1.9852759 | 1.92698331 |
| 18:30 | 301.0277977 | 297.7955263 | 1.980685734 | 1.933392105 |
| 19:00 | 300.4481821 | 297.483725 | 1.978105748 | 1.93985644 |
| 19:30 | 299.9737123 | 297.2052108 | 1.977314751 | 1.946356994 |
| 20:00 | 299.5728807 | 296.9549679 | 1.978045083 | 1.95288338 |
| 20:30 | 299.2307155 | 296.72895 | 1.980100762 | 1.959432479 |
| 21:00 | 298.9351047 | 296.5239787 | 1.983236357 | 1.96599349 |
| 21:30 | 298.6763084 | 296.3373362 | 1.987178601 | 1.972559003 |
| 22:00 | 298.4464947 | 296.1667072 | 1.991723892 | 1.9791241 |
| Average | 302.183941 | 298.0608706 | 1.936576075 | 1.896688339 |
| Maximum | 305.6759163 | 301.1623668 | 1.99738795 | 1.9791241 |
| Minimum | 296.5607302 | 294.3424066 | 1.840751108 | 1.840682064 |

**Appendix C**

Gradient maps extracted from output files representing the daily wind and temperatures patterns with 30 minutes saving intervals for all simulations. Samples are available beneath while all visuals are available on the soft copy.

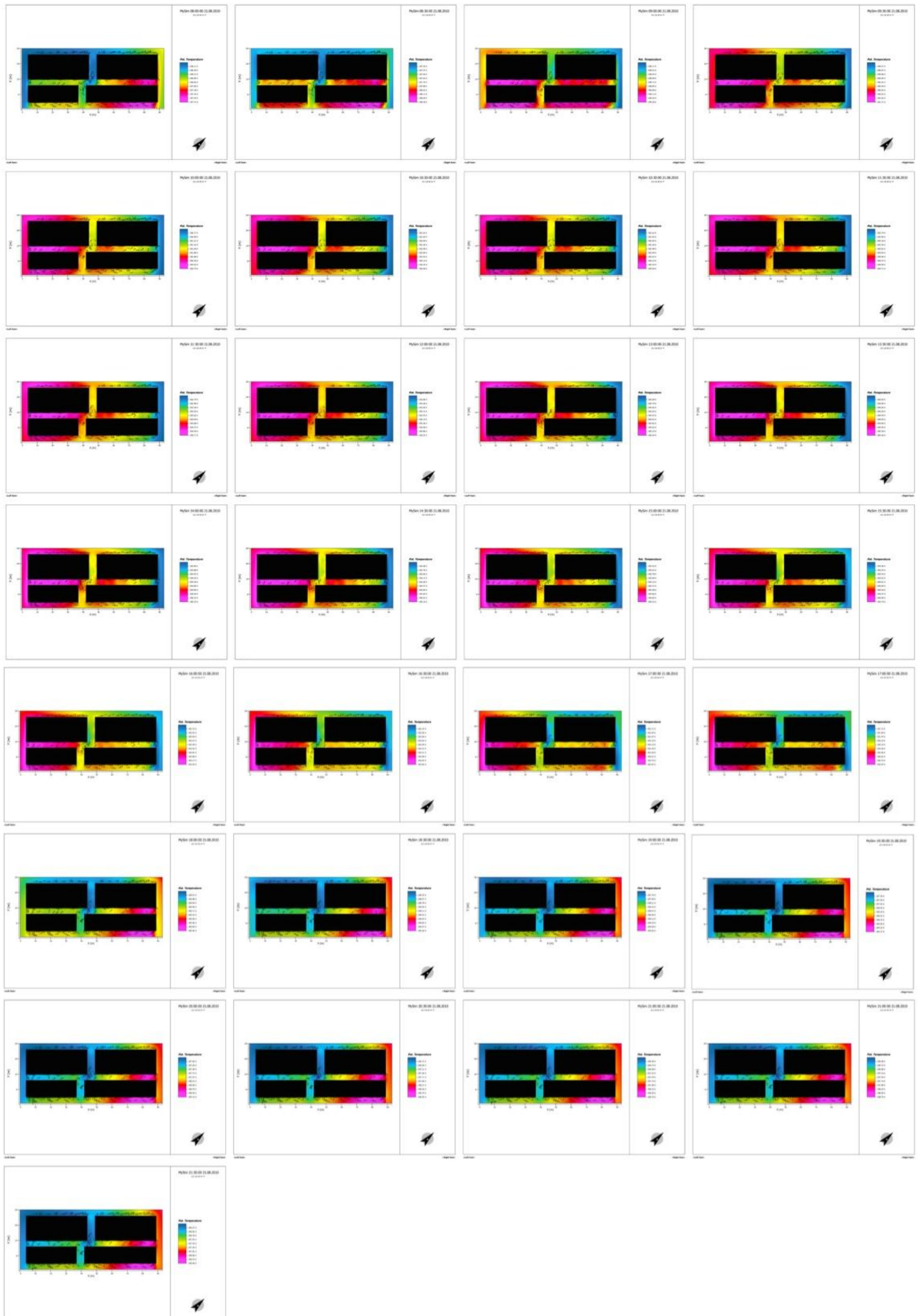

**Figure C.1 Daily temperature gradient every 30 minutes during summer for the existing scenario**

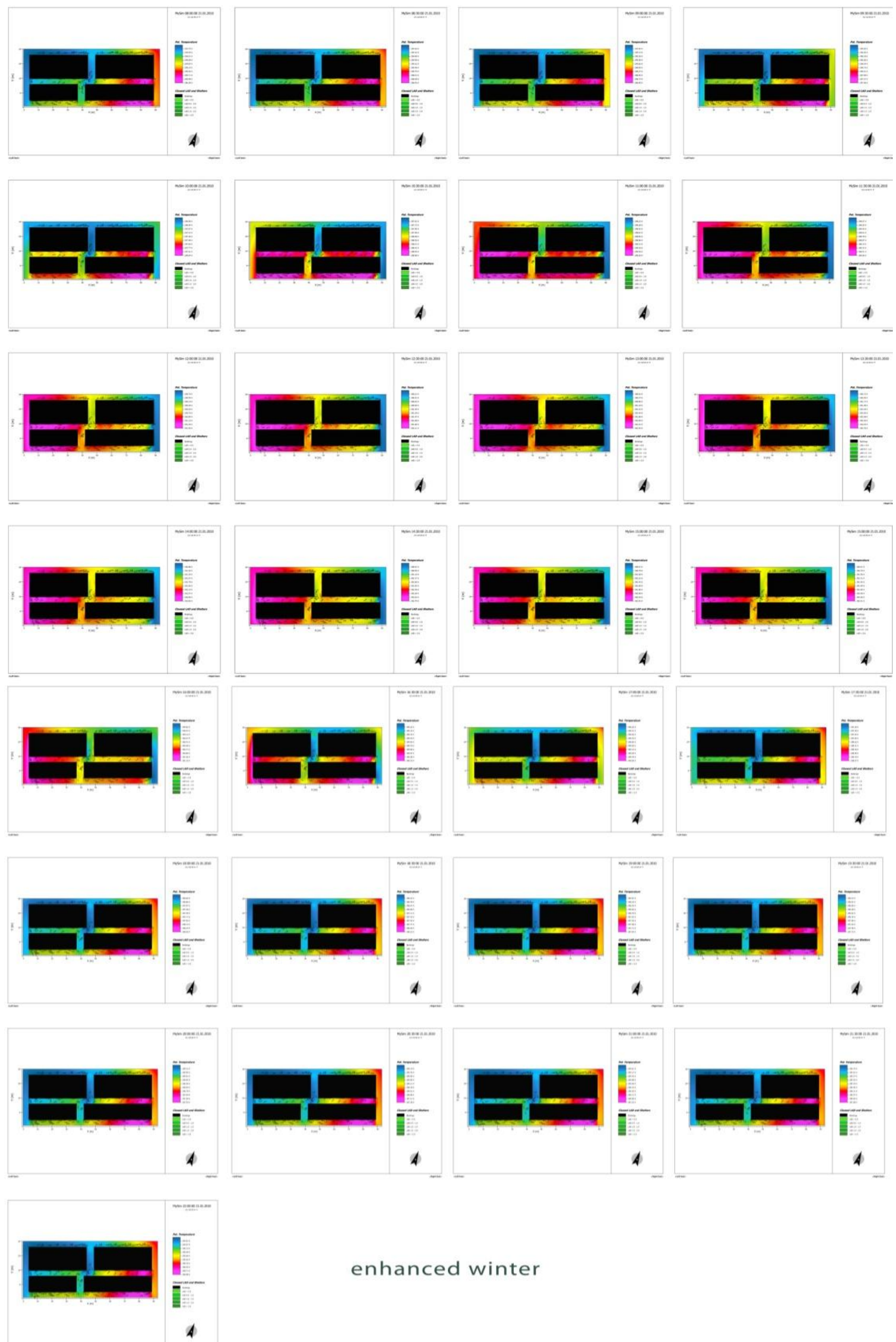


**Figure C.2 Daily temperature gradient every 30 minutes during winter for the existing scenario**

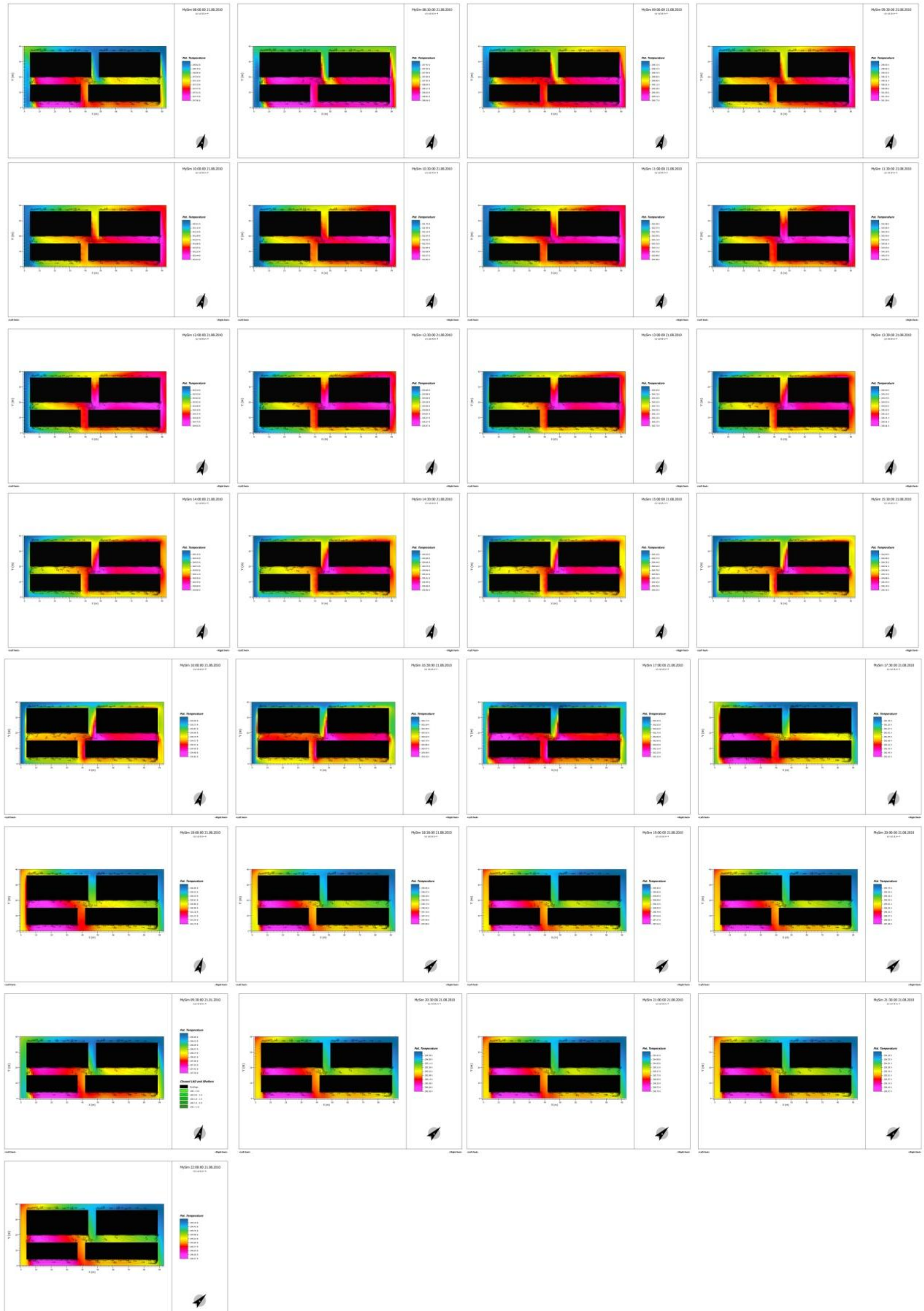

**Figure C.3 Daily temperature gradient every 30 minutes during summer for the existing scenario**

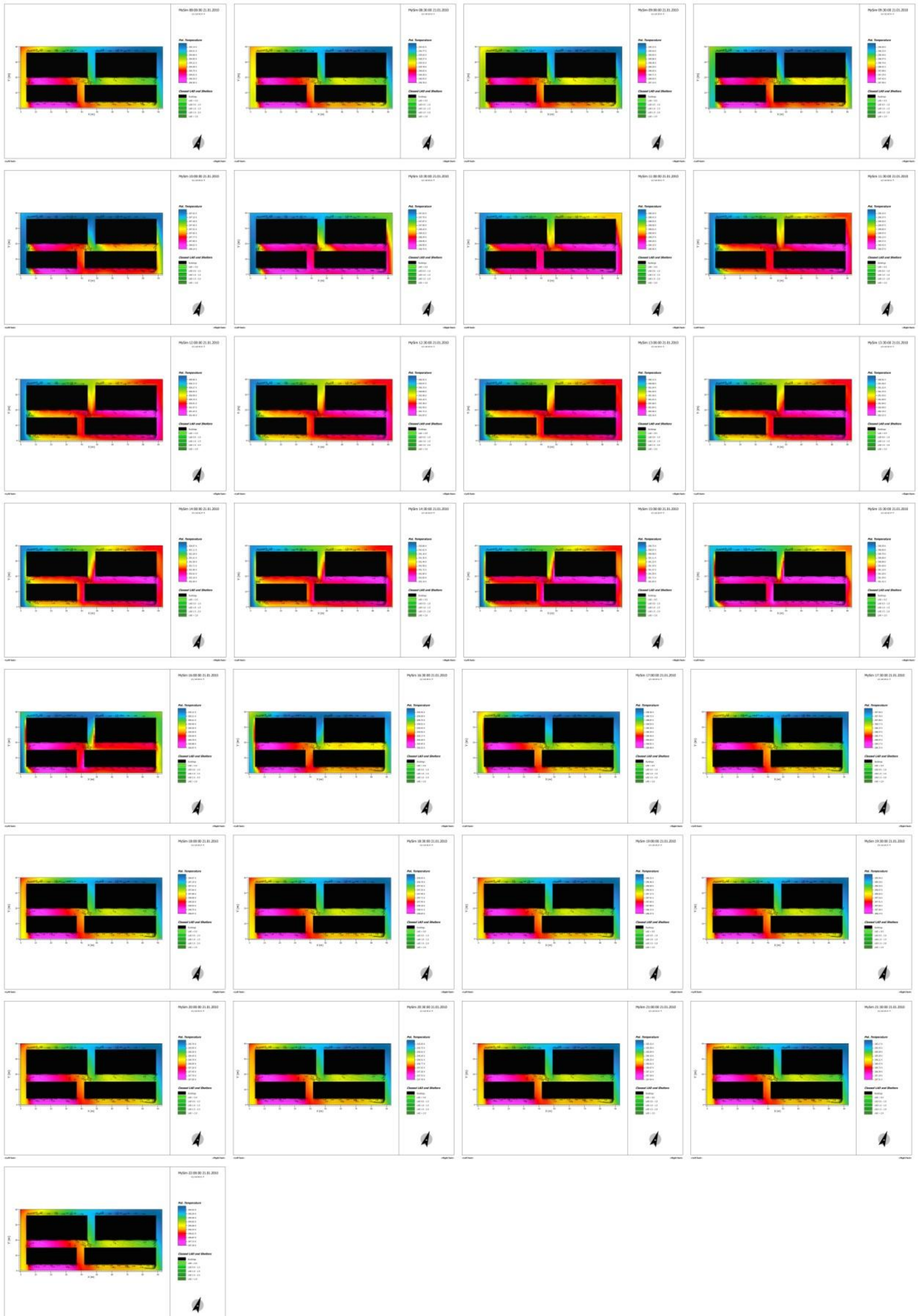

**Figure C.4 Daily temperature gradient every 30 minutes during winter for the existing scenario**

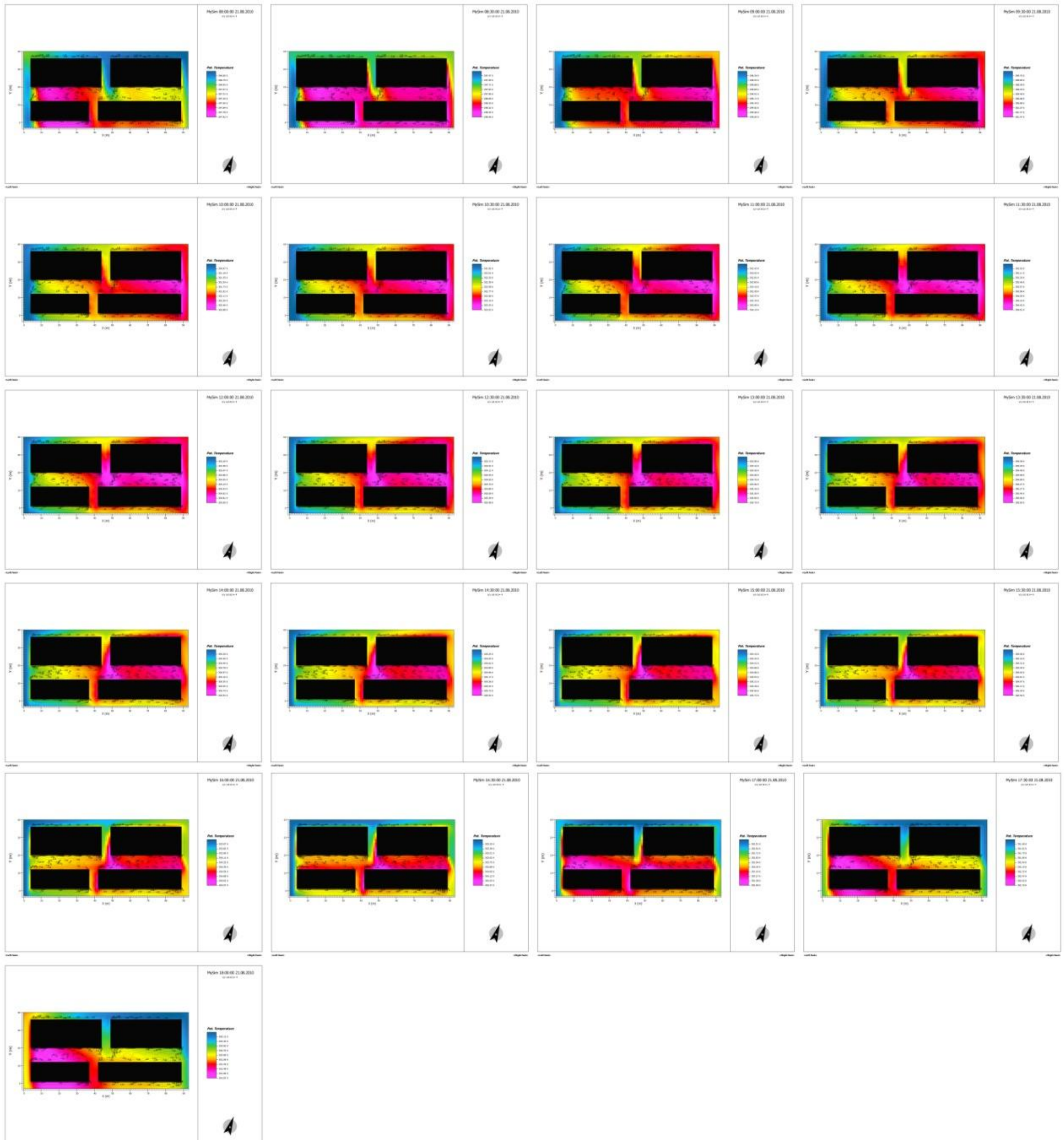

**Figure C.5 Daily temperature gradient every 30 minutes during summer for the 0.5 ratio**