The Impact of Urban Design Elements on Microclimate in Hot Arid Climatic Conditions: Al Ain City, UAE.

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Abstract

Improving microclimate can be a critical consideration when designing urban places, especially in hot arid climates, due to its relation to improving human comfort in outdoor places, mitigating urban heat island effect and reducing indoors air conditioning demand. This study set out to investigate the impact of urban design strategies on microclimate, specifically canyon ratio, orientation, vegetation shading and wind speed using the case study of Al Ain City in the UAE. Simulations using Grasshopper with OpenStudio, EnergyPlus and Radiance plugins were carried out, and the Universal Thermal Climate Index (UTCI) was employed. Larger canyon ratios (1 to 2) and North-South street orientation were found to produce more comfortable urban places. While shading surfaces were found to have the potential to reduce UTCI by 5^{o}C. Moreover, creating wind passages on the ground floor of the urban area was found to significantly enhance wind circulation in the scheme, reducing UTCI. This study can serve as an input for urban planning decision-making as well as provide guidance for urban designers in hot arid climates.

Keywords: Microclimate, universal thermal climate index, urban heat island, cooling demand, canyon geometry, urban vegetation

1. Introduction

Concern about microclimate in urban studies has increased since the 1970s (Santamouris & Asimakopoulos, 2005). While climate is defined as the average atmospheric conditions over a long period of time covering a large region, the term microclimate is used to describe small-scale climate patterns over a small area that are attributed to meteorological variables (Santamouris & Asimakopoulos, 2005; Robitu, Musy, Inard & Groleau, 2006; Bourbia & Boucheriba, 2010). These meteorological variables are often influenced by urban design elements, with urban geometry (urban canyon), materials and dissipation surfaces (green cover, water surfaces and soil) being the most impactful urban design elements on microclimate (Robitu, Musy, Inard & Groleau, 2006; Blazejczyk et al., 2013; Perini, Chokhachian, Dong & Auer, 2017).

Microclimate is directly correlated with urban heat island effect (UHI), a phenomenon where urban areas air temperature is higher than the surrounding suburban and rural area. The temperature difference between rural and non-rural areas, which is known as UHI intensity, can be as high as 15^{o}C (Santamouris & Asimakopoulos, 2005). Such increase in temperature contributes to increasing the energy consumption in buildings due to a rise in cooling demand. For instance, while a study by Salvati, Coch Roura, and Cecere (2017) estimates that 18-28% of the cooling load could be attributed to UHI, other studies reveal that this percentage could be as high as 50% (Hassid et al., 2000 Santamouris & Asimakopoulos, 2005).

Improving microclimate not only reduces energy consumption in buildings, but it can also reduce health issues related to heat stress as well as create more inhabitable urban spaces through increasing human comfort. This is especially important for extreme climates such as the hot arid climate of the Emirates. Initial simulation using Ladybug in grasshopper with EnergyPlus weather data file of Abu Dhabi weather station shows that there is high heat stress in more than 40% of the year (figure 5); which is defined as the periods that have above 32 ^{o}C according to (Blazejczyk et al., 2013; Bröde et al., 2012; Al Shaali, 2013)

Despite the growing research in urban microclimate, establishing quantifiable links between urban design elements/strategies and human comfort, as represented in the Universal Thermal Climate Index (UTCI), is still an emerging field. This is especially true in climatic conditions such as that of the Emirates. Therefore, this research aims to investigate the impact of urban design strategies on microclimate in hot arid climatic conditions, using the case of Al Ain town Centre, United Arab Emirates. The main scope of this research is to determine the impact of canyon ratio, street orientation, shading surfaces and wind speed on microclimate outdoor comfort (measured with UTCI), while reflecting on the effect these strategies can have on indoors air-conditioning peak load demand.

Nomenclature

UTCI	Universal thermal climate index
CR	Canyon Ratio
GS	Green shading surface
RH	Relative Humidity
CFD	Computational fluid dynamics
x	Air temperature
y_x	UTCI at air temperature x

1.1 Microclimate Definition, Main Variables and Importance in Mitigating Urban Heat Island Effect

Microclimate is a term used to describe small-scale pattern of climate conditions on a specific space. Four meteorological elements are used to evaluate microclimate: relative humidity (RH), wind speed, solar radiation (long wave and short wave) and air temperature. The change in microclimate from one zone to another in a small area is because each of these meteorological descriptors is influenced by certain urban design elements in the space. Lin et al., (2017) specify that the most influential urban design elements on micro climate are urban geometry, landscape materials and the presence of surfaces that dissipate heat, such as green and water elements. Each of the main three urban design elements has impacts on the four meteorological descriptors of microclimate. Urban geometry can impact the wind speed by either accelerating or buffering it. The geometry of buildings can also trap solar radiation through multiple reflections, which influence air temperature. Moreover, the presence of dissipation surfaces influences the saturation of air with water particles (relative humidity), as well as impact air temperature through evapotranspiration and providing shading from solar radiation. Meanwhile, the materials' ability to store heat (heat capacity) and reflect solar radiation (albedo) have significant impacts on surface temperature, which in turn impacts air temperature through convection and conduction. Figure 1 displays the connection between the main urban design elements and parameters of microclimate.

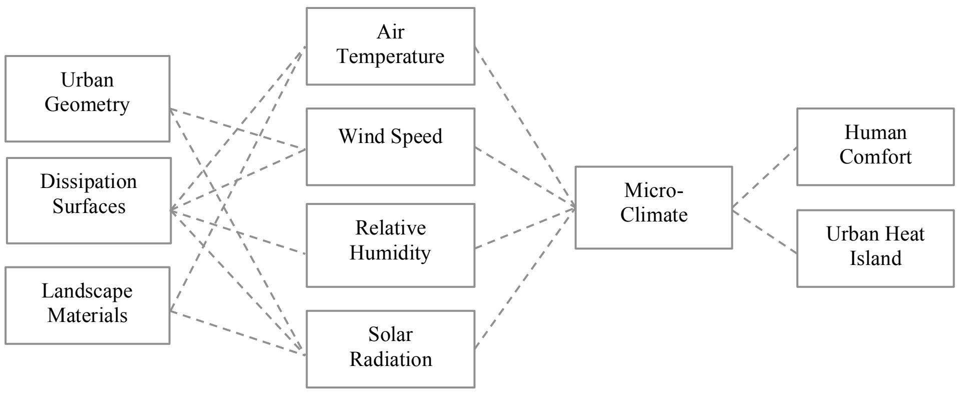


Fig. 1 Urban design elements and micro-climate parameters, and their impacts on UHI and human comfort

UHI has been a growing concern over the last few decades due to its effect on increasing energy consumption, climate change, as well causing heat-stress related health issues. In Athens, for example, Hassid et al. (2000) evidenced that similar buildings (construction type and scale wise) were found to have 50% more energy consumption in the city centre than buildings outside the city. A study by Santamouris and Georgakis (2003) showed that the difference in temperature between urban and rural areas (UHI intensity) can reach up to 16^{o}C. Simulations by Salvati estimate that UHI is responsible for 18-28% of the total cooling demand in Hong Kong (Lin et al., 2017), while Akbari et al. recognized that 3-8% of electricity demand in the US is used to compensate for UHI effect (Santamouris & Asimakopoulos, 2005). There is a wide consensus among researchers that UHI effect is mainly attributed to the canyon effect (which traps the emitted long-wave solar radiation and blocks wind circulation), loss of dissipation surfaces (green and water surfaces), hardscape materials (low albedo and high latent heat storage capacity) (Giridharan, Lau, & Ganesan, 2005). It is clear that the variables that impact the microclimate are the same ones that control the UHI effect, which means that the accumulating effect of improving microclimate in multiple urban places would not only create more comfortable urban places, but also significantly contribute to mitigating the UHI effect.

1.2 The Impact of Urban Design Elements on Microclimate: Urban Vegetation

Urban vegetation is a major urban design tool in regulating microclimate. In cooler climates, it serves as a buffer of undesirable wind when oriented correctly (Lin et al., 2017), and in hotter climates it reduces air temperature through evapotranspiration, shading and direction of wind (Lemes de Oliveira, 2017). Trees are found to be more effective in improving microclimate than grass due to their higher transpiration rate and their shading effect (Santamouris & Asimakopoulos, 2005). Furthermore, Perini and Magliocco (2014) estimate that vegetation has an albedo (ability to reflect long-wave solar radiation) of 0.2-0.3, which is much higher than hardscape surfaces like asphalt, with albedo of 0.05. This adds to vegetation's ability to improve the microclimate. They also recognized that the hotter the climate the more impactful vegetation becomes in reducing temperature, which have been shown to range from 2-3 ^{o}C in Mexico City (Jauregui, 1990) to 2-8 ^{o}C in Los Angeles (Taha et al., 1991).

1.3 The Impact of Urban Design Elements on Microclimate: Canyon Geometry

Canyon geometry is a term introduced by Oke in 1981 to relate the building height, street width and its length to each other (Lin et al., 2017). Studying the relationship between canyon geometry and the microclimate has been the subject of several researches, which attempted to specify the ideal height to street width ratio from a microclimate perspective (Toudert, & Mayer, 1997; Johansson, 2006; Giannopoulou, 2010). Some researchers also add street orientation to the variables (Toudert & Mayer, 1997; Taleb & Abu-Hijleh, 2013). The ideal canyon ratio recommended by such studies changes based on the climatic context of each area. Oke suggested, for instance, that an ideal height (H) over width (W) ratio is 0.4- 0.6 for mid-latitudes (H/W= 0.4 to 0.6). A study conducted in Athens in 2010 support these ratios, which concluded that the lower the ration the better the cooling (Giannopoulou, 2010). The enhanced cooling could be explained by the increased ventilation due to the wide distances between buildings, where wind is not blocked by compacted urban form. The large distances between buildings also mean that multiple reflections of the incoming short-wave solar radiation, and the re-emitted long-wave radiation are less likely, and therefore trapped heat carried by both long and short-wave solar radiation is reduced.

On the contrary, Johansson's study in Fez, Morroco (2006) shows that better cooling is achieved through higher ratio (more compact form) than the discussed above, which is supported by a previous study in Ghardaia, Algeria with similar climate (Toudert, & Mayer, 1997). This indicates that a more compacted urban form with deeper canyons would be desired. There could be several explanations for these contradictory recommendations. While a compact urban form tends to trap heat and block wind ventilation, it also often presents higher shading factors. Therefore, it seems likely that in Fez and Ghardaia, the shading factor is more effective as a cooling strategy than wind ventilation. In turn, in Athens wind ventilation seems to be more critical than sun shading when it comes to reducing air temperature. This could be attributed to the differences in climate characteristics. Although the three cities are in mid-latitudes, Athens' climate is less dry and slightly cooler than Fez and Ghardaia. In Dubai, an urban configuration that allows for better wind circulation (organic configuration) was found to reduce air temperature by more than 0.5^{o}C (not the UTCI temperature) compared to a less permeable configuration (orthogonal) (Taleb & Abu-Hijleh, 2013).

1.4 Universal Thermal Climate Index (UTCI)

UTCI temperature is not only dependent on the environmental conditions (meteorological variables), but also on gender, body mass, physical activity as well as clothing level. All these variables impact the human thermo-physiological response (Blazejczyk et al., 2013). Consequently, in 2000, the International Society of Biometeorology formed a commission for establishing a quantity to identify human perception of temperature (Bröde, n.d.). In 2009, the international and multidisciplinary group of experts in thermo-physiology, physiological modeling, meteorology and climatology developed the Universal Thermal Climate Index (UTCI). It is a one-dimensional quantity that measures human psychological response to actual thermal conditions, which is determined by multidimensional variables. The quantity is supposed to be valid for all climatic conditions, seasons and genders (Blazejczyk et al., 2013; Bröde et al., 2012; Jendritzky, de Dear & Havenith, 2012). This means that a UTCI of 24^{o}C would feel the same in the United Kingdom as it does in Morocco or in Brazil. UTCI model takes the input variables of wind speed, relative humidity, air temperature, mean radiant temperature, clothing level (measured by clo) and metabolic rate (MET) and calculate an equivalent temperature that considers these variables. The matrixes involved in the UTCI accounts for the differences caused by gender, age and weight (Bröde et al., 2012).

2. Methodology

In order to access the impact of canyon ratio, canyon orientation, shading by vegetation, and wind speed on Microclimate comfort; simulation using EnergyPlus and Open Studio was carried out. The results of the both simulations were combined and visually presented using Grasshopper. This integrated modelling approach allows for estimating the impact of building materials on micro-climate comfort as well as energy consumption. The simulation was implemented in The Town Square of Al Ain City. UTCI has been used as the descriptive quantity for microclimate and comfort maps have been produced for the different conditions. Moreover, to estimate one possible impact of changing the urban design elements on energy consumption, simulation of the peak air conditioning demand throughout the year was conducted.

2.1 Simulation Model and Algorithm

Figure 2 displays the software simulation model and the main inputs and outputs. EnergyPlus and OpenStudio, integrated with Grasshopper, were used to produce the UTCI comfort maps and air conditioning peak load demand. First, the canyon geometry and materials were created in Grasshopper (table 1) and divided into thermal zones (floors). The building characteristics and the analysis period, along with the meteorological variables (Wind speed, mean radiant temperature MRT, Air temperature, relative humidity) that have been extracted from Abu Dhabi weather station data file (.epw), has been input into EnergyPlus. EnergyPlus allows for layer-by-layer simulation of energy transfer through buildings' construction materials (EnergyPlus, 2018). It has been used in this study to simulate the peak required cooling demand for the buildings, energy gains and losses, indoor surface temperature, and the solar analysis of the glazing. The results of the simulation have been extracted in the form of .csv and imported into OpenStudio, where advance daylight assessment is included to simulate the outdoor surface temperature, including the outdoor context geometry and shading surface. This advanced daylight assessment also simulates the view factor, which is a necessary input to calculate and visualise UTCI in Grasshopper through its Outdoor Comfort Calculator Component.

Open Studio is a software that allows for whole building energy modeling through inclusion of advanced daylight analysis. It has been developed by the US Department of Energy and the National Renewable Energy Laboratory, and its validity has been supported by several articles (Roth, Brackney, Parker, & Beitel, 2016; Macumber, Ball, & Long, 2014). EnergyPlus has been verified by multiple published articles, including ASHRAE journal (Crawley, Lawrie, Pedersen & Winkelmann, 2000). Grasshopper Outdoor Comfort Calculator Component (in Ladybug Plug-in), were UTCI values are calculated and visualized, uses the source code of the equations developed by The International Society of Biometeorology in attempt to quantify human comfort through UTCI (Matzarakis, Mayer, Chmielewski, 2010; Jendritzky, Havenith, Weihs, Batschvarova, & DeDear, 2008; Perini et.al., 2017). Grasshopper is an algorithm-based plug-in for Rhinoceros. It allows users with no coding experience to manage, manipulate and visualize data through its visual interface. Figure 2 shows a diagram of the implemented tools, and figure 3 displays a portion of the simulation Algorithm in Grasshopper.

Several researchers have generated micro-climate comfort maps using Grasshopper (Perini et.al., 2017; Chokhachian, Santucci & Auer, 2017); however, they used TRNSYS as the simulating tool for energy transfer through building construction, and ENVI-Met to account for computational fluid dynamics (CFD) and vegetation. Both software performances are well verified. In this paper, a clothing level of 1 clo (a three-piece suit) was used as a constant in the comfort simulations, which is an assumption that is based on mild winters and that the clothing level in summer does not decrease due to the conservative culture of the city. A metabolic rate of 1 Met was assumed since leisure activities (slow walking and sitting) are targeted in the town square.

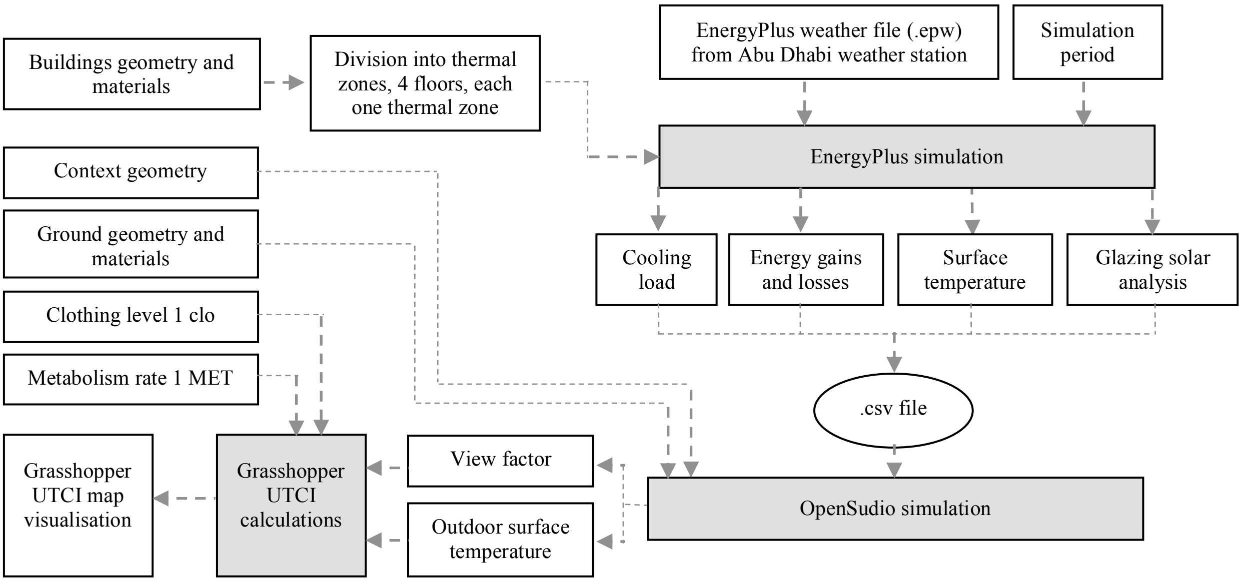


Fig.2 Diagram of the implemented software model with the main inputs and outputs

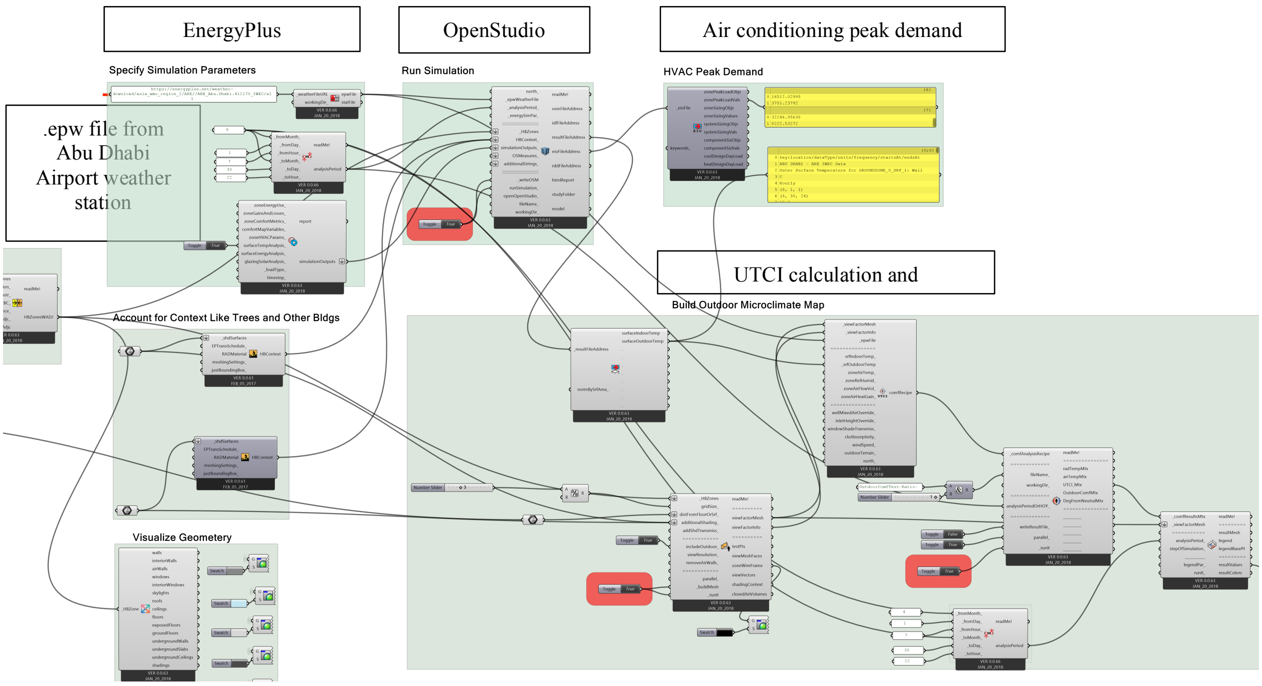


Fig.3 A portion of the algorithm in Grasshopper showing the integration of EnergyPlus with OpenStudio and the extraction of the simulation meteorological outputs into the UTCI calculator. Full script is available in data in brief, figure 1.

2.2 UTCI Model

The matrices and equations used inside the UTCI calculator in grasshopper are based on the equations from the UTCI-Fiala model. This is done through, first, modeling the heat exchanges within the body. Second, modeling the heat exchanges between the surface temperature of the body and the surrounding environment. Third, measuring the thermoregulatory reaction of the central nervous system and the perceptual response (Fiala, Havenith, Bröde, Kampmann, Jendritzky, 2012).

The calculations of the heat exchanges within the body includes three exchanges; the dynamic heat transfer within the body systems using Bioheat Transfer equation. This includes variables such as Arterial blood temperature and Tissue temperature. The second internal heat exchange is due to the resultant heat from blood circulation. While the third heat exchange within the body is the Metabolic Heat Production (Fiala, Havenith, Bröde, Kampmann, Jendritzky, 2012). These equations are calculated in the UTCI calculator in grasshopper based on the input data of metabolic rate and clothing level (1 MET and 1 clo in this research).

The EnergyPlus in Grasshopper simulate the resultant meteorological conditions that are impacted by the context variables; where the input meteorological data from .epw file are analyzed in the new context. These meteorological variables (Wind speed, mean radiant temperature MRT, Air temperature, relative humidity) are impacted by the Canyon ratio, orientation, the construction materials of the surrounding buildings and ground, and the vegetation shading elements (Milošević, Bajšanski, Savić, & Žiberna, 2016, p.25), and in (Roudsari, Pak, Smith, 2013). The new meteorological conditions are then used in the UTCI calculator to model the heat exchanges between the surrounding environment and body surface temperature; which has been calculated based on the metabolic rate and clothing level.

Finally, a thermoregulatory system equations are used to calculate the psychological responses of different conditions. This system measures the thermoregulatory responses of the human central nervous system to different conditions of transient, cold stress, cold, moderate, warm, and hot stress, in comparison with the steady state, as well as under different activity levels (up to heavy exercise), and actual sense of temperature values has been assigned (UTCI values). This system has been developed through physiological experiments (Fiala, Havenith, Bröde, Kampmann, Jendritzky, 2012).

2.3 Model Validation

In order to validate the Software simulation, a similar validation approach to Perini et.al. (2017) has been adopted. The field measurements of air temperature from Abu Dhabi weather station has been compared to the simulated air temperature of the model using EnergyPlus and OpenStudio combination in Grasshopper (data in brief, table1 and figure 2). Abu Dhabi weather station is located at 24°43' N, 54°65' E, and on an elevation of 27m (Weather Data Download - Abu Dhabi 412170, n.d.). The average measured hourly air temperature from 7 AM to 10 PM in August was compared to the average hourly simulated air temperature for the same period. The simulation was conducted on the no vegetation scheme with canyon ratio of 1, and at 1.6 m (human level).

It appears that the simulated values are very comparable to the field measurement ones, with an average error of 1.95% (average absolute error of 1.23 C^{o}) between the measured and simulated results at every hour. Higher accuracy is noticed at lower temperatures during night time (figure 4), where the software seems to overestimate the actual temperature. The measured data is at 27 m altitude, while the simulated data is at 1.6 m height (human level in the tests). The model simulates the ambient temperature in the context of the study with surrounding buildings that has the construction materials of table 1 and canyon ratio 1. Therefore, the main different variables between the simulated and measured data are the presence of shading elements, blocking the wind profile, the stored heat in the thermal mass of the buildings in the simulated case, and long wave radiation. These elements in the simulated case should contributes to increasing the ambient temperature, with the exception of the shading elements that can reduce the temperature. This could be an interpretation of why the simulated hourly ambient temperature is slightly higher than the measured one (data in brief, figure 2 and table 1). The graph shows that at evening hours the simulated temperature is very close to the measured data, which can be attributed to less differences in the variables between the simulated and measured data.

The low discrepancy between the measured and simulated data suggests a high validity of the simulation method.

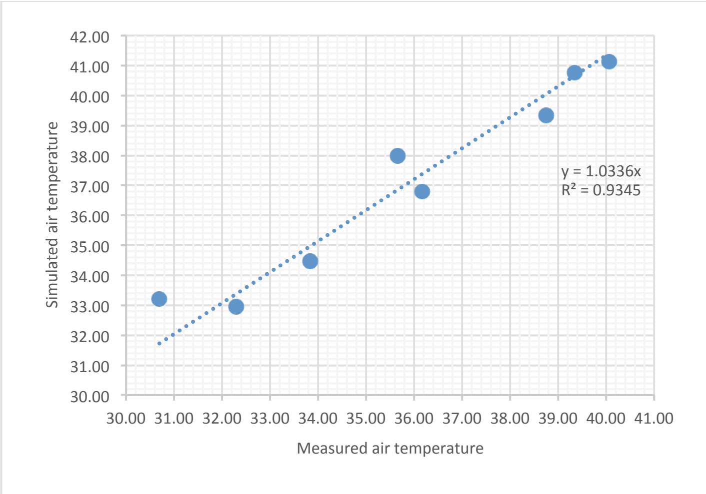


Fig.4 Validation of the simulation model. Low discrepancy between the simulated air temperature and the measured air temperature indicates a high validity of the model.

2.4 Test Period

April, August and December were selected to represent three different conditions of the year: moderate heat stress (26-32 ^{o}C, which is in April, May, October, November), extreme heat stress (above 32 ^{o}C, in June, July, August, September) and no heat stress (9-26 ^{o}C, in January, February, March, December). This has been assessed based on the data from EnergyPlus weather file (.epw) of Abu Dhabi weather station, visualized in Climate Consultant and Grasshopper (Ladybug, figure 5), and using the assessment of air temperature ranges by (Blazejczyk et al., 2013; Bröde et al., 2012; Al Shaali, 2013). It is possible to bring the hours that falls in the moderate heat stress range to comfort through passive strategies (Blazejczyk et al., 2013; Al-Shaali, 2013), and mitigate the high heat stress hours, where 43% of the hours have a risk of high heat stress (Figure 5). The simulations were averaged for each of the three months (April, August, December) for the period between 7:00 AM and 10:00 PM, which is the assumed occupation period of public spaces in the city centre of Al Ain (a mixed-use area). A similar testing approach of using a continuous test period is performed by (Taleb & Abu-Hijleh, 2013; Perini et.al., 2017).

2.5 Test Variables and Simulation Limitations

In order to understand how much wind speed can impact UTCI in a moderate heat stress range under constant relative humidity, mathematical modeling of the impact of different wind speeds (between 0 m/s to 10 m/s) on UTCI from 26^{o}C to 32^{o}C were conducted. The wind speed range was selected based on the initial assessment of climate characteristics of the area using Climate Consultant Software, where the dominant wind speed range was found to be between 2.5 m/s and 6 m/s (data in brief article, figure 4). These values fall within Lawson criteria for pedestrian comfort levels, where the range is 0 m/s to 10 m/s (Pedestrian Wind Comfort Analysis Report, 2016). Air conditioning peak load estimation was performed using EnergyPlus ideal air loads air system. This assumes 100% efficiency in removing heat and humidity from outdoor air to the requirement of the indoors. It does not consider the energy loss through heat transfer in air/water loops of the air conditioning system. While it is sufficient for the purpose of the study in quantifying how much urban design strategies impact the peak demand, it should not be used as design reference for air conditioning systems. The actual peak energy demands are expected to be higher.

Additionally, the simulation considered basic wind flow using wind speed from the Abu Dhabi epw. weather data file. It does not consider the complex computational fluid dynamics (CFD) in the analysis that would be influenced by geometry. For more accuracy, CFD component could be integrated in Grasshopper or, alternatively, ENVI-MET software could be used. Another limitation of the study is that a 1 clo level has been assumed for both the cool and hot months to simplify the simulation, and due to lack of studies concerning the local subjective thermal comfort and UTCI. An experimental field study of UTCI, such as the one performed by (Bröde et al., 2012) in Brazil as well as in Canada and Korea (Park, Tuller, & Jo, 2014), can be valuable in relating UTCI to the local subjective thermal comfort in the region.

Figure. 6 and 7 display the tests variables. First, the impact of canyon ratio was investigated through testing three canyon ratio (CR) configurations (0.5, 1 and 2 CR). Second, testing north-west, and south-east orientations was carried out. Third, the impact of shading by vegetation has been tested through comparing 16% and 32% effective shading surfaces with no shading configuration. Finally, the wind speed impact on UTCI was assessed using UTCI calculator in Grasshopper [developed by the International Society of Biometeorology in (Matzarakis, Mayer, Chmielewski, 2010; Jendritzky, Havenith, Weihs, Batschvarova, & DeDear, 2008; Perini et.al., 2017), by plotting wind speeds from 0.1 m/s to 6 m/s (the range of wind speed at the case study location according to Abu Dhabi weather station) against UTCI temperature. Which is conducted at constant relative humidity of 50% for every air temperature increment between 26-32°C (the moderate heat stress range).

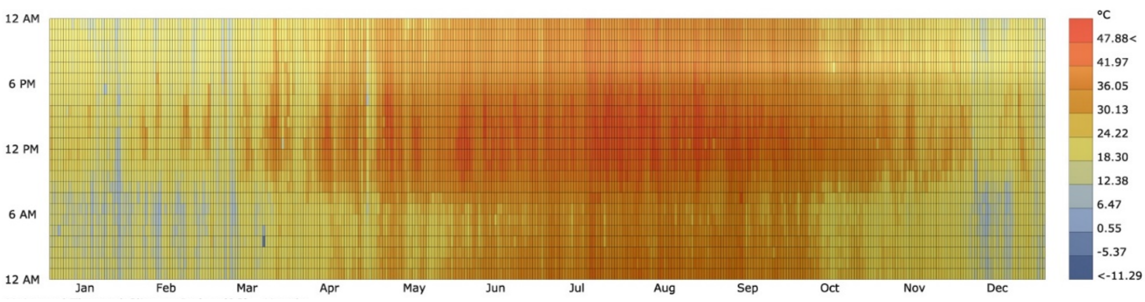


Fig.5 UTCI in Al Ain/ Abu Dhabi generated using Ladybug, Grasshopper, 43% of the hours have a risk of high heat stress.

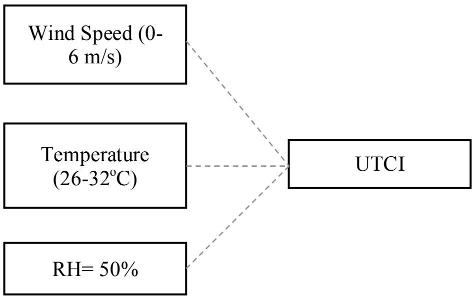


Fig.6 Modelling of the impact of wind speed on UTCI under constant RH.

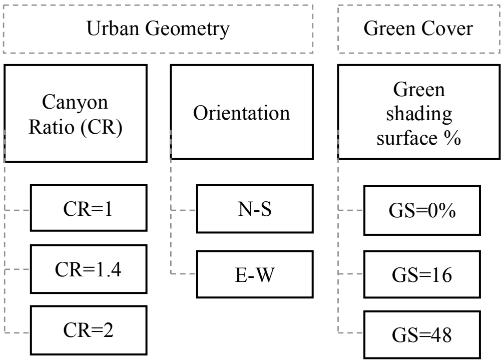


Fig.7 Tested urban design strategies in Al

3. Contextual Analysis

The city of Al Ain is located at 24.1302° N, 55.8023° E, and characterized by a sprawled urban fabric, which is to some extent a result of the lack of large-scale urban planning at the beginnings of the city's development, since Abu Dhabi (the main political region) Urban Planning Council was only founded in 2007. Moreover, the city has a policy of maximum allowed building height of four stories plus the ground floor, instilled by the founder of the country Sheik Zayed in order to preserve the city's cultural value (Yildirim & El-Masri, 2010). See Figures 8, 9 and 10 for the town square neighbourhood urban characteristics. As for the building characteristics, Figure 11 and table 1 display the buildings' geometry and materials in the town square, which have been used to build the model for simulation.

Fig.8 Al Ain town square street widths

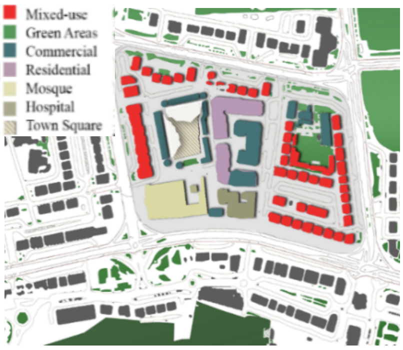


Fig.9 Al Ain town square, functional distribution

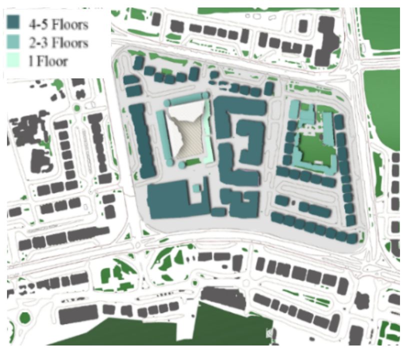


Fig.10 Al Ain town square, building heights

Table.1 Buildings construction materials

Construction Element	Construction Layers	u-value
Exterior wall	100 mm brick/ cladding 200 mm concrete block 50 mm insulation board Air space 19 mm Gypsum board	0.459
Window	3 mm clear panel 13 mm air space 3 mm clear panel	2.369

Roof	100 mm lightweight concrete Ceiling air space Acoustic tile	1.449
Ground (external) floor	50 mm insulation board 200 mm heavy weight concrete	0.556

Fig.11 Buildings geometry in the town square

4. Results and Discussion

4.1 The Impact of Canyon Ratio on Microclimate

In order to assess how much canyon geometry impact the microclimate comfort and energy consumption in buildings in Al Ain/ Abu Dhabi climate, a simplified model was created based on the contextual analysis. Four-story buildings are found to be the most common in Al Ain central district, therefore building heights of 14 m are used (3.5 m for each floor, ignoring slab thickness and parapet height). Street widths range from 7 to 35 m inside the neighbourhood and 50 to 55m outside. Therefore, street widths of 10, 14 and 28 m are tested to cover the different ranges and determine which is the most favourable ratio (Figure 12). Higher street widths are not included in this simulation due to the insignificant impact of buildings on each other at such large distances (decided based on a preliminary simulation). Table 2 summarizes the main simulation variables.

Table.2 Constant variables in the simulation of the impact of canyon geometry on microclimate

Street Orientation	**East-West**

Glazing percentage of the long façade	30%
Trees/ shading elements	None
Air-conditioning	Ideal air flow
Ground material	Asphalt
Buildings materials	Refer to table.1
Simulation height from the ground	1.5 m

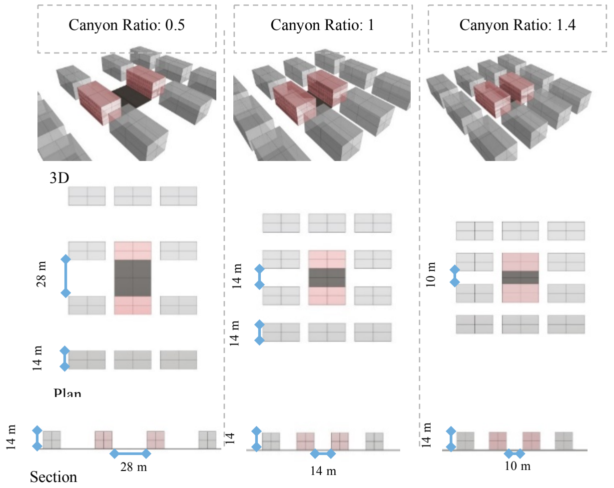


Fig.12 CR tests geometry

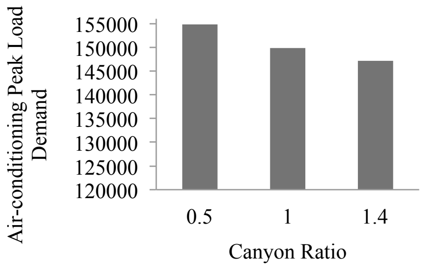


Fig.13 Air conditioning vs. canyon ratio

Figure.14 displays the outdoor microclimate comfort maps for the months April, August and December for canyon ration (CR) 1.4, 1 and 0.5. It is clear that higher canyon ratios, which characterise a more compacted urban form, is more suitable for hot arid climate. This aligns with the results by Johansson's study of urban geometry in Fez, Morocco (2006) as well as the study of Ghardaia, Algeria (Toudert, & Mayer, 1997), where both researches suggest higher canyon ratios between buildings at the hot climates. The larger canyon ratio would allow less wind filtration, but it appears that the shading factor is more critical than the cooling by wind.

At the hottest point in the outdoor space, the UTCI temperature in CR0.5 is higher by 0.79°C than in CR1 (in April) and it it is higher by 0.82°C in August, with no significant difference in December (Table 3 and Figure 14). This appears to be mainly to lack of shading by the buildings. At the coolest point of the outdoor space, which is the area close to the north façade of the lower block (Figure 14), the temperature difference is less significant between canyon ratio 0.5 and 1, with the maximum difference being 0.53°C in August. On the other hand, 0.5 CR is significantly higher in maximum temperature than 1.4 CR, with temperature difference as high as 1.25°C in August at the middle of the canyon and 0.53°C close to the northern façade (August). In December the canyon ratio seems to have no significant impact on the UTCI temperature. It is clear that the hotter the temperature, the more significant it is the impact of higher canyon ratio in reducing UTCI temperature.

Within canyon ratio 0.5, the temperature feels less by up to 3.62°C close to the northern façade than it does in the centre of the outdoor space, and less by up to 2.53°C than areas close to the southern façade (in April). This could be especially significant in allocating outdoor seating for cafes and restaurants, where in addition to other strategies the outdoor spaces can be brought to comfort in April and the similar months. In canyon ratio 1.4, the difference between the centre and the edges of the canyon is less prominent than in 0.5 CR, with 2.9°C difference in UTCI between the centre and the outdoor area close to the northern façade. While the impact of increasing the canyon ratio might not appear that significant in enhancing human comfort, its impact on reducing air conditioning peak demand is more apparent. With no additional strategies peak air condition demand can be reduced by 5% in a block when the canyon ratio is planned to be 1.4 instead of 0.5, and reduced by 3.2% between canyon ratios of 1 and 0.5 (figure.13). Any slight increase in peak load demand can have a considerable impact on the required equipment size for air condition, contributing to significantly higher equipment and operational costs. In Los Angeles, it was estimated that 5-10% increase in the peak energy demand caused by air condition cost the rate payers around 100 million dollars annually (Akbari, Pomerantz & Taha, 2001). The 100-million-dollar figure is from 2001 and do not account for inflation; hence the cost in 2018 would be around 142 million according to the inflation calculator by Saving.org.

Table.3 CR impact on UTCI

Month	**Max UTCI (Canyon centre)**			**Difference (°C)**		**Min UTCI (Close to N façade)**			**Difference (°C)**	
CR	0.5	1	1.4	$CR_{0.5}$-CR_1	$CR_{0.5}$-$CR_{1.4}$	0.5	1	1.4	$CR_{0.5}$-CR_1	$CR_{0.5}$-$CR_{1.4}$
April	32.25	31.46	31.06	0.79	1.19	28.63	28.33	28.16	0.30	0.47
August	43.91	43.09	42.66	0.82	1.25	40.45	40.14	39.92	0.31	0.53
December	20.06	20.06	20.02	0.00	0.04	18.53	18.53	18.90	0.00	-0.37

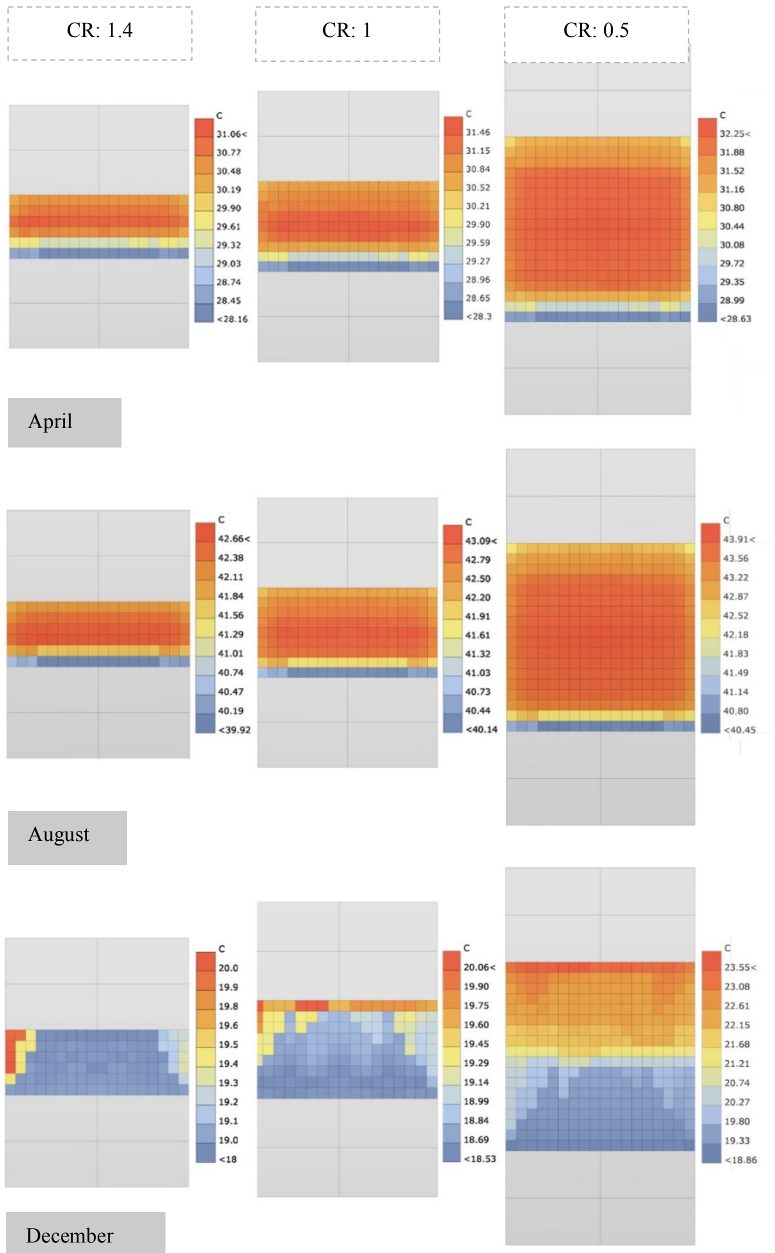


Fig.14 CR impact on UTCI test results

4.2 The Impact of Street Orientation on Microclimate

In order to examine which street orientation results in better outdoor comfort and energy consumption, testing of the same canyon ration (1 CR) was conducted for two orientations: long canyon axis north-south and long canyon axis east-west (Figure 15). Other model testing variables are similar to the testing of the impact of canyon geometry (table.4).

Table.4 Constant variables in the simulation of the impact of orientation on microclimate

Canyon Ratio	**1**
Glazing percentage of the long façade	30%
Trees/ shading elements	None
Air-conditioning	Ideal air flow
Ground material	Asphalt
Buildings materials	Refer to table.1
Simulation height from the ground	1.5 m

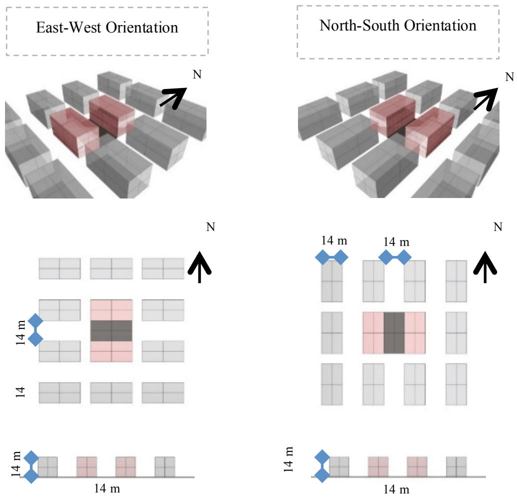


Fig.15 Street orientation test geometry

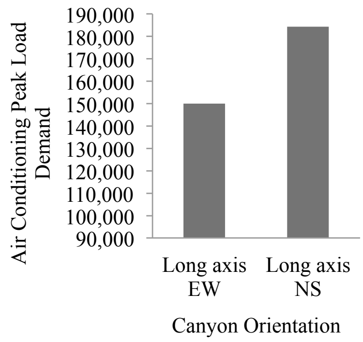


Fig.16 Air conditioning vs. street

The calculations showed that having the long axis of the canyon on the north-south orientation can lead to reducing the UTCI temperature by 2.35°C in April and by 2.53°C in August at the central zone of the outdoor space (Figure 17). In turn, in December the impact of canyon orientation seems less critical in comparison with hotter months, which shows that E-W orientation has an opposite impact in winter, creating a generally warmer environment by up to 1.35°C (Table 5). One explanation to the reduced impact in cooler months could be attributed to the lower solar elevation angle in winter, especially from south, where the highest altitude angle in December is 40° at noon, compared to 89 ° and 78 ° in April and August respectively (from Abu Dhabi weather station .epw file). This leads to longer shading from by the southern building on the canyon in the E-W orientation (figure 17). Meanwhile, the lower solar elevation angle in the N-W orientation is uninterrupted by the buildings, which explains why the temperature in the N-W canyon increased slightly the in December.

However, the North-South orientation of the canyon long axis (and the buildings with it) had a negative impact on the peak air-conditioning demand. The simulation shows that having the buildings longer façades facing east and west (long axis on North- South) can increase air conditioning peak demand by around 23% (figure 16). This result is mainly due to the fact that windows were only allocated on the longer facades in this simulation, regardless of the orientation. So, in the case or the North-South canyon orientation, the main glazed facades are facing East and West, which appears to cause more solar heat gain than having the main glazing on the northern and southern facades. Therefore, while it is advisable to allocate the main outdoor areas on a North-South street orientation, it is also critical to allocate the building longer axis on the East-West direction; meaning that the building longer facades would face north and south (refer to urban strategies section).

As mentioned in the impact of canyon ratio section, the coolest areas in the outdoor space are closer to the north façade in the E-W orientation. While in the N-S orientation the coolest areas are close to the Eastern façade. To sum up, it seems that having the longer axis of the public space on the north-south axis leads to a more comfortable urban environment in Al Ain/ Abu Dhabi climate; in April and August it reduces the UTCI temperature, while in December it slightly increases it.

Table.5 Street Orientation impact on UTCI

Month	**Max UTCI**		**Difference (°C)**	**Min UTCI**		**Difference**
orientation	NS	EW	CR_{EW}-CR_{NS}	NS	EW	CR_{EW}-CR_{NS}
April	29.11	31.46	2.35	28.27	28.33	0.06
August	40.56	43.09	2.53	39.82	40.14	0.32
December	20.79	20.06	-0.73	19.88	18.53	-1.35

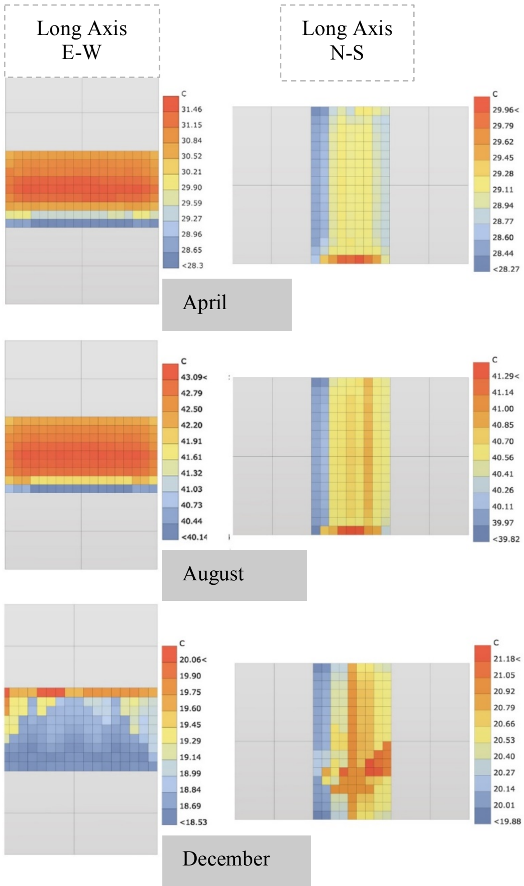


Fig.17 Street orientation impact on UTCI test results

4.3 Case Study Application: Impact of Canyon Ratio and Street Orientation on Micro Climate in Al Ain Town Square Neighborhood

In this section, applying the simulation on the actual geometry of the town square was conducted for the April month to test how representative the abstract scenarios are of the actual geometry. Subsequently, some strategies were proposed in the urban strategies section to enhance the performance and liveability of the town square.

An overview of the map shows that canyons with higher ratio (Section A, Figure.19) are significantly better performing than canyons with smaller ratio (section F), with difference of around 2-3^{o}C UTCI at the centre of the canyons. It also shows that at similar canyon ratios (Section B & C) N-S street orientation has a better cooling effect than E-W orientation. In addition, even a wider canyon in the N-S orientation perform better than a narrower street in the E-W orientation (section D and section A, and section D and E). The positive impact of the N-S orientation is also clear between sections F and G, with difference of around 3^{o}C UTCI between the central areas.

Fig.18 Tensile structure in Al Ain Town Square (AlMawed, 2018).

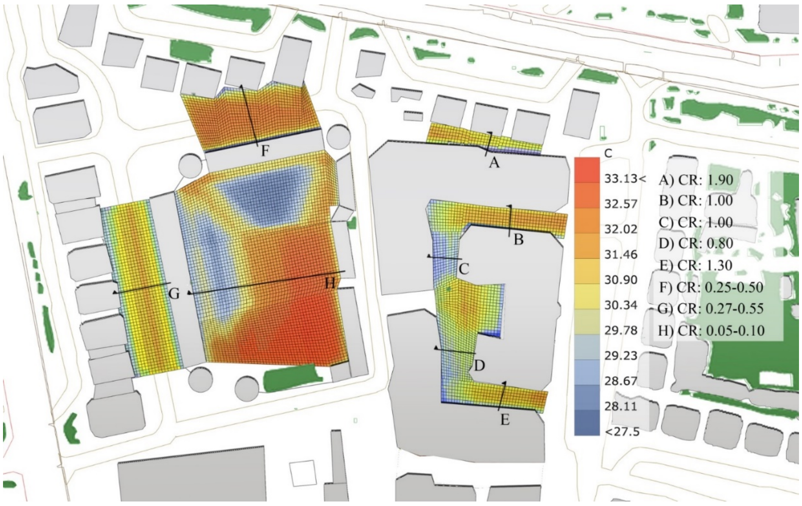


Fig.19 Application of UTCI micro-climate analysis on Al Ain Town Square Neighbourhood

Eastern and northern facades seem to be the coolest, and the large tensile structure that shades the outdoor space (Figure 18) seems to have very significant impact in cooling the outdoor space as it seems to make the outdoor space around 6^{o}C UTCI cooler. These tensile structures are one of the defining characteristics of the square and take inspiration from the Bedouin tents that were one form of vernacular architecture in the region.

4.4 The Impact of Shading by Vegetation on Microclimate

As discussed in the literature review section, many researchers agree that vegetation is one of the most impactful strategies in mitigating urban heat island and improve the microclimate. To test how much this strategy could improve the microclimate in Abu Dhabi/ Al Ain climate, simulations were conducted to compare green coverage of 16% and 48% (effective green coverage part) of the ground area, with the no shading case. The trees were assumed to have 3m clear height (6 m total height) and the effective shading volume is assumed to be 27m^2 (3x3), based on *Prosopis Cineraria*, a native tree in UAE (ICRAF, 2009), with leaf area density (LAD) 2.18 m^2/m^3 (Perini et.al., 2017). In this paper only the shading impact of vegetation is studied. The evapotranspiration impact was not included, where vegetation is treated as shading element only. Therefore, it is expected that the actual influence of the green cover could be significantly higher than the simulated one. Accordingly, other tree variables such as leaf temperature and leaf vapor flux were not studies. Figure 20 displays the three testing scenarios and Table 6 previews the constant variables in the test.

Table.6 Constant variables in the simulation of the impact of trees' shading on microclimate

Street Orientation	**East-West**
Canyon Ratio	1
Glazing percentage of the long façade	30%
Air-conditioning	Ideal air flow
Ground material	Asphalt
Buildings materials	Refer to table.1
Simulation height from the ground	1.5 m
Leaf area density (LAD)	2.18 m^2/m^3

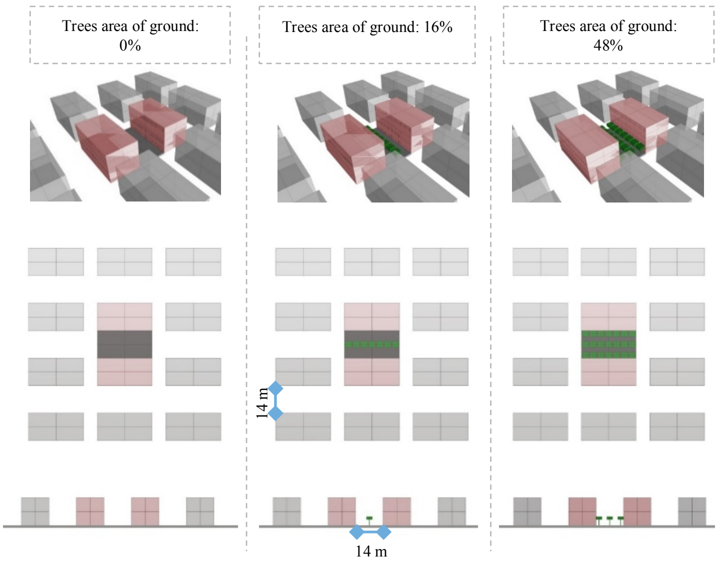


Fig. 20 Urban vegetation test geometry

Figure 23 shows the impact of introducing green shading on improving microclimate. The simulation shows that the temperature can feel up to 5°C less than without vegetation (Table 7). This result falls within the same range reviewed by other studies. Table 7 also shows that the higher temperature, the more impactful vegetation is. This agrees with Perini and Magliocco's (2014) observation about the increased impact of vegetation the hotter the temperatures. It should be pointed out that the literature reviewed measured the impact on air temperature, while this study uses UTCI temperature. However, the review can be used as an indicator that the simulated results are reasonable.

Table.7 Shading by vegetation impact on UTCI

Month	UTCI (maximum)			Difference (°C)		UTCI (minimum)			Difference (°C)	
Vegetation %	0%	16%	48%	$Veg_{0\%}$-$Veg_{16\%}$	$Veg_{0\%}$-$Veg_{48\%}$	0%	16%	48%	$Veg_{0\%}$-$Veg_{16\%}$	$Veg_{0\%}$-$Veg_{48\%}$
April	31.46	30.65	30.3	0.81	1.16	28.33	27.17	26.48	1.16	1.85
August	43.09	42.39	41.85	0.70	1.24	40.14	38.81	38.06	1.33	2.08
December	20.06	20.06	19.62	0.00	0.44	18.53	18.39	18.32	0.14	0.21

To further illustrate how much shading by greenery can add to microclimate, Figure 21 and 22 present how much each tested shading surface percentage can impact the felt temperature (UTCI). For Example, in April 0% shading, 78% of the total tested outdoor area feels like above 30 °C, while 22% of the total area feels between 28 and 30°C**.** However, when 48% vegetation is introduced, less than 15% of the total outdoor space feels hotter than 30°C, while quarter of the space feels between 28 -30°C and more than 60% of the total area have a mild heat stress, with a UTCI temperature range of 26 to 28°C. Figure 21 could also provide an approximate method to interpolate the expected impact of other green-cover percentages for April, and possibly the months with similar climatic characteristics (May, October and November). It could be used as an approximation method to roughly estimate how much shading surface should be used. For example, a 32% increase in vegetation surface would roughly make 40% of the outdoor space in the <28°C UTCI range, and decrease the outdoor area that feels 30°C> from 78% (at 0% shading) to 40%. Meanwhile, Figure 22 can be used to estimate the impact of vegetation in mitigating the intensity of heat stress in June, July, August and September.

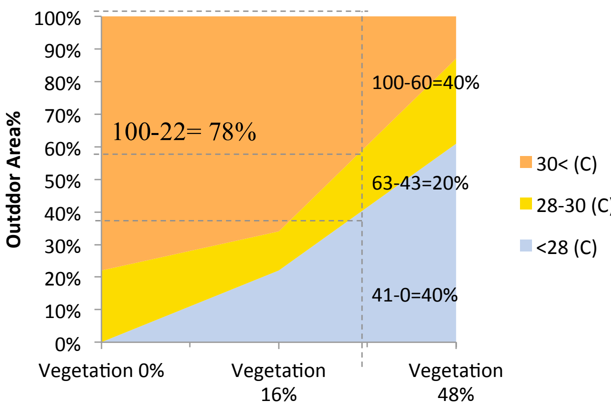


Fig.21 Shading surface% impact in April

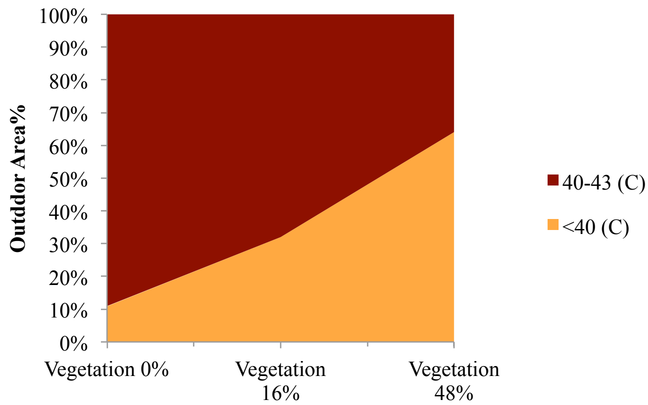


Fig.22 Shading surface% impact in August

On the other hand, the simulation shows no significant change in peak air conditioning demand. It appears that there is barely 1% reduction in peak demand between 0% (150 kW) and 48% (148.5 kW) vegetation, and around 0.15% reduction between 0% and 16% vegetation. These results contrasts with Akbari's book (2009) which shows a much higher potential for decreasing peak air conditioning demand. His work shows that in Phoenix (one of the closest examples to UAE climate characteristics), 12% to 17% saving in annual energy can be achieved through increasing the green cover by 10% to 25%. The reason for such variation is that

Akbari's study is conducted on one floor houses while this study is performed on a four-story building with a significantly higher cooling demand, and the shading effect of the trees mainly impacts the ground floor. This makes the impact of shading on cooling demand in this study not very significant when compared to the overall energy demand of the multi-story building. Moreover, the trees are positioned in shading position in Akbari study, while in this research the trees are shading one side of each building that form the outdoor envelope (Figure 20) since the main focus of the research is the impact on outdoor areas. This leaves the southern façade of one of the buildings nonshaded. Additionally, Akbari (2009) has included the evapotranspiration impact, which can significantly contribute to reducing cooling demand. He argues that in well-insulated buildings, the shading effect becomes less significant than the evapotranspiration effect; that out of the 17% cooling reduction in a well-insulated house in Phoenix, 10% reduction is caused by evapotranspiration and 7% by tree shading. He argues that in older, less insulated houses the tree shading effect becomes more important than the evapotranspiration one. Evidence of this can be seen in an older study by Simpson and McPherson (1998), where they simulated the impact of vegetation shading by planting three trees per house on 254 houses in California (around 25% increase in green cover), and around 7.1% reductions in cooling demand were achieved.

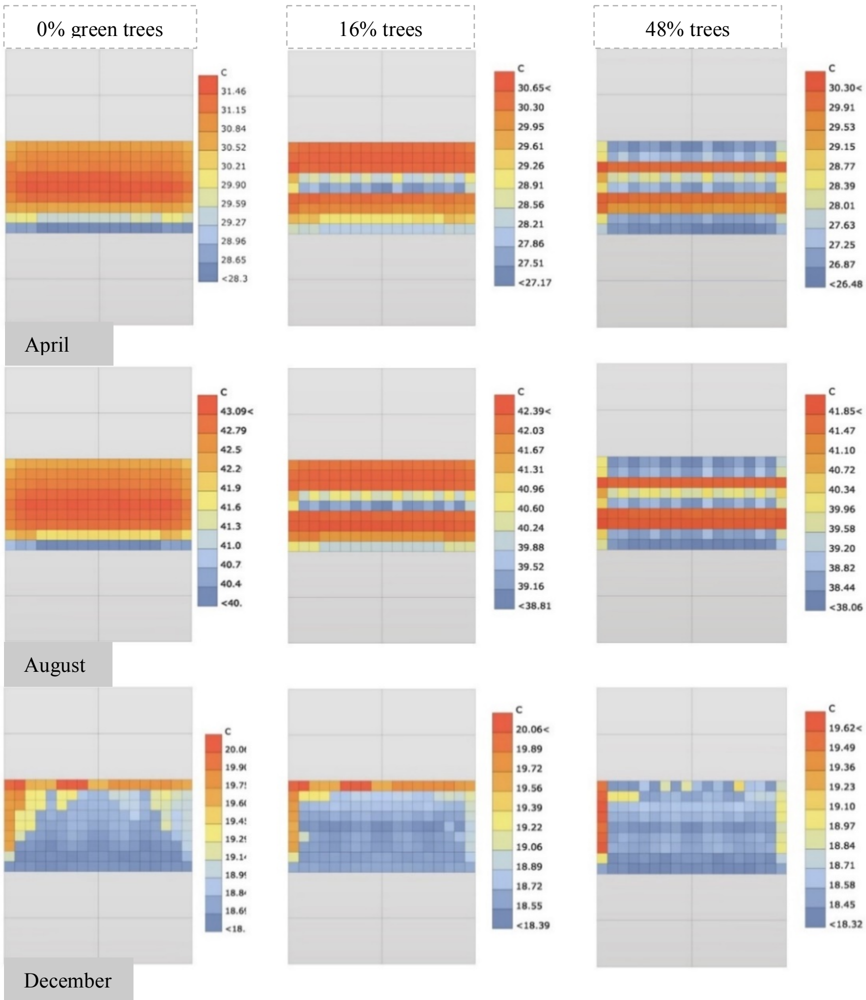
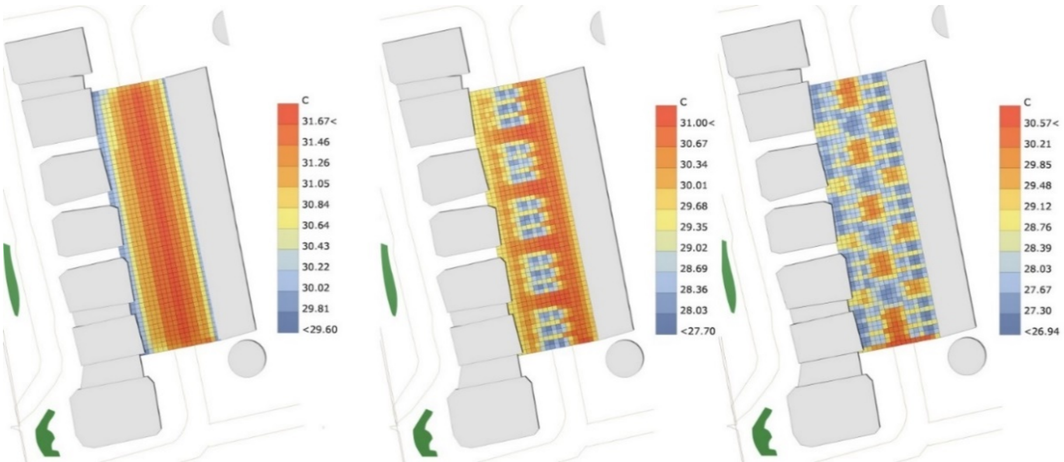


Fig.23 Shading by vegetation impact on UTCI test results

4.5 Case Study Application: Impact of Vegetation on Micro Climate, in Al Ain Town Square Neighborhood

One region of the neighborhood has been selected to apply the impact of vegetation on. Figure 24 displays the comfort map for section G, with no shading surface (A), 12% shading surface (B) and 35% shading surface (C). Under the shading surface the UTCI temperature can be lower by around 5^{o}C compared with no shading, making 50% of the outdoor area in the 26-28 ^{o}C (in the case of C, which is defined by Outdoor Comfort Calculator in Grasshopper as comfortable for a short-time temperature). Moreover, according to Al-Shaali (2013) this range can be brought to comfort through accelerated wind speed. He suggests that 27-30^{o}C temperatures can be made to become completely comfortable through accelerated wind speed (for UAE climate).



1. 0% shading
2. 12% shading
3. 35% shading surface

Fig.24Application on Al Ain Town Square Neighbourhood

4.6 The Impact of Wind Speed on UTCI

Wind dynamics around buildings forms complex flow patterns that could have contradictory impacts, such as acceleration and buffering of wind speed (Ishugah, Wang & Kiplagat, 2014). Some of these patterns of acceleration include corner jetting and downwash (Heywood, 2015). A compact urban form has the advantage of improving microclimate through shading, but it can also present a negative impact by blocking wind circulation. The literature review indicates that in hotter climates, compact urban forms are preferable over sprawled forms (smaller canyon ratio) even though the compact form compromise the ventilation effect. This indicates that wind ventilation should be integrated without compromising the shading effect.

Analysis through climate consultant of Al Ain/ Abu Dhabi climate showed that the prevalent wind direction throughout the year is from NW, with a speed ranging from 2 to 6 m/s (data in brief, figure 4).

Accordingly, a north-western wind of 2 m/s, 4 m/s and 6 m/s had been simulated (using Flow Design software) for Al Ain town square neighbourhood, to first observe the wind circulation in the scheme, then observe the impact of opening the ground floor of some of the buildings in the north western direction. The ground floor openings would enhance the ventilation in the outdoor areas without compromising the shading factor.

The applied wind direction was assumed to be un-buffered by other buildings outside the neighbourhood, where there are 50-55 m main streets separating the town square neighbourhood from the surrounding ones (refer to Figure 8). Moreover, only the prominent wind direction from the north west was considered. Additionally, UTCI comfort maps using the changed geometry were not generated due to time limitation. Figure 25 shows the existing geometry, while Figure 26 shows the changes made to allow more air circulation in the scheme. The wind simulation in Flow Design shows better ventilation with the edited geometry (Figure 27). When 2 m/s was applied, the original scheme showed very minimal wind circulation, which increased to become between 1 to 2 m/s with the new opening. Similarly, with 4 m/s initial wind velocity the air circulation in the area had been enhanced and reached a speed of 2.7 m/s. Meanwhile with 6 m/s, the wind speed in the scheme was as high as 6 m/s.

Fig.25 Existing geometry, very little air passages on pedestrian level

Fig.26 Edited geometry, some ground floors in NW turned to outdoor areas creating wind passages and increases the permeability to the

Meanwhile, Grasshopper (with Ladybug Plug-in, Outdoor Comfort Calculator) was used to record the possible impact changing wind speeds would have on how the temperature feels (UTCI), at a constant relative humidity of 50%, 1 clo and 1 MET (Figure 28). Wind speeds from 0 to 6 m/s were applied to temperature from 26 to 32^{o}C, which is the moderate heat stress range that is targeted to be brought to comfort as discussed previously. This range is mainly in April, May, October and November. In the Impact of Shading Surfaces section (4.5), simulations show that it is possible to bring more than half the outdoor space to the temperature range 26-28^{o}C through a shading 35% of the outdoor area (considering all the other constant variables), this indicates that the area could be brought completely to comfort through accelerating the wind circulation in the outdoor space.

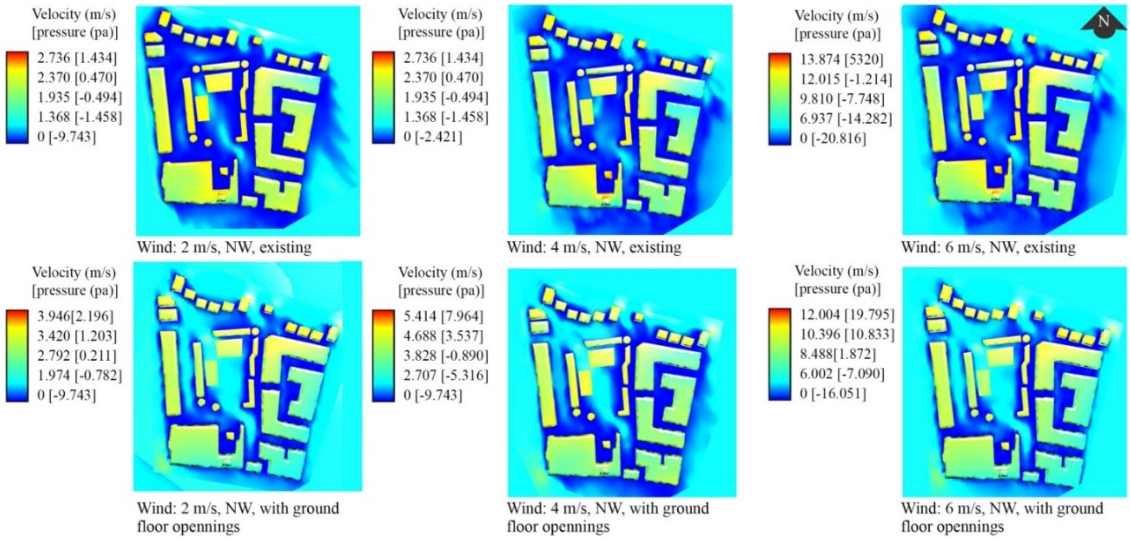


Fig.27 Wind circulation in the scheme for initial applied wind speed of 2 m/s, 4 m/s and 6 m/s from north west. It is clear that the edited geometry provides better wind ventilation for the scheme.

For example, if air temperature is 28 ^{o}C, a wind speed of 2.7 m/s would cause UTCI to be:

- y_{28} = -0.8853(2.7 m/s) + 28.776
- y_{28}= 26.39 ^{o}C UTCI.

For the same air temperature and a wind speed of 6 m/s:

- y_{28}= -0.8853(6 m/s) + 28.776= 23.46 ^{o}C UTCI.

If air temperature 32 ^{o}C, and wind speed is 3.6 m/s:

- y_{32}= -0.6331(3.6) + 33.259

  y_{32}= 30.97 ^{o}C UTCI, while a wind speed of 6 m/s would result in felt temperature of 29.46 ^{o}C.

It is noticed from the line graph that the lower the temperature, the larger the impact of wind speed (steeper slope for y26 than y32). It appears that the UTCI equations developed by the International Society of Biometeorology, which this simulation of UTCI is based on, indicates that higher temperatures the increased wind speed becomes less effective in reducing the human perception of heat stress. These UTCI equations involve meteorological as well as non-meteorological variables relating to human comfort as discussed in literature review. Therefore, further research in assessing the equations that calculate UTCI need to be made for more accurate explanation of the decreased wind speed impact on UTCI at higher temperatures.

The results are very comparable to what was found by Taleb & Abu-Hijleh (2013). Their study, conducted in Dubai using ENVI-Met software, found that wind speed of 3.6 m/s could reduce an initial temperature of 32^{o}C to 29.06^{o}C ± 2.72 (the volume orthogonal configuration, June). The slight differences could be attributed to the different simulation software's calculation methods.

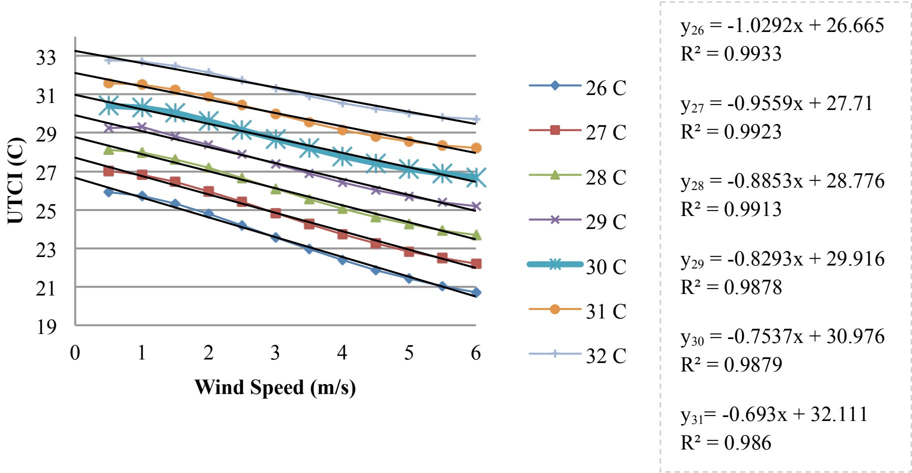


Fig.28 The impact of wind speed on how the temperature feels at 50% relative humidity, where x is wind speed and y is the resultant UTCI value. Data obtained from outdoor comfort calculator, grasshopper.

5. Urban Strategies

Based on the previous tests, Figure 29 displays some recommendation/ strategies that can be used to enhance the microclimate comfort and vitality of Al Ain town square. Meanwhile, Figure 30 displays some recommended strategies for a new neighbourhood block design for Al Ain/ Abu Dhabi climate based on orientation, canyon ratio and wind circulation. Figure 31, in turn, shows guiding strategies for urban vegetation considering buildings height and functions.

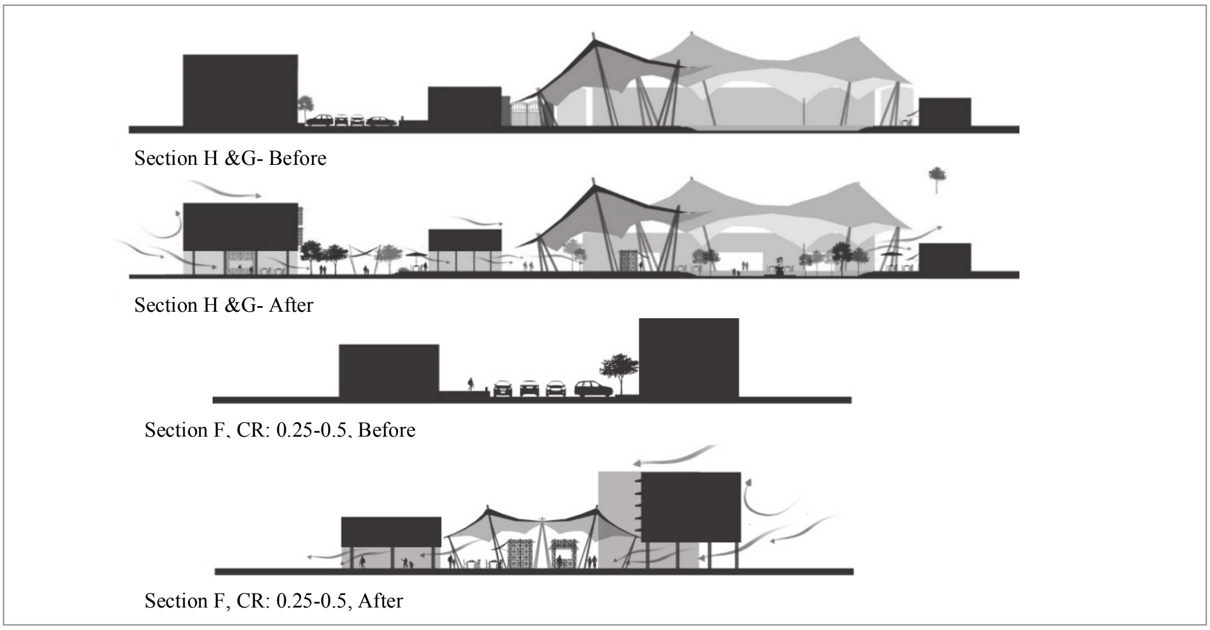


Fig.29 Strategies for Al Ain town square

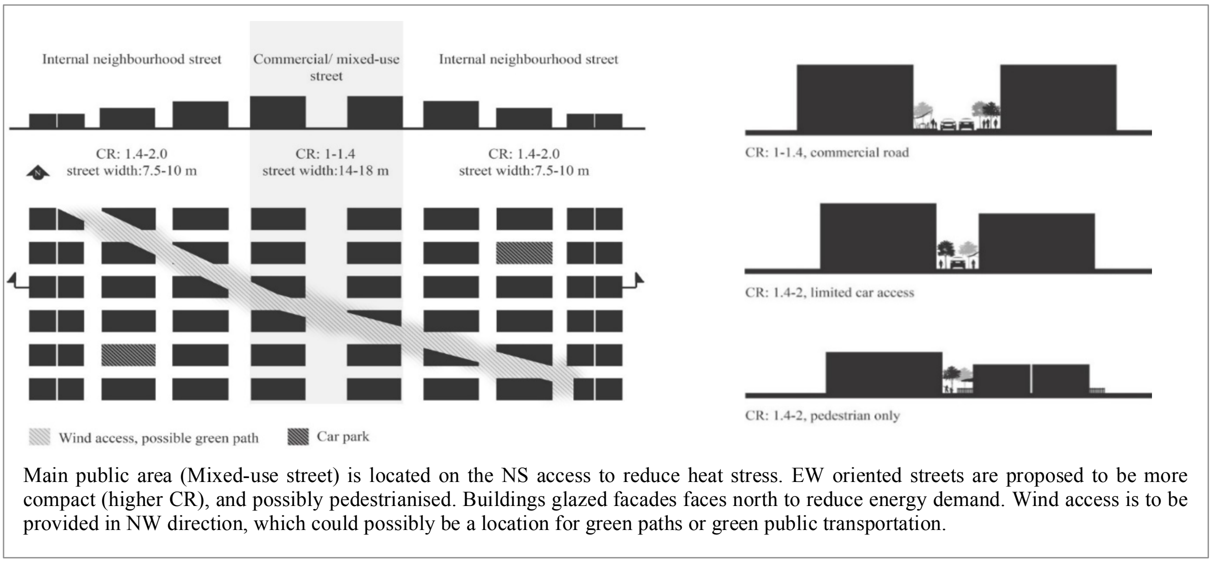


Fig.30 General strategies for new communities in UAE climatic conditions

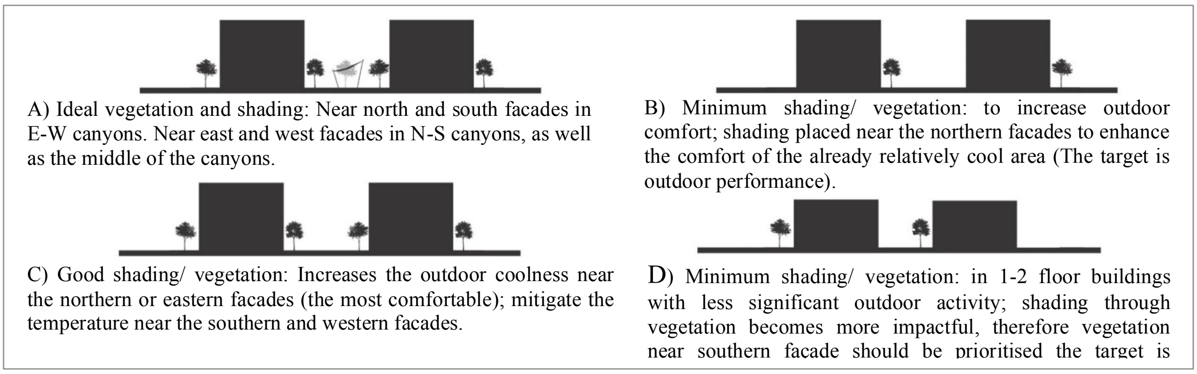


Fig.31 General strategies for shading by vegetation

6. Conclusion

The present study was designed to determine the impact of urban design strategies on microclimate in hot arid climatic conditions. The study focuses on assessing the impact of canyon ratio, outdoor orientation and wind speed in Al Ain city. Higher canyon ratios appear to be better performing in hot arid climate, where the shading impact of the compact urban form seems to be more significant than the wind circulation impact that can be compromised with compact forms. A canyon ration (CR) no less than 1 is recommended, with an overall range from 1 to 2 CR depending on the street hierarchy. This study has found that NS orientation of outdoor public spaces is significantly better performing in terms of microclimate comfort (2-3^{o}C cooler) with the coolest zones being next to the northern or eastern facades.

Moreover, it was found that shading surfaces/ vegetation shading can contribute to reducing UTCI temperature by around 4-5^{o}C in April and August in UAE climate, and higher impact was recorded at the hotter seasons. Another finding to emerge from this study is that creating "openings" in the prominent wind direction can contribute significantly to ventilation in the outdoor area without compromising the shading effect, which can dramatically reduce UTCI temperature from the moderate heat stress range (26-32 ^{o}C) to comfort or close to comfort. The resultant interpolated graph (Figure 28) can possibly allow to predict the expected felt temperature at a certain wind speed (0 to 6 m/s) and air temperature range of 26-32 ^{o}C.

These findings can have significant implications for advising decision making in urban planning and urban design in UAE, as well as in similar hot arid environmental contexts. They can be applied in both new developments and in strategies for improving the existing urban fabric, which could contribute to more liveability and vitality in outdoor areas. Finally, the produced estimation methods of the impact of shading surfaces and wind speed on outdoor comfort can possibly help designers in evaluating the impact of their urban design strategies in similar climates.

A limitation of this study is that EnergyPlus uses a simple wind profile that do not account for obstructions. Computational fluid dynamics (CFD) component can be used for higher accuracy of the results, which was not used in this study due to time and resource limitations. Moreover, the study did not evaluate the impact of evapotranspiration in trees, and considered only their shading effect, which indicates that the actual cooling effect is expected to be even higher. Finally, the results of wind simulation using Flow Design are valuable in showing the general behavior of wind in a scheme in the initial stages of design, however, more advanced software (such as ENVI-Met) can give more accurate results for the advanced stages of design.
Additional field research should be performed to validate the accuracy of UTCI simulations in hot arid contexts experimentally. While UTCI calculations has been validated experimentally in sub-tropical climate of southern Brazil, as well as in Canada and Korea, similar study can be performed in UAE context to test the local subjective thermal comfort in the region.

A greater focus on how to accelerate wind in urban areas in hot arid climates through urban structures could produce interesting findings on how to bring the moderate heat stress periods of the year to comfort, which would also reduce the intensity of high heat stress months. Moreover, a further study could assess the evapotranspiration impact of vegetation in UAE climate. Finally, more research on the economical implication of reducing peak air conditioning demand in UAE could help this research to be more impactful to decision makers in urban planning.

Acknowledgements

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