The Impact of Different Urban Configurations on Outdoor Thermal Comfort: A Case Study of the Military Camps in Abu Dhabi, UAE

تأثير التكوينات الحضرية المختلفة على الراحة الحرارية في الهواء الطلق: حالة دراسية لمعسكرات الجيش في أبوظبي، الإمارات العربية المتحدة

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ABSTRACT

One of the major challenges facing the urban planning sector is the rapid pace of growth of the world’s urban populations. In particular, the urban, economic and institutional conditions of Abu Dhabi, the capital city of the United Arab Emirates (UAE), are unique. However, Abu Dhabi is a significant case study of conflict between political, economic, and urban design in terms of large- scale project planning that makes this city suffer from the negative impact of urbanism. This is known as the Urban Heat Island (UHI) of urban settings.

Military camps are different from other standard urban settings: the urban design of camps aims to provide an integrated approach to security, transformation and environmental challenges. The balance between security and prosperity through sustainability will be addressed in this research.

This research aims to study the impact of different urban configurations of forms, courtyard proportion, height and orientation on outdoor thermal comfort, particularly, the reduction of air temperature and influence of wind conditions. Computer simulation was preferred as the main methodology in this research and ENVI-met 4.0 software was used as the main simulation tool.

The investigations in this research were performed in three Phases. Phase One focused on identifying the most favourable urban configuration in terms of thermal behaviour out of six different proposals: existing linear blocks with a rectangular courtyard; proposed fortress blocks with a square courtyard; proposed fortress blocks with a rectangular courtyard; proposed U-shape blocks with a square courtyard; proposed L-shape blocks with a square courtyard; and proposed developed linear blocks with a rectangular courtyard. In Phase Two, three different heights were applied on the most favourable and existing urban configurations. Phase Three investigated the impact of orientation in identifying the optimal urban configuration for military camps.

Simulation outcomes confirmed that developed linear F with three storeys and a courtyard proportion of 12:12 (length:height) has the best thermal behaviour and is considered as the most favourable urban configuration. The results show that north west–south east orientation provides the most comfortable outdoor environment. The findings from the three phases of the research showed that selecting the optimal urban configuration decreases air temperature by 2 °C from 33.6 to 31.54 for the base case and the most favourable developed linear from F respectively. Also, it was concluded that both height and orientation had negligible effects in comparison to urban form and courtyard proportion on reducing air temperatures in this particular study.

One main conclusion is that bioclimatic urban design can be used to achieve a significant improvement of outdoor thermal comfort. For instance, three storey buildings, orientation of north west–south east, and developed linear building form can be considered as the most favourable building prototype in military camps in Abu Dhabi. However, the behaviour of the outdoor parameters remains quite multifaceted and unpredictable and requires further research.

الملخص

أحد أهم التحديات الرئيسية التي تواجه قطاع التخطيط الحضري هو سرعة وتيرة نمو سكان في العالم, على وجه الخصوص فى أبو ظبي، عاصمة دولة الإمارات العربية المتحدة بسبب الظروف الحضرية والاقتصادية والمؤسسية الفريدة فيها ،. ومع ذلك تعتبر أبو ظبي حالة دراسة كبيرة للصراع بين الظروف السياسية والاقتصادية و التصميم العمراني فى المشاريع الضخمة مما يجعل هذه المدينة تعاني من الآثار السلبية للتحضرو المعروفة باسم ظاهرة الجزر الحرارية الحضرية (UHI).

معسكرات الجيش مختلفة من المناطق الحضرية القياسية الأخرى: حيث يهدف التصميم الحضري للمعسكرات الى توفير نهج متكامل للأمن، والتحديات الناتجة من التحول و التغيرات البيئية. وسيتم تناول التوازن بين الأمن والإزدهار الحضرى من خلال الاستدامة في هذا البحث.

يهدف هذا البحث إلى دراسة تأثير التكوينات الحضرية المختلفة من تكوين، شكل البناء والنسبة بين طول و إرتفاع المبنى للفناء الداخلى وتوجية المبنى على الراحة الحرارية في الهواء الطلق، وخاصةالحد من درجة حرارة الهواء وتأثيرعلى الرياح. وقد تم إستخدام بنامج حاسب الى ENVI-met لمحاكاة النماذج المختلفة كأداة بحث ريئسية. أجريت التحقيقات في هذا البحث في ثلاثة مراحل. المرحلة الأولى تركز على تحديد التكوين الحضري الأكثر ملاءمة من حيث السلوك الحراري من أصل ستة مقترحات مختلفة وهى: مقترح البناء القائم مع فناء داخلى مستطيل ؛ : مقترح بناء شكل القلعة مع فناء مربع, مقترح بناء شكل القلعة مع فناء مستطيل, مقترح بناء شكل (U) مع فناء مربع, مقترح بناء شكل (L) مع فناء مربع و مقترح بناء شكل طولى معدل(F) مع فناء مستطيل. في المرحلة الثانية، تم تطبيق ثلاثة ارتفاعات مختلفة على تكوينات الحضرية الأكثر ملاءمة ومقارنها مع الوضع الحالى القائم. أما المرحلة الثالثة ركزت على تأثير التوجه في تحديد التكوين الحضري الأمثل لمعسكرات الجيش.

أكدت نتائج المحاكاة أن مقترح بناء شكل طولى معدل(F) مع فناء مستطيل مع ثلاثة طوابق ونسبة ساحة 12:12 (طول: الارتفاع) لديه أفضل السلوك الحراري وتعتبر مثل التكوين الحضري الأكثر ملاءمة. وأظهرت النتائج أن توجة شمال الغربي والجنوب الشرقي يوفربيئة مريحة أكثر في الهواء الطلق. مقارنة النتائج المستخلصة من المراحل الثلاث من البحث أكدت أن اختيار التكوين الحضري الأمثل يقلل درجة حرارة الهواء بنسبة 2 من 33.6 الى 31.54 درجة لحالة القائمة والطولية المطورة الأكثر ملاءمة F على التوالي. أيضا، تم التوصل إلى أن كلا من الارتفاع والتوجه له آثار ضئيلة بالمقارنة مع الشكل الحضري ونسبة الفناء على خفض درجة حرارة الهواء في هذه الدراسة.

واحد الاستنتاجات الرئيسية هو أن التصميم الحضري الحيوي المناخي يمكن استخدامة لتحقيق تحسن كبير من الراحة الحرارية في الهواء الطلق. على سبيل المثال، ثلاثة طوابق لشكل البناء الطولى المعدل فى توجة الشمال الغربي والجنوب الشرقي ، يمكن اعتباره النموذج الأكثر ملاءمةلبناء معسكرات الجيش في أبو ظبي. ومع ذلك، لا يزال سلوك محددات التصميم الحضرى في الهواء الطلق متعدد الأوجه جدا وغير متوقع، ويتطلب إجراء مزيد من البحوث.

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This work is dedicated to the spirit of my father; I have truly felt the presence of his love and care in every moment of my academic journey with BUID. Tremendous gratitude goes to my mother for her prayers, and to my five sisters who have been a great source of love and support. I thank my old sister Dr. Badria Mohammed, who has been the best of friends and certainly a true gift from Allah beside the rest of family.

Last, but never the least, this thesis would have never been accomplished without the love and support of my husband Amjed. He has always inspired me and strengthened my will. I would like also to dedicate this thesis to my loving two sons and little daughter: Ahmed, Yamin and Leen. Their love helped me to bear all the stressful moments during the programme. I am nothing without them and their love.

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1 INTRODUCTION

1.1 Urbanism

According to a 2015 United Nations annual report, more than the half of the world's population (54%) today live in urban areas, a figure that will reach 90%—6.3 billion people—by 2050 (United Nations 2015). This percentage is continually increasing in developing countries, especially those located mainly in the hot and humid zones as illustrated in Figure 1 (Salata et al. 2016).

The urbanism trend has seen considerable spatial manifestation in order to accommodate the growing urban population, which will continue in the future. Under these conditions, we will need to adapt to this process. Therefore, effective governance and planning to achieve a more sustainable urban form are crucial for urban planners and policymakers. Urban areas and their spatial extensions are needed to minimise wasteful use of non-renewable resources to avoid the disruption of the ecosystem equilibrium, to reduce social inequities, and to promote inclusive and sustainable development. Urbanism sprawl has gradually become one of the dominant urban spatial expansion patterns throughout the world regardless of differences in time, causes, and consequences (Mosammam et al. 2016).

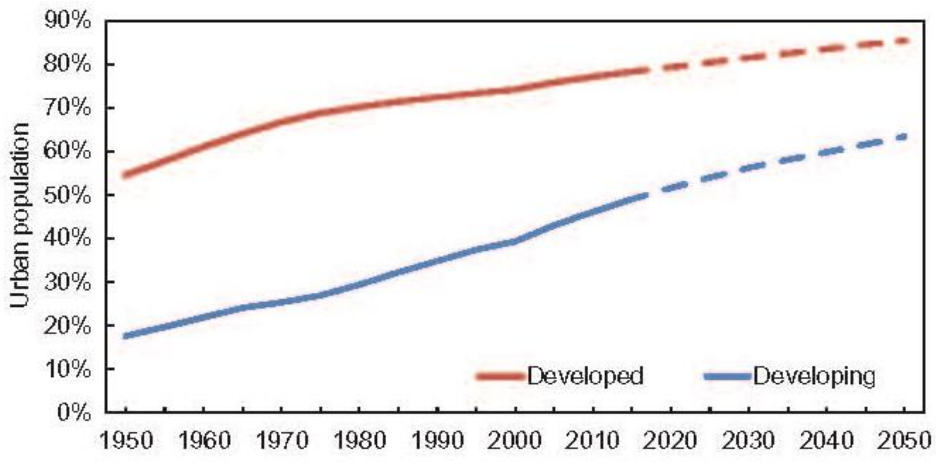


Figure 1.1: Historical and projected rates of urbanisation in developed and developing countries, 1950–2050 (Ameen, Mourshed & Li 2015, p. 112)

Some 70% of global CO_2 emissions are due to the impact of urban developments, which was the key finding of a recent report of a critical review of environmental assessment for sustainable urban design by six widely-used tools such as BREEAM Communities, LEED-ND, Comprehensive Assessment System for Built Environment (CASBEE), SBTool for urban development, Pearl Community Rating System in United Arab Emirates (PCRS), and Qatar Sustainability Assessment System (QSAS). In addition to all existing vulnerabilities, rapid urbanism, as shown in Figure 1.1 and 1.2, urban development's pose global warming and climatic changes all over the world. Urban configurations form urban developments, and are generally considered the tool to create the future of urban patterns and cities to accommodate the changes in the future (Ameen, Mourshed & Li 2015).

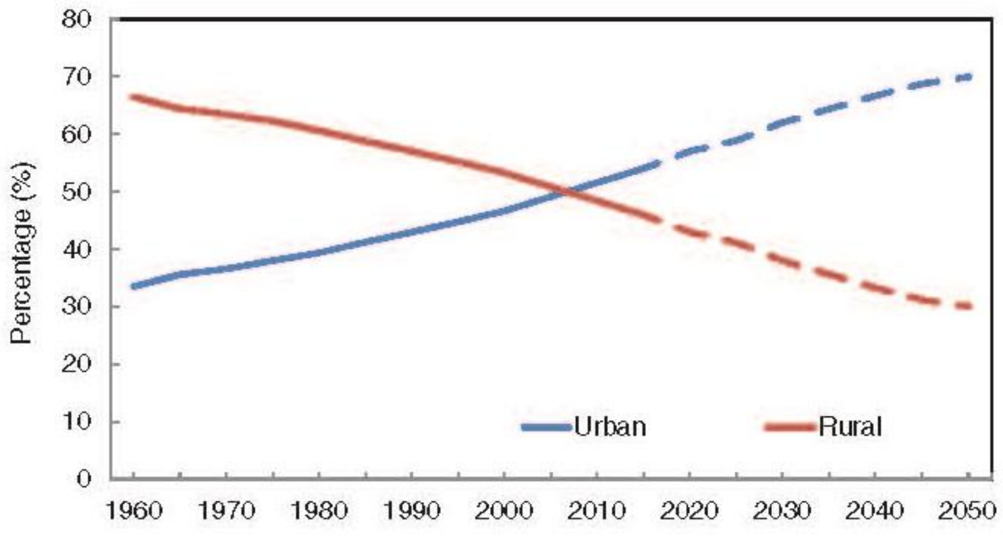


Figure 1.2: Historical and projected urban and rural population percentages of the world, 1960–2050 (Ameen, Mourshed & Li 2015, p. 112)

By the end of the current century, 75% of the world's population will be urban. Similarly, recent research conducted by Ignatius, Wong, and Jusuf (2015) expects that 61% of the world's population will live in urban areas by 2030. Sustainable urban design is the future, and poses an exceptional challenge which many researchers address. Rapid urbanisation has many negative impacts and consequences, mostly in social, economic, and environmental aspects (Ritchie & Thomas 2009). The consequences of urbanism lead to changes in the natural landscape which will be transformed into hardscape and buildings, and eventually green spaces will be reduced and outdoor spaces will be less comfortable for human beings. As a result the negative impacts of urbanism and its consequences, urban areas are significantly warmer than surrounding rural areas, a phenomenon known as the urban heat island (UHI) effect, where cities have recorded higher temperatures in comparison to their non-urbanised surroundings or those located in suburbia, as shown in Figure 1.3.

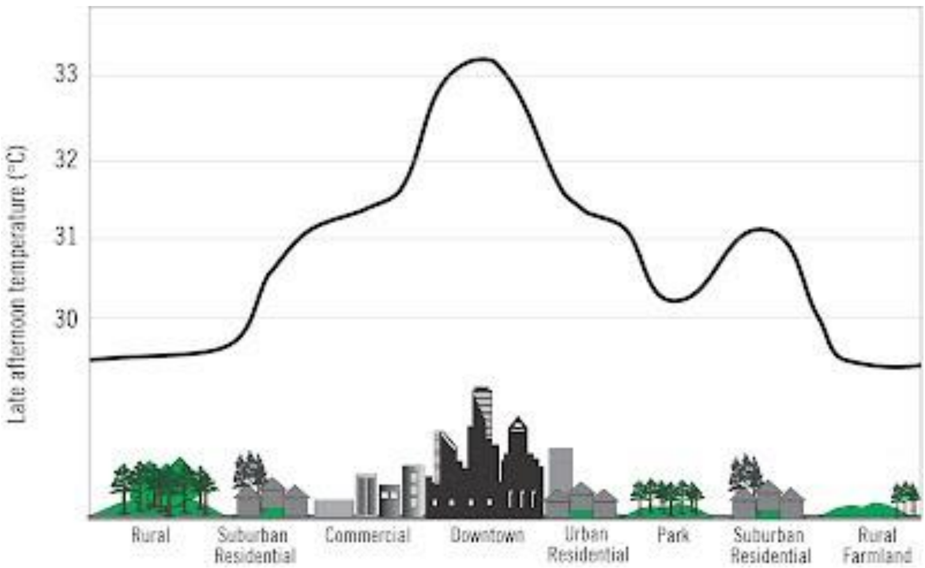


Figure 1.3: The urban heat island phenomenon (Arrau & Pena 2011, p. 1)

Cities, especially capital cities, are panarchies of urban adaptive cycles. In these cities, the urban environment is constantly changing, with new residents moving to existing urban areas, while others extend urban boundaries to create new urban developments (B.A. Harmon, Goran & W.D. Harmon, 2013). As a result of temporary workers, Abu Dhabi's population doubled between 1986 and 2005, reaching 1.4 million in 2007. During the current reign of Sheikh Khalifa bin Zayed Al Nahyan, economies and business models have been influenced dramatically by Western economies. Moreover, the ruling elite have had Western educations, accelerating decisions on economic diversification and growth. There are two key factors for rapid urbanisation within cities: the first is faster transportation to facilitate movement, such as trains and ships, and the second is economic stability in high-income cities, which provides better opportunities and occupations for people to build their career (O'Brien, Keivani & Glasson 2007).

1.1.1 Sustainable Urban Design

Global warming and climate changes currently form the most critical environmental conditions for human beings. Since the early 2000s when researchers highlighted the strong relationship between global climate changes and rapid urbanism, sustainable urban design has gained growing international popularity to control the consequences of growing population. Nowadays, the concept of sustainable urban development is one of the most important issues among the four pillars of sustainability concerning the urban context—environmental, economic, social, and cultural—in the urban design and building professions. This issue is important to accommodate growth needs whilst preserving a sense of community. The need for global policies and standards becomes more apparent as both the number of practical initiatives and international cooperation increases (Joss 2015).

The concept of sustainable urban configuration is the most important issue among the four sustainability pillars listed earlier. This issue is important to satisfy a rapidly increasing population's needs at the same time as preserving the sense of community in future while meeting needs of the present. Finding a balance to development models for future generations needs to be considered.

Based on market and economic considerations, sustainable urban design provides city developers with social and ecological design criteria and enhances tenant awareness of sustainability. Consequently, the concept of sustainability becomes the keystone of the urban development process. Through controlling an urban development's lifecycle starting from planning to operational stage, suitable urban design has significant impact on improving the quality of outdoor spaces and, hence, on the overall quality of human life. Environmentally friendly urban development is a fundamental discourse for cities in the governmental sector. This is particularly so for new governmental development in rapidly-developing countries where the environment has been significantly influenced by economic growth.

1.1.2 History of Urban Design in Abu Dhabi (Economic Impact)

The economic conditions of Abu Dhabi are significant, the conflict between these conditions and rapid growth of population create the need of large scale project planning. One of the most important mega-development projects is the Saadiyat Island, which includes a cultural district, hotels, and retail and residential areas, with outstanding architecture. Architects and urban designers created a positive and communicative image of this project around the Middle East region. Taking the socio-economic changes that occurred in Western countries as an example, and the impact of hiring well-known urban planners to provide a competitive advantage over other countries and cities, Abu Dhabi city now strives for signature urban planning and architecture. In regard to urban context, size, and role in the global environment, cities such as Abu Dhabi will influence the democratic decision-making of urban effects (Ponzini 2011).

In the public discourse, investments in sustainability require long-term planning and strategies; the Abu Dhabi economy is reliable for this type of investment because of the stability of its oil-based economy. Consequently, the economic vision influences urban planning strategies. The history of the first general urban master plan for Abu Dhabi goes back to the 1980s, when the city's Urban Development Program began. In 2007, the Abu Dhabi Urban Planning Council (UPC) was founded under the law Amiri No. 23 of 2007. The UPC is responsible for leading, providing direction, and enhancing sustainability of Abu Dhabi's urban development strategy for the future of the built environment to 2030. However, the city's population began to increase rapidly year by year, and challenges of facing urbanism subsequently faced the UPC leadership, (Ponzini 2011). The most important consequence of urbanism is UHI; for example, construction of new buildings and roads has compromised the open space dedicated for landscape and liveable open space has eventually been vastly reduced. The deterioration of the urban environment because of urban construction will lead to incremental increases in temperatures in cities compared to their non-urbanised surroundings (Ignatius, Wong & Jusuf 2015).

The UAE is considered to be one of highest-income developing countries, where environmental policy guidelines and established strategic decisions to mitigate urbanism deterioration have had a significant impact on the economy. In regard to implementation of suitability and relevant strategies, the UAE, as an important member of the GCC, is strategically well-positioned to play an important role (O'Brien, Keivani & Glasson 2007).

1.1.3 Sustainability in Abu Dhabi

Abu Dhabi's government establishes a leading vision for sustainability to protect the environment; this vision has strategies to be followed as design guidelines for all new built environments in the Emirate of Abu Dhabi. This commitment, led by UPC, is also known as Estidama in the professional environment field, not only provides a distinctive overarching sustainability framework, but also an inspired vision for better liveable communities in this city.

In Arabic the word “estidama” means sustainability. Sustainable urban development is a fundamental discourse for United Arab Emirates cities, and particularly Abu Dhabi city. The UPC’s aim is to balance the four pillars of Estidama throughout creating sustainable communities, cities, and rural areas in the region, as illustrated in Figure 1.4. Estidama began in 2008, and has made significant strides since to improve the rapid growth of built environment within the Emirate of Abu Dhabi, throughout the project lifecycle including planning, design, development, construction, and operation and maintenance stages.

Figure 1.4: The four pillars of sustainability (UPC 2010)

Estidama’s rating system—the Pearl Community Rating System (PCRS)—is one of Estidama’s key initiatives to achieve sustainable urban design. As illustrated in Figure 1.5, PCRS is organised into five levels from 1 pearl to 5 pearls, across seven categories:

Integrated Development Process which aims to enhance the teamwork among all project stakeholders.

Natural Systems to reserve natural environments and habitats

Liveable Communities to improve the quality and connectivity of outdoor and indoor spaces

Precious Water

Resourceful Energy to reduce demand and enhance renewable resources through passive design techniques

Stewarding Materials to consider of the life cycle of construction material selection.

Innovating Practice aiming to invent new ideas for current and future market needs.

Each section includes two credits that can be achieved: one mandatory and one optional. For 1 pearl level, all the compulsory credit requirements must be achieved. However, for government-funded projects such as military camps, school campuses, mosques, and public piazzas, the minimum requirement is to achieve two pearls. It is important to know that military camps are government-led projects and therefore sustainable urban design is the fundamental concept to achieve the set goal (UPC 2010).

Credit Section	Maximum Credit Points
IDP - Integrated Development Process	10
NS - Natural Systems	14
LC - Livable Communities	38
PW - Precious Water	37
RE - Resourceful Energy	42
SM - Stewarding Materials	18
IP - Innovating Practice	3
TOTAL	159*

Requirement	Pearl Rating Achieved
All mandatory credits	1 Pearl
All mandatory credits + 55 credit points	2 Pearl
All mandatory credits + 75 credit points	3 Pearl
All mandatory credits + 100 credit points	4 Pearl
All mandatory credits + 125 credit points	5 Pearl

Figure 1.5: The seven rating categories and rating levels of PCRS (UPC 2010)

The cornerstone of the Estidama goal in terms of suitable urban design is creating liveable space communities, particularly in government-funded projects to satisfy present needs without compromising the success of future communities. Liveable outdoor spaces require a human scale of urban environment to provide comfortable, walkable, and safe outdoor spaces to reflect the cultural identity of the UAE. In addition, suitable urban design shall create a community and facilitate mass transit of all modes of movement, particularly pedestrian and cycling.

1.2 Military Camps

Urban design of Military camps as unique urban settings aims to provide an integrated approach to the three main challenges of security, transformation, and environmental . The proposed research is the introduction of sustainability of urban configurations in military camps that not only affects the way camps adopt sustainability goals within the UAE, but also have a collective national impact in line with the overall framework structure.

This hypothesis is based on personal experience as a designer and observer of the lack of sustainability practice in military camps in the UAE. However, the implementation of sustainability goals set by UPC over the past few years for military camps is noted; in general military camps are considered as stand-alone communities with all the required facilities and diversity of land use.

1.3 Military Camps in the United Arab Emirates

As the government led-projects, military camps must comply with the merits of sustainable design and development to achieve the values of energy and infrastructure management. As discussed earlier, UAE militarily camps must achieve a two-pearl rating level in compliance with UPC design and Estidama goals guidelines. Looking holistically, to bring together the cumulative effects of sustainable development requires more strategic thinking. Installations need to embrace a master planning process to insert sustainable planning principles into their goals and objectives, and use this process when implementing planning recommendations. Planning more holistically around focused area or neighbourhood development rather than project-focused initiatives is essential.

Military camps are scattered across the UAE, but there is a greater concentration of bases in the desert northwest such as;Al Hosn Military Camp, Khawla Bint Al Azwar Military School, the Gulf region's first military college, Al Manama camp, Al Nahyan Camp in Abu Dhabi, Al Ain Camp, Rahmania Camp in Sharjah and Liwa Camp in Al Gharbia. (The National 2016).

1.3.1 Outdoor Activity in Military Camps

Outdoor life and thermal comfort are important concepts in military camps for two main reasons: the first is soldier well-being and the healing stress associated with their jobs, and the second is enhancing soldier capability for army fitness tests. Soldiers suffer from physical and mental stress, especially during operations in other countries, and this stress will influence their family and communities. The days before deployment preparing to travel out of their country and the period after reintegration into family and community are particularly stressful. Therefore, for example, the U.S. and the U.K. governments have military camp projects aimed to provide liveable outdoor spaces to help soldiers return back to nature and to enjoy recreational activities such as gardening, walking, farming, hunting, jogging, fishing, and cycling. In addition to rehabilitation centres, outdoor adventure experiences are required. Ultimately, outdoor space and liveable community are important for community well-being and healing in military camps (Krasny et al. 2013).

Smith (2016) reported that physical exercise training made soldiers perform better on the battlefield. The U.S. Army was the pioneer of innovative physical readiness training in order to enhance a soldier’s physical capability. Since 1980, U.S. soldiers have been required to pass the Army’s formal physical fitness test comprising three exercises: push-ups, sit-ups, and a 2-mile run. As illustrated in Figure 1.15, outdoor physical exercises occurred on a daily, weekly, and monthly basis.

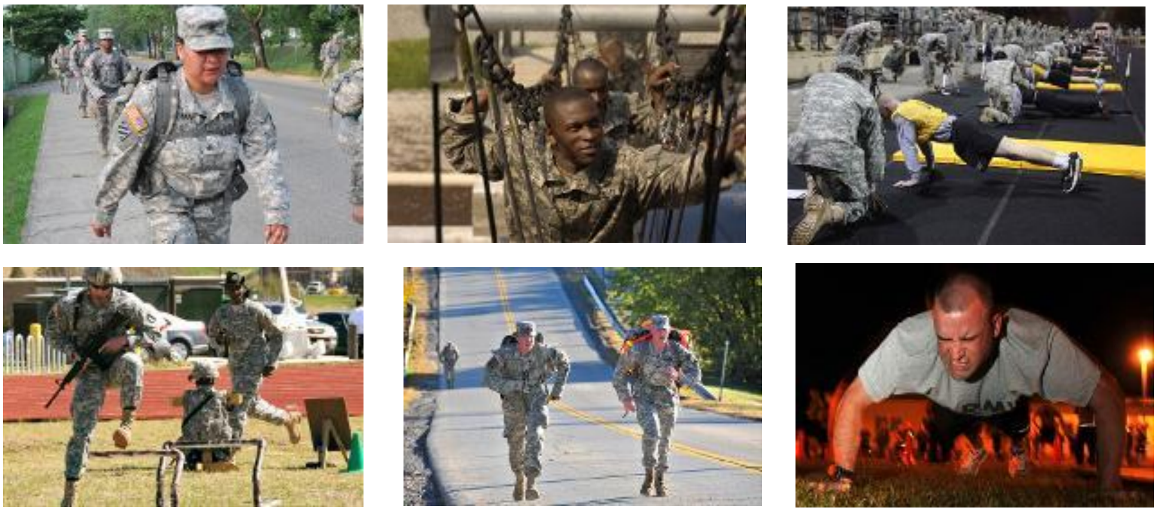


Figure 1.6: Outdoor physical exercise in military camps (Smith 2016)

Outdoor thermal comfort is negatively influenced by rapid urbanism, and cities in hot arid climates such as Abu Dhabi are suffering from gradually increasing discomfort in outdoor life. At the building level, such discomfort of indoor thermal comfort leads to increased demand for energy used for cooling systems. In order to make outdoor space comfortable, it is important to make the open space comfortable as much as the microclimate allows.

In military camps, outdoor physical exercise—which is a fundamental part of the military training program—is directly affected by outdoor thermal conditions. In order to determine conditions of outdoor thermal comfort, human comfort needs to be defined to understand the parameters that influence the comfort zone and indices based on outdoor thermal comfort can then be assessed. Thermal comfort, its parameters and indices are explained in the coming sections (Harmon, Goran & Harmon 2013).

1.4 Outdoor Thermal Comfort and Urban Configuration

Human health is significantly affected by outdoor thermal conditions in urban spaces. Urban microclimate characterises and forms urban air quality and the energy performance of buildings. Nowadays, global warming and rapidly increased urbanisation make outdoor thermal comfort an acute issue for urban planners consider. Taleghani et al. (2015) conducted an urban investigation and defines thermal comfort as “that condition of mind which expresses satisfaction with the thermal environment”. It focuses on the heat balance of the human body, known as thermo-physiology.

1.4.1 Outdoor Thermal Comfort and UHI

UHI and its mitigation strategies are still the most attractive topic for researchers in sustainability and urbanism. UHI, which is the most negative impact of urbanism as mentioned earlier, is a wide area of research which is not the direct focus of this study. This research focuses on outdoor thermal comfort by investigating different urban configurations, however this passive design strategy is considered as a mitigation strategy related to the UHI phenomenon. Generally, there are two main UHI mitigation strategies: increasing softscape, and reduction of hardscape absorbability (Arrau & Pena 2011).

Urban configurations comprise building forms and open space physical characters, and have a major impact on outdoor thermal comfort as a result of UHI influence. For example, in high- and mid-latitude urban areas, urban configurations need to be designed to increase shelter to protect pedestrians from wind, maximise scattering of air pollutants, and reduce air temperature to avoid the need for space cooling, however solar access needs to be increased. The balance between urban densities, compactness, radiation exchange, and thermal behaviour needs to be maintained to achieve a broad compatibility zone. Moreover, orientation of urban configuration has a significant impact on UHI; studies have confirmed that a north-south orientation provides less summer and more winter canyon-floor irradiance than an east-west street orientation. In hot arid climates, the height-to-width (H/W) ratio influences shaded areas and outdoor thermal comfort accordingly. For example, increasing H/W results in a stronger cool period and a weaker hot period because of a larger shaded zone (Hien et al. 2012).

Therefore, passive design strategies of urban configurations are required to reduce the impact of UHI. Increasing public awareness of the importance of liveable, walkable, and comfortable outdoor spaces led to a large number of researchers addressing microclimate design parameters to improve outdoor thermal comfort, particularly in hot–humid climates; human beings spend more time in outdoor spaces in hot–humid climates. Moreover, the studies addressing the impact of urban configurations on outdoor air quality are more recent than those addressing the indoor air quality. Different urban configurations lead to variable of outdoor thermal comfort zones because of the different microclimates which are formed by these configurations.

1.4.2 Parameters Influencing Outdoor Thermal Comfort

The parameters affecting outdoor thermal comfort— such as mean radiant temperature, solar radiation, air temperature, wind velocity and, to a lesser extent, humidity—were ranked from most significant impact to least. Shading is the most important parameter for thermal sensation in hot arid climates, followed by natural ventilation or air movement. Hien et al. (2012) reported that during direct solar radiation conditions, a doubling of wind speed from 1 to 2 m/s causes a decrease of the physiological equivalent temperature (PET) index value by 3.5 °C, however, the impact is negligible during shading conditions. Cumulatively, a decrease of PET index value by 6 °C is felt in the case of an increase of wind speed from 1 m/s to 3.5 m/s.

Sun radiation and air temperature mostly influence thermal comfort. The mean radiant temperature (Tmrt) is defined as the even temperature of an imaginary spherical surface surrounding a certain substance where emissivity is equal to 1. Researchers have revealed that Tmrt has a strong impact on the thermo-physiological significant factors such as PET (Andreou 2016), which will be discussed in the next sections.

The effect of configuration character of urban settlements on the microclimate has significant importance. In hot, arid climates, shading conditions have great impact on pedestrian comfort particularly in summer, when it helps to reduce exposure to the sun. Therefore, a scattered urban layout has a negative impact on thermal comfort since a pedestrian is exposed to more direct and diffused solar radiation, while on the other hand, a compact urban layout has less exposure to sun and less reflected radiation from the horizontal street surface (Liu, Niu & Xia 2016).

1.4.3 Outdoor Thermal Comfort Indices

Outdoor thermal comfort is important because it is strongly related to health and well-being, especially in hot, arid climates such as Abu Dhabi, where outdoor areas are extremely hot and humid, and where many people suffer from heat stroke in summer. Furthermore, comfortable outdoor thermal conditions, which allow human beings to enjoy outdoor activities, is affected by both weather and human factors.

Thermal comfort is related to three different approaches: psychological, thermo-physiological, and one based on the heat balance of the human body; however, the psychological factor is more prominent in outdoor areas, because people have different adaptation levels to the environment, hence theoretical models and actual models of thermal comfort are always variable.

In hot, arid, and humid climates, people spend most of their time in outdoor open spaces, and therefore thermal indices affecting comfort are well studied, while in cold climates these indices are less important because people prefer to stay mostly indoors. Outdoor thermal comfort connects climatology to biometeorology to develop thermal comfort indices.

Three thermal indices have been studied extensively in hot, arid climates to evaluate outdoor thermal comfort and human perceptions: Physiological equivalent temperature (PET), standard effective temperature (SET), and the universal thermal climate index (UTCI) (Liu, Niu & Xia 2016). Andreou (2016) defined PET as the equivalent indoor air temperature for a standard human being in standard conditions of core and skin, taking under complex outdoor conditions, while ignoring the wind and solar radiation for indoor settings. PET can be calculated through the computational software RayMan, and expressed in °C units, with which people who are not experts in meteorology are more acquainted. The grade of physiological stress varies from extreme cold stress to extreme heat stress, leading to thermal perception variables from *very cold* to *very hot*, respectively. PET is similar to comfort index because both use the PMV as the assessment scale. PET has the most important variables for human thermal comfort, such as airflow, air temperature, radiant temperature, and humidity. Moreover, the outcomes give a clear indication of the comfort temperature because it is still in degrees, and therefore logical to most people. Taking into consideration that internal heat production is 80 W, and heat transfer resistance of clothing is 0.9 clo, Table 1.1 was developed by Taleghani et al. (2015) to identify physiological stress and thermal perception by comparing two main indices of thermal comfort: a) predicted mean vote (PMV) and b) physiological equivalent temperature (PET).

A recent study by Salata et al. (2016) addressed outdoor thermal comfort and reported that PMP was created to evaluate thermal perception for indoors areas which is influenced by sensors associated to air-conditioning systems firstly, and then used for outdoor spaces.

Table 1.1: Grades of human thermal comfort (Taleghani et al. 2015).

PMV	PET °C	Thermal Perception	Grade of physiological stress
		Very cold	Extreme cold stress
-3.5	4		
		Cold	Strong cold stress
-2.5	8		
		Cool	Moderate cold stress
-1.5	13		
		Slightly cool	Slight cold stress
-0.5	18		
		Comfortable	No thermal stress
0.5	23		
		Slightly warm	Slight heat stress
1.5	29		
		Warm	Moderate heat stress
2.5	35		
		Hot	Strong heat stress
3.5	41		
		Very hot	Extreme heat stress

1.5 Statement of the Problem and Research Interest

Sustainable urban design is not a new initiative, especially during this century, as in all recent studies researchers linked global warming to UHI due to its contribution to the greenhouse effect and the increase of urban area temperatures (Ignatius, Wong & Jusuf 2015). Urban areas have higher air temperature compared to rural area because of the heat storage capability of construction materials and low wind speed (Younsi & Kharrat, 2016). Researchers in sustainable urban design have helped to increase public awareness of the goals of sustainability, of how to live while observing conservation goals to ensure a better future.

The motivation for the current study comes from the practical issues facing human beings as a result of climatic changes and global warming. Human beings need to seek better health in hot–humid climates through enjoying outdoor spaces and reducing the time spent in indoor spaces and air-conditioned areas. The lack of studies addressing outdoor thermal comfort, particularly in military camps, has stimulated the need for this investigation. Achieving thermal comfort is not only limited to indoor spaces, it is especially desirable for prominent urban settings such as military camps, where outdoor spaces and associated activities are essential to the function and operation of the camps.

The interest in this area of research came from awareness that the level and volume of coverage on global warming has grown enormously over the past 10 years and, further, my awareness of the subject had also grown through needing to take into consideration Estidama requirements as a professional working in the field. An extensive literature review has been conducted on sustainable urban design in general, and outdoor thermal comfort in particular, it have been realised that researcher covered comprehensively and this research will add nothing or little knowledge in comparison to the efforts have been carried out.

By contrast, it was my understanding that the impact of urban configurations on energy on outdoor thermal comfort in the media was a relatively under researched area and as such, it was my belief that if I undertook an examination of the topic I could contribute something to what small debate existed. Moreover, and based on personal experience of lack of sustainability consideration ns in military camps (MC), no study has been conducted to examine the outdoor thermal comfort in local militarily camps in particular.

1.6 Aims and Objectives

This research aims to investigate the impact of different urban configurations on outdoor thermal comfort in, UAE, Abu Dhabi. The research question is whether or not different urban configurations within a certain military camp behave differently in terms of temperature and wind variations in the hottest day in summer. In the UAE, Abu Dhabi is the selected location for this study to compare thermal behaviour of existing urban configuration with five different urban design proposals. The six main configurations investigated will be, Existing linear blocks with rectangular courtyard, proposed fortress blocks with square courtyard, proposed fortress blocks, rectangular courtyard, Proposed U-shape blocks with square courtyard, and proposed L-shape blocks with square courtyard and Proposed developed linear blocks with rectangular courtyard. Studying in advance the growth of the urban areas general and military camps specially and which urban form is best suited for its climatic conditions will reduce, on the longer run, problems arising from urban heat islands. The aim of this research will be answered through the following set of objectives:

I. Identification the most important microclimatic variables influence outdoor thermal comfort in hot arid climate throughout literature review

II. Proposal of five different urban configurations in addition to the existing one of residential area on military camp to address the impact of different building forms, open space proportion, height and orientation on outdoor thermal comfort

III. Identification of the most favourable building form and open space proportion in terms of thermal behaviour throughout computer software to simulate the vital parameters influencing the outdoor thermal behaviour such as air temperature and wind speed averages. Acquiring numerical data for of these climatic parameters compare averages for the six different urban configurations.

IV. Identification of the most favourable building height in terms of outdoor thermal behaviour.

V. Identification of the most favourable orientation terms of outdoor thermal behaviour

VI. Define and justify the most favourable urban configuration in terms of thermal behaviour in summer in, UAE, Abu Dhabi.

1.7 Research Outline

This research presents a study of the influence of urban configurations comprising physical characteristics of building forms and courtyards. The first chapter introduces and presents an overview of sustainable urban development, especially urban configurations, including its definitions and types. The chapter also highlights the importance of suitability in military camps, the challenges facing determination of suitability, and understanding of these challenges leads to the proposed solution through implementation of sustainable urban configurations as urban design guidelines.

Chapter 2 will be a comprehensive literature review of recent similar studies on the impact of different urban configurations of microclimate, and in hot climates in particular. The various factors impacting outdoor thermal comfort will be highlighted through the reviewing scientific papers. Studies will be reviewed based on their preferred methodologies to determine the best tool to investigate outdoor thermal comfort in Chapter 3. Pros and cons will be listed for each methodology addressing a similar topic to conduct comparisons. The chapter will justify the selection of simulation methodology for this dissertation, research parameters, and site selection, followed by a section on software and validation.

Parametric design and model applications to investigate the variable research parameters will be proposed and analysed in Chapter 4. The existing urban configuration will be described as a base case in addition to five design proposals to identify the three best of six urban configurations in terms of thermal behaviour. Then another set of simulations will be carried out for these three urban configurations to investigate the impact of building height.

Chapter 5 will provide information of results and findings, simulation results will be compared and analysed extensively, and pros and cons for each design proposal will be listed to identify the optimal design proposal among the six alternative options addressed. Ultimately, recommendations for further studies and future work in this area of research will be suggested in Chapter 6.

2 CHAPTER

LITERATURE REVIEW

2.1 Introduction

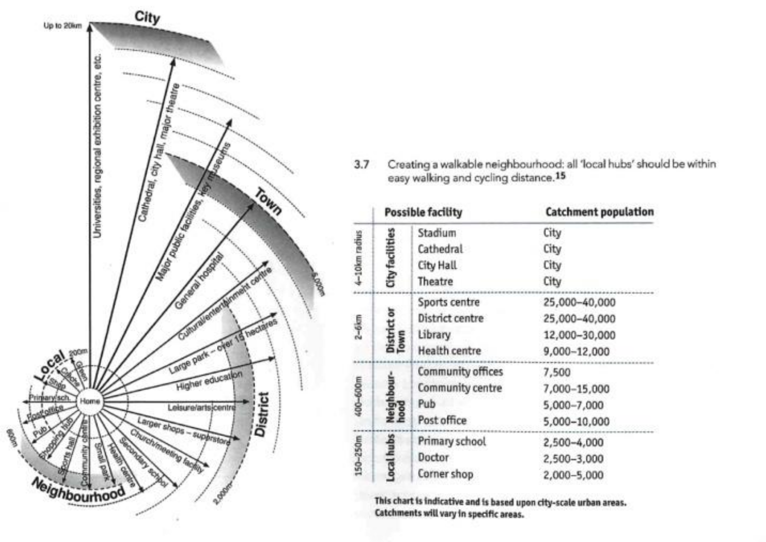
This chapter will highlight the main research investigating outdoor thermal comfort in general. The factors which have the most significant impact on human thermal comfort in hot arid climate—ambient air temperature, wind speed, and humidity—will be addressed in particular and in more detail. In this section, the reviewed papers will be presented as they discuss some of the major influences that affect outdoor thermal comfort. The proposed parameters of urban morphology, building height, orientation, and eventually configurations of open spaces and their influence of outdoor thermal comfort will be highlighted throughout the literature review. The impact of different urban configurations, including building geometry and courtyard proportion, on outdoor thermal comfort in both hot and hot arid regions were keywords for the literature search in the current investigation. This helps to broaden the information discovered, as there is a lack of scientific papers addressing urban configurations solely comprising building forms and open space physical characteristics in hot, arid climates, and specifically in military camps.

2.2 Urban Configurations

Since urban developments and neighbourhoods are constantly changing and evolving new forms, the urban identity is therefore characterised by natural, social, and built elements. At present, urban developments are not created by natural evolution processes, but rather throughout the evolution of the local urban context with respect to economic aspects. Nowadays urban developments are often a type of imposed reaction to economic needs and less caring of human needs; for example, material selection is determined by finance factors regardless the environmental ability of these materials to mitigate the UHI phenomenon (Ritchie & Thomas 2009). In general, old urban configurations are more organic because they were developed by natural evolution processes; on the other hand, newer cost-oriented urban configurations are simpler and mostly linear and block forms.

The rapid growth of economic-oriented urban development has a negative impact and places challenges on the environment; the most important challenge is the mitigation of UHI, which can be approached through the selection of the optimal urban configuration for local hubs, neighbourhoods, districts, and cities. Sustainable urban configuration aims to arrange buildings in an urban area in a way to increase natural ventilation between buildings, insert softscape within urban open spaces, and ultimately to cool down the effects of solar radiation (Hien et al. 2012).

The selected urban space of this study is a part of a large existing military camp located in Abu Dhabi, with a total plot area of 16,770 m^2 (1.6 ha) according to urban design guidelines provided by Ritchie and Thomas (2009). Ritchie and Thomas provided information about the catchment required for each specific space based upon urban areas and city-scale, under which the entirety of an existing military camp is considered as a neighbourhood, a1.7.



		Possible facility	Catchment population
4–10km radius	City facilities	Stadium	City
		Cathedral	City
		City Hall	City
		Theatre	City
2–6km	District or Town	Sports centre	25,000–40,000
		District centre	25,000–40,000
		Library	12,000–30,000
		Health centre	9,000–12,000
400–600m	Neighbour-hood	Community offices	7,500
		Community centre	7,000–15,000
		Pub	5,000–7,000
		Post office	5,000–10,000
150–250m	Local hubs	Primary school	2,500–4,000
		Doctor	2,500–3,000
		Corner shop	2,000–5,000

This chart is indicative and is based upon city-scale urban areas. Catchments will vary in specific areas.

Figure 2.1: Catchment based upon urban scale (Ritchie & Thomas 2009, p. 25).

The connection between human beings and places is urban design, which comprises many elements such as buildings, public space, streets, transport, landscape, and hardscape. The hierarchy of urban space in terms of urban scale ranges from small public spaces called blocks (street and building), to neighbourhoods (district and corridor), or whole regions (city and town), as shown in Figure 1.6. The area of this research is part of an existing military camp, which is considered a neighbourhood, and the main focus will be on the accommodation zone, which is considered as an urban block comprising street, open spaces, and buildings (Urban Design, nd).

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The region: city and town	The neighbourhood: district and corridor	The block: street and building

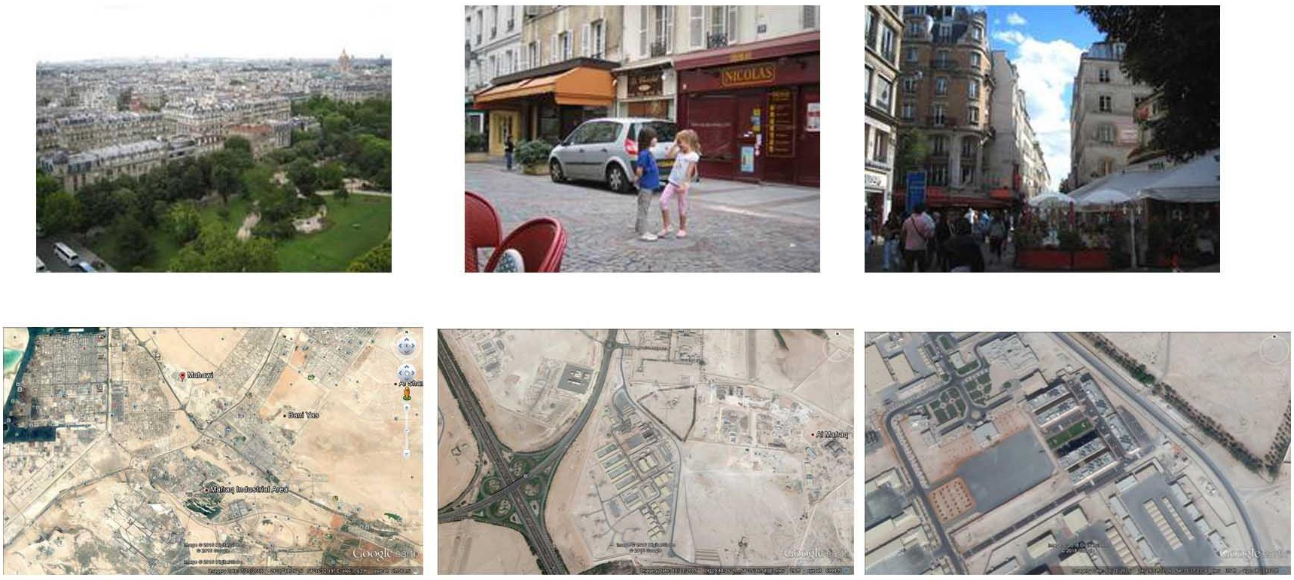


Figure 2.2: Mahawi site (adapted from Google Maps 2016).

2.2.1 Building Forms

Urban configuration in this research refers to the physical properties of building forms and open spaces (courtyards) designed in certain arrangements. Two types of building form will be investigated in this research: the first is *linear,* to represent the base case (existing buildings), and the second is a *courtyard* with different alternative design options, as recommended through a literature review.

In general, urban forms and city configurations are affected by factors that include social structures, industry, density, and the distribution of the various functions within the city. A brief description of the three main urban configurations is presented in order to identify the main features of each to enhance comparisons and recommendations at the end of this research. In this research, urban forms are referred to as urban configurations for the built elements including buildings, forms, and open space forms. It is also important to note that most of the literature reviewed for this research used the term *urban form* interchangeably to also refer to building forms, such as courtyard houses or linear houses.

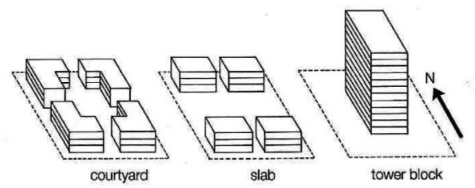


Figure 2.3: Buildings forms. (Ritchie & Thomas 2009, p. 48).

As illustrated in Figure 1.8, Ritchie and Thomas (2009) investigated the optimal thermal behaviour of three different urban forms for housing, comparing the pros and cons for three typical urban forms: courtyard, parallel slabs, and tower blocks. Courtyard urban configurations create a strong sense of community; self-shading effect of buildings allows for controlling sun exposure and reducing heat gain by controlling the width, height, and orientation of built forms. The slab form provides a sense of boredom, and urban planners may treat this issue carefully to enhance the liveable community. The tower form has a distinguishing character with both pros and cons, including over shadowing other buildings depending on the urban context, and maximising open space dictated for the landscape. The three different urban configurations can be designed to unify the footprint, site coverage, and the space buildings occupy on the site.

The courtyard is recommended as the optimal form in terms of thermal comfort, due to reduced exposure to direct sun and provision of more shading areas. In addition, courtyards allow better natural ventilation, reduce air temperature, and improve the community's sense for liveable space. Moreover, the courtyard divides urban spaces into private, semi-public, and public spaces to enhance privacy, improve the natural surveillance distinguishing public and private areas, providing a flexible form for urban transformation, and therefore, the courtyard is selected as one of the main urban configurations of this research (Ritchie & Thomas, 2009).

A comprehensive urban study undertaken by Ratti, Raydan and Steemers (2003) revealed that the courtyard building form has the best thermal behaviour among the five different forms. Ratti, Raydan and Steemers divided building forms mainly into two types: courtyard and pavilion, and each type was sub-divided in categories illustrated in Figure 1.9.

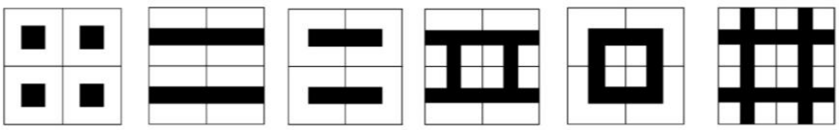


Figure 2.4: From left, the building forms of pavilions, slabs, terrace, terrace –court, pavilion–courts, and courts (Ratti, Raydan & Steemers 2003, p. 51).

In contrast, a recent urban design study conducted by Taleghani et al. (2015) revealed that the courtyard form has the best thermal behaviour in the Netherlands, as shown in Figure 1.10. The study investigated the outdoor thermal comfort of five different configurations which were mainly designed out of three urban forms: singular block, linear block, and courtyard block. The comprehensive study confirms that the courtyard is the best building form in terms of energy saving, environmental behaviour, and land use.

Figure 2.5: Main three urban forms in the Netherlands (singular, linear, and courtyard block). (Taleghani et al. 2015)

2.2.2 Courtyards and Fortresses

Open space is essential for the urban environment, particularly in military camps which host training, functions, and events that are vital to the character of camps and the quality of life that they provide to soldiers and trainees. The size and geometric proportions of the open space influences their microclimates and, accordingly, outdoor thermal comfort.

Courtyards play a multifunctional role, especially in hot arid climates: they provide shaded recreation areas, in addition to protection against harsh weather and sandstorms. Basically, courtyards covered with thermal mass material store heat during the day and releases the heat during the night, making the courtyard appropriate for hot arid climate regions, because day temperatures are significantly higher than those at night. Similarly, courtyards perform well in terms of seasonal thermal behaviour of summer and winter.

2.3 The Need for Sustainable Urban Design of Military Camps

Military camps in the twenty-first century are almost identical with similar dynamics and facing similar challenges. Taking into consideration the hierarchy of command and control, the camps function and respond to missions issued by command. The conventional organisations of military camps respect and obey the command hierarchy, however experiments and solutions to urban issues require top-down decision making. Military camps need to be flexible to survive the ever-changing environment and the uncertain threats of future urbanism.

Urbanism in both military camps and cities is very similar; however, the camps are managed and organised by the government sector alone. The standard military camp looks like the standard neighbourhood area, comprised of administration, accommodation, healthcare, education, recreational area, storage, and industrial zones. On the other hand, military camps are not only the workplace and accommodations, but also they concentrate on missions to be accomplished within a very short timeframe (Harmon, Goran & Harmon 2013).

For example, Camp Edwards military camp in Massachusetts has historically been one of the premier training facilities in the north-eastern United States and comprises similar buildings and urban facilities to the Mahawi military camps in Mahawi, Abu Dhabi, UAE. As shown in the Figure 1.11, master plan facilities for military camps in the UAE and the United States are almost identical.

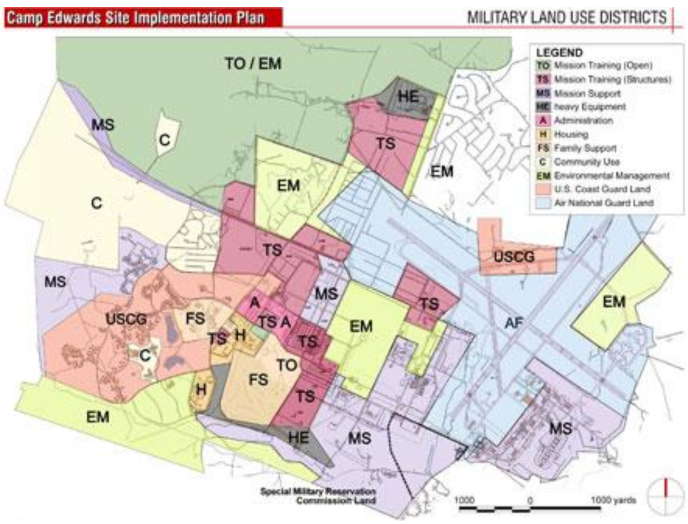


Figure 2.6: Military Camp of Edwards, Massachusetts, U.S. (Cecil Group 2016)

Within these facilities, different operational activities can take place and accordingly a different stream waste will be generated. Apart from ammunition waste, all other types of waste are similar to ordinary civilian neighbourhoods, including wastes from the accommodation zone, administrative office zones, softscape wastes, and construction and demolition (Medina & Waisner 2015).

The main characteristic of military camps is simplicity and flexibility to accommodate mission changes. Demountable, removable, and expandable temporary camps are very common such as SEAhut base camp shown in Figure 1.12, 1.13 and 1.14. Similarly, the Habitation Institute (2007) reported that a standard military camp provides refit services of security protection, reconstruction, and re-funding. It also provides social and recreation life for army staff. Based on the mission, a camp may be constructed as a temporary camp or a permanent camp for variable durations, ranging from days to years.

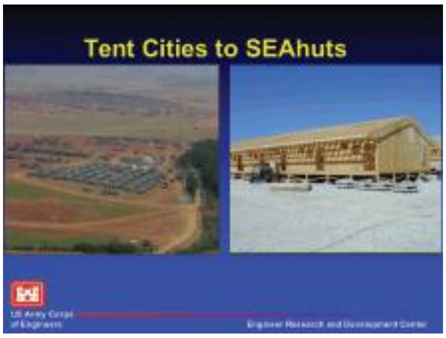


Figure 2.7: Example of military camps in the UAE (Habitation Institute, 2007)

Figure 2.8: Al Dhafra military camp in the UAE (Stanley Consultants 2015).

Figure 2.9: Facility Fort Drum, New York, U.S. (Stanley Consultants 2015).

Project phasing is significant characteristic of military camp planning systems for short-term and long-term projects necessary to maintain and improve facilities and training grounds. In military camps, the commander is responsible for all the assets and operations—land, personnel, facilities, and services—within the camp security fence and boundaries. The main function of military camps is to respond to hierarchical decision-making within authorities established by government legislation and overseen by number of bureaucracies created by the typical defence departments. This function usually requires large payrolls, and the population of military camps significantly increases (Harmon, Goran & Harmon 2013).

The unique functional processes to operate military camps occurs as a result of three main challenges influenced the urban design of military camps directly: the first challenge is security-related issues which have the most significant impact, the second challenge is transformation, and third challenge is environmental-related issues such as brownfield.

The challenges are a comprehensive area of research, where each topic could be a wide examination outside the focus of this study. This research focuses on sustainable urban configurations as a design tool to enhance sustainability in military camps. There are several causes, consequences, and mitigation strategies related to these challenges which will be discussed in detail in the next section.

2.3.1 Security Challenges of Military Camps

Security is another challenge which has caused a number of problems globally, and which increases the need for new construction of military camps, in particular of suitable urban design. One of the most important causes of this growth in military camp construction is oil production, which has recently been the target of radicalism and terrorist attacks. The GCC countries produce 65–70% of the world's oil. The major security issues targeting GCC countries is the free flow of oil to international markets from the Gulf region, which if impeded poses a risk the stability of the Gulf region and oil-importing countries such as the UAE. There are many security-related problems in the region, including wars and conflicts in involving Arab countries, Israel, Iran, Iraq, and other Gulf states. Preventive strategy, not pre-emptive strikes is more suitable for energy supply security, and the fight against radicalism and terrorism is also important for the security of oil supply. The UAE plays an important role in securing oil in the

Gulf region. Şen and Babali (2007) listed four security strategies to be considered to tackle this issue: improving cooperation; improving peace, particularly between the Arabs, Iran, and the United States; construction of a new security system; and fighting against radicalism and terrorism.

Nowadays, one of the most critical and controversial security issues which influences UAE national security is the Yemen crisis. The UAE Armed Forces will continue their role in Yemen alongside Saudi Arabia until the end of the war (Wam 2016). Emirati soldiers perform their combat role in the Saudi-led Arab fusion; credible, professional, and operational training is required and therefore the need for new military camps is fundamental; temporary training camps were erected for the 2015 mission Operation Decisive Storm. In the political and military context, the UAE remains a close, reliable ally to Yemen, regardless of the large transformation occurring in UAE military camps to accommodate larger payrolls and increased staff. ('UAE Armed Forces stay in Yemen till war is over, Gargash says', *The National* 2016).

2.3.2 Transformation Challenges of the Military Camps

Military camps have their own dynamic rhythms of transformation; for example, military staff and populations rapidly increase as a result of forces build-up for deployment during military training, and a reduction of staff occurs when units deploy to operational theatres. In the case of high occupancy loading of military camps, troops under training may use temporary and prefabricates structures for accommodations. During periods between deployments, troop numbers may rapidly decrease and buildings deconstructed or dismantled to be reused elsewhere. In general, the most significant cause of military camp transformation is decisions and initiatives that change the structure of all operational units, and the impact of urbanisation ranges from social, cultural, and economic problems to environmental consequences (Medina & Waisner 2015).

Two examples of urban plan transformation of military camps will be addressed in this section. The first example is the implementation of national service for Emirati men in UAE—a major decision that caused rapid transformations resulting in urban design changes. In January 2014, the president, Sheikh Khalifa, ordered the Cabinet to draw up a bill for a new national defence and reserve force requiring mandatory military service for all Emirati men aged between 18 and 30. Military service is non-compulsory for women who may be trained for nine months, regardless of their education, according to the law (Salem 2014). Emirati men who have finished secondary school must serve for a year, and those who have not completed school will serve two years. The training includes military exercises, and those enlisted in the Armed Forces receive additional security training. Therefore, new military camps need to be constructed to accommodate Emirati trainees every year. The UAE military training program aims to upgrade the capabilities of the armed forces and is not limited to procurement of the latest equipment and arms technology, but also to preparing human resources capable of dealing with different defence technologies. The fully-equipped military camp Seih Hafair Camp National Service School of the Presidential Guard was built especially for national service recruits and opened in March 2, 2016 to accommodate more than 1400 students in the first phase of the project (*The National* 2016).

The second example of military transformation is the Global Rebasing and Base Realignment and Closure (BRAC) located in the U.S. Army Corps of the Engineers Military Program and Directorate of Public Works interface, aimed at handling the military transformation of the BRAC urban project. In 2003 the installation management command revitalised the Army master planning team to design and execute the project for BRAC. Transformation of government-funded army camps in the U.S. is usually completed within a short-range master plan (5–7 years), and the master plan is designed to accommodate the current projected size of BRAC personnel who will be stationed at the new camps by 2020. However, in 2004, the U.S. army announced plans to transform some divisions to combat brigades to accommodate units "rebasing" from overseas to the United States, consequently the master plan was forced to provide facilities and additional occupancy loading for 60,000 soldiers and their families. That transformation was beyond the long-range master plan. Master facility plans had to be developed and executed in very limited time frame of months rather than years. Garrison planners accomplished the mission in 2005, proving capability and liability to handle the task, and further plans were made resulting in the movement of more than 140,000 people needing facilities on well-planned installations (U.S. Army Installation Management Command 2007).

Military camps experience radical changes in population over time. Sharp spikes in population during active training periods, and facilities that serve as bases for Army units, will experience sharp declines in populations during deployments. Second, these facilities can have unique waste streams, particularly munitions, munitions constituents, and residuals of munitions (Medina & Waisner 2015).

2.3.3 Environmental Challenges of the Military Camps – Brownfields

Besides all these functional challenges, military camps face a number of environmental challenges that not only decrease the quality life in urban areas, but also contribute to global climate change and the deterioration of natural resources worldwide. Apart from explosive munitions, wastes generated at military camps are similar to all urban settings such as civilian accommodation and administration facilities. However, training facilities, in particular, provide considerably different waste concerns than those commonly found in civilian urban settings.

Bagaeen (2006) studied military camps as examples of developed brownfields in the United Kingdom, Germany, and Jordan to highlight experiences for redevelopment of military camps as brownfield to reduce government spending, develop income generation, and promote government targets for brownfield housing development. The paper goes on to argue that the challenge in military base redevelopment, as in other brownfield sites, will be to guarantee competitive advantage through revenue-generating activities that can transform these sites into reliable economic opportunities while also looking after the interests of all the parties involved.

Management of base camp solid waste materials is critically important and an area that necessitates continued research; military camp transformation leads to complex and varying compositions of waste streams to accommodate troops of variable occupancy loading.

Military camps operate a wide range of activities, to accommodate and train troops. Storage and industrial facilities are very common in standard military camps, with roles such as storage weapons and ammunition, general storage to support operational demands, and spaces to conduct research and development into the production of munitions (Medina & Waisner 2015).

Medina and Waisner (2015) evaluated waste management plans for five military camp and revealed that hazardous waste is generated as a result of different operational activities mostly related to weapon and ammunitions. Waste minimisation and recycling opportunities were identified, and lifecycle analyses indicated potential for cost savings.

2.3.4 Solution Synopsis and Key Idea

The key idea is to develop sustainable urban design configurations in UAE military camps at all levels. These optimal urban configurations are capable of supporting the operational mission in the most effective, efficient, and sustainable manner to minimise negative impacts on the environment. The UAE army requires design guidelines of standard military facilities to plan and design, construct and deconstruct, and operate and manage military camps in the most effective and efficient way. Sustainable urban configurations in UAE military camps will resolve the above -mentioned challenges because they will:

- Increase flexibility in military camp operations through improvement of urban design standards and guidelines that have a unity of design and are modular, scalable, and adaptable.
- Reduce the threat of opportunistic radicalism and terrorist attacks because of the fortress protection.
- Decrease construction/deconstruction requirements (time, material, equipment, personnel), using a modular urban design configuration allowing flexibility for military camp transformation,
- Reduce negative environmental impacts, offsetting the brownfields issue, and allow for a proper waste management plan to substantially reduce the disposal of excess hazardous material, while also reducing procurement costs.
- Improve operations management (power, water, and waste) to require less soldier, civilian, or contractor oversight and/or support (U.S. Army Training and Doctrine Command 2009).

2.4 The Climate and Micro Climate

Climate is the identical characteristics of weather over years in a certain region and it is divided into two in urban field, the macro climate and micro climate which means forming a small-scale pattern of climate. 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. While Bioclimatic urban design as explained in Chapter 1 is the to design urban spaces and buildings where humans adapt to the surrounding environment to reduce use of energy and minimize our ecological footprint.(Larasati &Mochtar 2013)

2.4.1 The Micro Climate

Climate is the identical characteristics of weather over years in a certain region and it is divided into two in urban field, the macro climate and micro climate which means forming a small-scale pattern of climate. 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. While Bioclimatic urban design as explained in Chapter 1 is the to design urban spaces and buildings where humans adapt to the surrounding environment to reduce use of energy and minimize our ecological footprint.(Larasati &Mochtar 2013)

2.4.2 Parameters Affecting the Microclimate

The parameters affecting outdoor thermal comfort are complex compared to indoor areas because of the controllable and limited number of surfaces that affect each other in indoor spaces. However, outdoor surfaces are numerous and difficult to control. Outdoor thermal comfort is therefore calculated based on certain assumptions. The parameters of a microclimate are enormous and researchers are still working to investigate them. However, the main parameters that influence outdoor thermal comfort, that is, the main four physical parameters that affect the thermal sensation of humans within an open space are: ambient air temperature, mean radiant temperature, relative humidity and air velocity. Some of these parameters are considered to be more important than others in some regions based of their climatic characteristics. Nevertheless, researchers have considered air temperature as the most important parameter in hot and cold regions. Generally, urban planners design urban space based on environmental guidelines and design strategies that are developed by analysis of the climatic characteristics of that particular region. This is known as bioclimatic Urban Design (Mahmoud 2011).

2.4.3 Bioclimatic Urban Design

Improving outdoor thermal comfort is the main benefit of considering bioclimatic design. The environmental quality of urban spaces can be improved significantly through considering tested and developed bioclimatic parameters. *Bioclimatic* urban design means to collect, investigate, and analyse the climate conditions (*climatic*) of urban space to create liveable, environmentally-friendly spaces for human (*bio*). Urban design processes integrate these climatic data into the initial design stage to improve efficiency of the urban spaces, and achieve optimal outdoor thermal comfort. The most popular phenomenon of urbanism is that urban open spaces are warmer than surrounding areas due to positive thermal balance caused by a shortage of softscape and the use of dark-coloured hardscape. This phenomenon is known as urban heat island (UHI), as explained in Chapter 1, which influences human comfort negatively, especially by decreasing air movement and increasing ambient air temperature.

For example, a recent research paper focused on adaptable passive design strategies for an existing Lhasa building in a mountain climate in China (Zhang & Lian 2015). An analysis of basic climate parameters such as temperature, relative humidity, solar radiation, and air velocity was undertaken to provide design strategies such as natural vegetation, solar windows, and thermal mass. These design strategies will be considered in future as guidelines for architects to design energy-efficient buildings.

Another study investigated the impact of urban micro-climatic conditions on renovations to existing open space in Albania (Fintikakis et al. 2011). This group of researchers revealed that using microclimate parameters can reduce the ambient temperature by up to 3 °C to improve outdoor thermal comfort. Fintikakis et al. (2011) carried out a microclimatic survey during daylight in summer, and their simulation tool was validated with the data collected from the monitoring exercise to identify climate conditions. Shaded configurations revealed 1.4–2.0 °C less ambient air temperature compared to similar configurations without shade, and the difference reached 10 °C for shaded configurations covered with grass. Softscape and light-coloured pavement reduced the ambient temperate by 0.5 °C from that of conventional dark-coloured pavement. In an analysis conducted by Tsitoura, Michailidou and Tsoutsos (2016), it becomes clear for a designer that bioclimatic urban design is the key concept in renovating an existing urban space.

2.4.4 Abu Dhabi Climate

Abu Dhabi lies on the coordinates of 24.43_°N, 54.45_°E and classified to be a hyper-arid climate with an extremely hot and humid summer. The average temperature is 40 °C (104 °F) approximately, and is associated with humidity of up to 90%, however, the average overnight low is 30 °C (86 °F). The temperature range in the United Arab Emirates is 17-26 °C in winter and .Rainfall is concentrated in winter between December and March which are the coolest months of the year and the sun is high during the summer season between June and December and heat stresses are high from June to September. as shown in figure 2.10.

The prevailing wind direction is mostly on a north-west axis as shown in Figure 2.11. The maximum wind speed is 9 m/s, recorded in May.

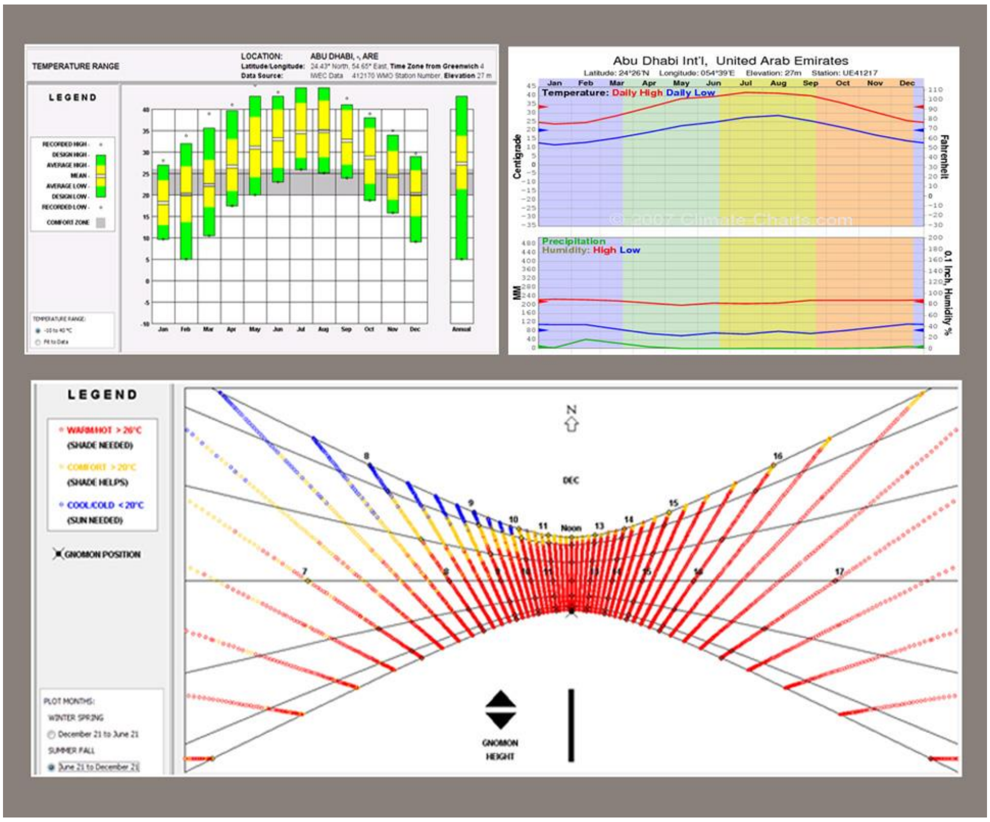


Figure 2.10: The climate of Abu Dhabi , temperature Range ,Cold & Rainy Months and Sun Chart (Climate Consultant 2012).

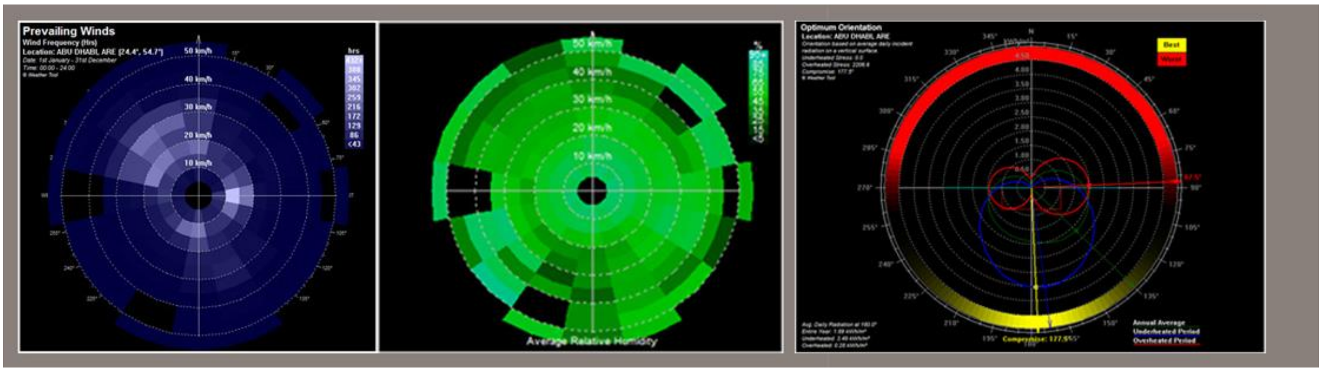


Figure 2.11: Prevailing wind, humidity average and optimum direction in UAE (Ecotect 2012).

In Abu Dhabi, the humidity is considered to be a crucial aspect which influences outdoor thermal comfort negatively. High levels of relative humidity, especially during summer, are markedly high and contribute to a reduction of the thermal comfort sensation because humidity amplifies the heating effect of air temperature. This weather makes outdoor life joyful for only a few months of the year and most of buildings are artificially cooled.

The weather conditions of Abu Dhabi remain a challenging environment for urban planners to achieve thermal comfort. However, applying bioclimatic design and understanding the main parameters controlling the environment leads to outdoor thermal comfort. Thermal stress periods are identified during June and July with maximum values in August which need climatic precautions that do not overcome the extreme coldest levels that occur in January (Islam, Alili & Ohadi 2016).

Figure 2.12 shows the psychometric chart which shows the standard indicators for the human thermal comfort levels of an individual within different climatic zones. This simple visualisation is very helpful for urban planners to clearly identify weather data information regarding the temperature and moisture levels within the climate in relation to one another.

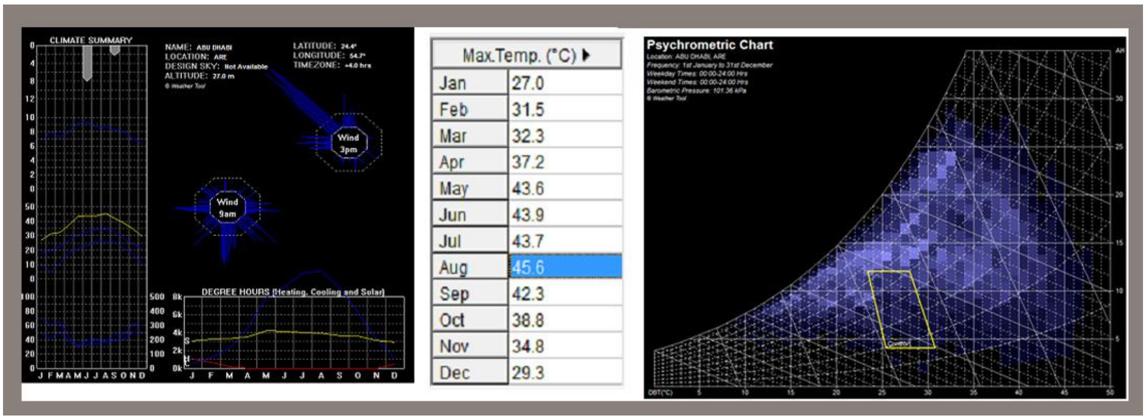


Figure 2.12: Climate summary and psychometric chart. (Ecotect 2012)

2.5 Urban Configurations Parameters

There are many of uncontrollable variables that affect outdoor thermal comfort. They can be divided into two groups of parameters: climatic and morphological. Air temperature and wind speed are the most important climatic parameters in outdoor thermal comfort levels. The key, complementary, morphological parameters are building form and open space (courtyard) proportions, which are considered to be interrelated. This research focuses on this interrelationship in order to control thermal comfort factors, allowing urban planners to improve outdoor thermal comfort throughout bioclimatic urban design, hence achieving the most favourable urban configurations for military camps. Sufficient information about all various parameters has to be gathered carefully, particularly when dealing with an outdoor environment.

The interrelationship between urban configurations and outdoor thermal comfort has been an area of interest for many researchers and urban design professionals. Early research can be categorised into three main groups. The first group concentrates on research on the impact of different urban configurations on UHI mitigation. The second group concentrates on the psychological and physical impact of urban green spaces on outdoor thermal comfort. The third group concentrates on thermal performance characteristics and human comfort considerations of urban morphology parameters. Since UHI and green spaces are not the main focus of this research, this literature review chapter will concentrate on the third group of previous work.

For the purpose of clarity, this chapter reviews the body of research and analysis on this topic in detail. Classification and prioritisation of reviewed research papers is conducted based on urban morphological configurations parameters as applied within the urban space. Each of these categories is discussed in the following sections:

- Studies on the impact of urban configurations parameters as building form/W ratio and orientation.

- Studies on the impact of urban configurations parameters -open space and courtyard.

It is important to mention that climatic parameters will be reviewed simultaneously with these two categories.

2.5.1 Studies on the Impact of Urban Configurations Parameters - H/W Ratio and Orientation

The body of research in this area focuses on different specific aspects of application and impact of different urban morphologies on outdoor thermal comfort. However some studies focus on the overall relationship between the physical character of building forms such as H/W ratio, building typology, and height of the buildings, while other studies focus on the impact of orientation.

By using the ENVI-met model, researchers demonstrated that H/W ratios and sky view factor (SVF) were the most important factors influencing outdoor thermal comfort; moreover, the widest streets were the least comfortable. Three different height–width ratios were investigated—4, 1, and 0.25—and four different orientations were studied—north–south, east–west, north east–south–west, and north west–south east—as demonstrated in Figure 2.13. An H/W ratio of 4 provided acceptable thermal comfort during hot seasons, as higher buildings provided more shaded area and less space exposed to direct sun. In contrast, and H/W ratio of 4 reduced ambient temperature by 8.48 °C less than that provided under an H/W ratio of 0.25. On the other hand, during daylight more space was exposed to solar heat penetration at an east–west orientation to confirm that a north–south orientation was the best scenario, allowing prevailing wind to reduce heat gain during the day (Younsi & Kharrat 2016).

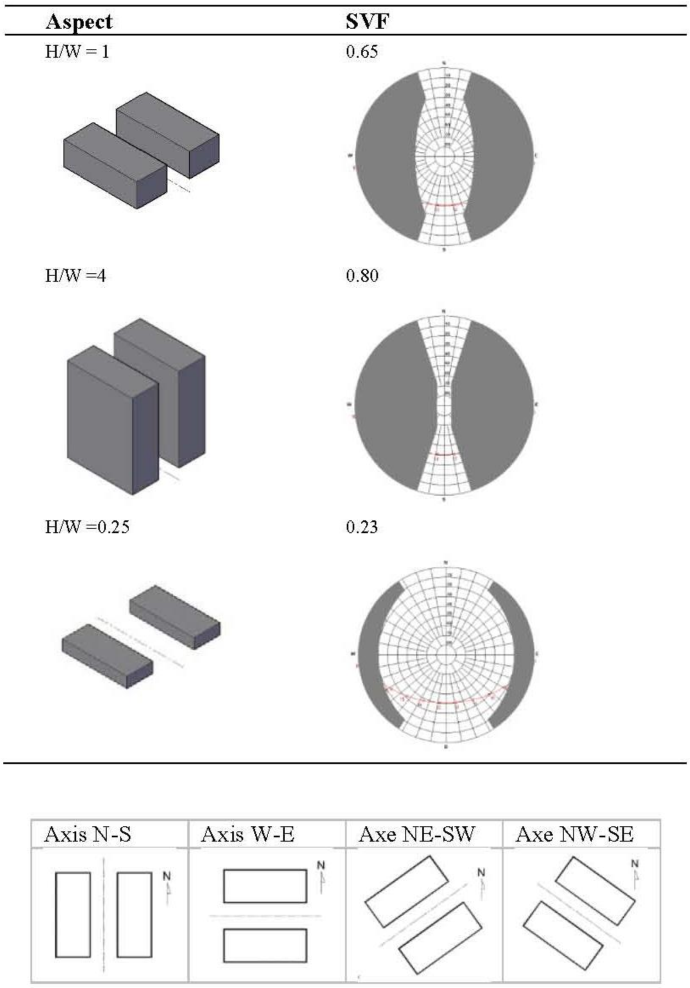
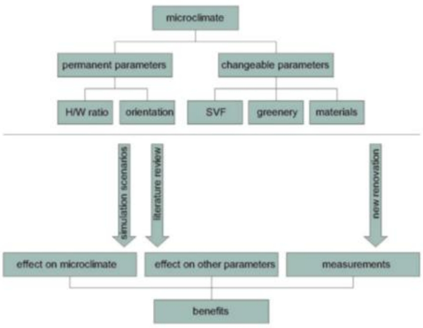


Figure 2.13: Different simulated scenarios, H/W ratios, related SVF, and orientations (Younsi & Kharrat 2016, p. 695)

A study focusing on the quantification and prioritisation of the effects of basic parameters regarding the design of urban open spaces was conducted by Tsitoura, Michailidou and Tsoutsos (2016). In this research, renovation of existing urban space was addressed, investigating the SVF, H/W ratio of an urban canyon, and softscape and hardscape material property parameters separately and simultaneously. Both existing and planned urban space were considered. They found using bioclimatic design to improve outdoor thermal comfort at the initial planning stage was more effective compared to adapting existing urban space, where design modification and improvement options were limited. Accordingly, parameters were categorised into two types: fixed parameters, such as H/W ratio and orientation, and changeable parameters such as material properties of hardscape, percentage coverage of softscape, and SVF as illustrated in Figure 2.14. Changeable parameters most significantly affected decisions of urban designers, as they control the microclimate.



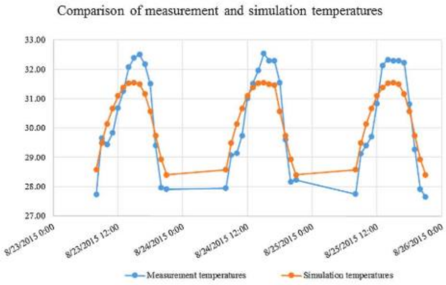


Figure 2.14: Methodology chart (Tsitoura, Michailidou & Tsoutsos 2016, p. 50)

Figure 2.15: Comparison of the measured and simulated temperatures within the area of study.Fig. 2. (Tsitoura, Michailidou & Tsoutsos 2016, p. 53)

However, good transformation of existing spaces was achieved and outdoor thermal comfort was fulfilled. The researchers used a combined methodology of simulation and literature review. ENVI-met software was used to simulate 16 different scenarios, as shown in Table 2.1, and then results validated as shown in Figure 15.

Table 2.1: Simulation case parameters (Tsitoura, Michailidou & Tsoutsos 2016, p. 49).

Case	No of open sides	Canyon width (m)	Building height (m)	H/W	Material mean albedo	SVF	Percentage of trees (%)	Percentage of grass	Orientation
1	2	15	16	1.07	0.25	0.3	0.00	0.00	North–South
2				1.07	0.25	0.3	0.00	0.00	East–West
3	2	15	16	1.07	0.21	0.13	25.00	0.00	North–South
4				1.07	0.21	0.13	25.00	0.00	East–West
5	2	15	16	1.07	0.19	0.09	45.00	0.00	North–South
6				1.07	0.19	0.09	45.00	0.00	East–West
7	2	15	16	1.07	0.15	0.3	0.00	45.00	North–South
8				1.07	0.15	0.3	0.00	45.00	East–West
9	2	15	8	0.53	0.25	0.45	0.00	0.00	North–South
10				0.53	0.25	0.45	0.00	0.00	East–West
11	2	15	8	0.53	0.21	0.15	25.00	0.00	North–South
12				0.53	0.21	0.15	25.00	0.00	East–West
13	2	15	8	0.53	0.19	0.1	45.00	0.00	North–South
14				0.53	0.19	0.1	45.00	0.00	East–West
15	2	15	8	0.53	0.15	0.45	0.00	45.00	North–South
16				0.53	0.15	0.45	0.00	45.00	East–West

The bioclimatic aspects of temperature, surface temperature, humidity, radiation environment, and wind speed for the existing area were measured, and the measurements compared to results achieved from the ENVI-met simulation—the difference was less than 1°C for the 16 points.

Taking into consideration Mediterranean climates have 7 months of hot–dry summer, this study revealed that H/W ratio had significant influence on an east–west orientation of canyons, but only minimal impact on north–south orientations. In this regard, an east–west orientation most significantly affected solar penetration and shaded area, while sun penetration was lower on NS canyons. A higher H/W ratio on an east–west orientation could significantly decrease the air temperature by 1.70 °C at a height of 1.80 m. Mean surface temperature was reduced by approximately 8.45 °C.

Some researchers have focused on the impact of urban morphology and area typology on outdoor thermal comfort. Ignatius, Wong, and Jusuf (2015) believed that addressing the effect of physical density and form of urban configuration on surface ambient temperature, urban ventilation, external heat gain, and outdoor thermal comfort would provide comprehensive insight into urban microclimate analysis. Their study concentrated on commercial office buildings in the urban area of Singapore, with a plot area of 9 ha, comprised of six buildings with a total area 63,000 m^2, and a maximum plot ratio set at 10 to comply with local authority guidelines. Four different hypothetical building configurations with five different site coverages (20%, 30%, 40%, 50%, and 60%) were proposed on an empty block, as shown in Figure 2.16. In order to simplify the analysis, the height of buildings was unified within each configuration, and variable density was addressed by splitting the building into two, four, and six smaller sizes. The SVF was also calculated for each urban configuration.

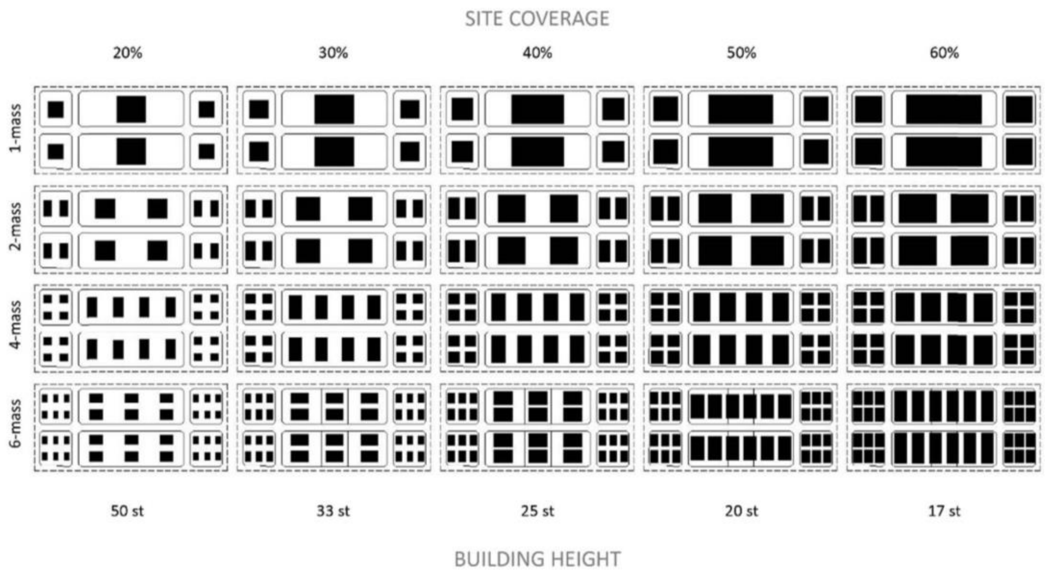


Figure 2.16: Parametric design results using site coverage, compactness, and building height iterations. (Ignatius, Wong & Jusuf 2015, p. 124)

Then, the Screening Tool for Estate Environment Evaluation (STEVE) utility was used to investigate different parameters of outdoor thermal comfort. Thermal load and heat gain was calculated to investigate which urban configuration had the most negative thermal impact on outdoor areas.

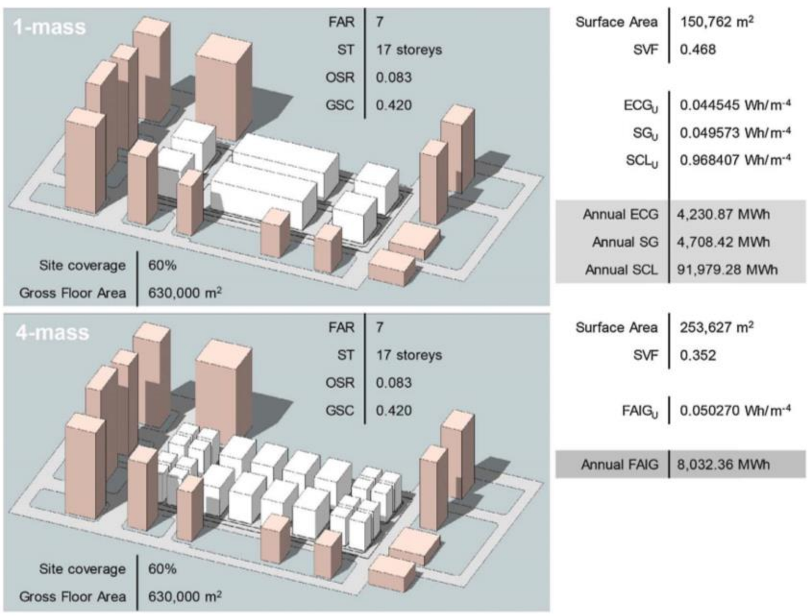


Figure 2.17: Design configurations with the lowest solar gain per annum (Ignatius, Wong & Jusuf 2015, p. 128)

The STEVE simulation revealed that outdoor thermal comfort, particularly in terms of thermal load, was increased when the SVF reduced. The floor area ratio (FAR) was set to comply with building codes as shown in Figure 2.17, and variable heights of buildings were used to investigate different gross site coverage (GSC) values. Less compact urban configurations provided the most envelope conduction gain per annum, as illustrated in Figure 2.18; for example, a site coverage of 60% had the least heat gain, while the highest heat gain was predicted on 20% site coverage.

Predicted total thermal load for each design iteration.

ANNUAL ENVELOPE CONDUCTIONG GAIN (ECG)					
Site Coverage	**20%**	**30%**	**40%**	**50%**	**60%**
1-mass	5,411.63	4,936.25	4,671.24	4,448.96	4,230.87
2-mass	7,298.24	6,512.62	6,006.13	5,593.94	5,214.80
4-mass	9,496.49	8,378.88	7,676.78	6,994.77	6,461.07
6-mass	11,104.88	9,908.42	9,039.87	8,427.10	7,888.99
ANNUAL SOLAR GAIN UNIT (SG)					
Site Coverage	**20%**	**30%**	**40%**	**50%**	**60%**
1-mass	12,427.33	8,316.74	6,488.77	5,394.20	4,708.42
2-mass	16,310.24	10,668.68	8,120.72	6,624.74	5,688.73
4-mass	20,563.77	13,294.72	10,074.35	8,032.60	6,870.69
6-mass	23,729.86	15,581.20	11,782.82	9,655.12	8,291.06
ANNUAL FRESH AIR INTAKE GAIN UNIT (FAIG)					
Site Coverage	**20%**	**30%**	**40%**	**50%**	**60%**
1-mass	18,154.06	13,850.26	11,886.23	10,235.49	9,143.58
2-mass	17,590.86	12,985.56	11,004.52	9,667.85	8,841.36
4-mass	15,595.92	11,332.68	9,784.63	8,314.42	8,032.36
6-mass	15,521.89	12,016.36	10,608.29	9,739.47	8,500.57
ANNUAL SENSIBLE COOLING LOAD UNIT (SCL)					
Site Coverage	**20%**	**30%**	**40%**	**50%**	**60%**
1-mass	177,612.40	137,272.74	118,165.36	102,615.31	91,979.28
2-mass	187,874.70	140,908.16	119,357.29	104,564.81	94,852.81
4-mass	184,410.64	136,306.31	116,849.42	99,312.25	93,564.84
6-mass	191,553.77	148,772.39	129,492.52	117,204.04	102,847.08

(Unit: MWh) LOW HIGH

Figure 2.18: Envelope conduction gain per annum for different urban configurations (Ignatius, Wong & Jusuf 2015, p. 129).

Moreover, the impact of hardscape and softscape on ambient temperature was examined against baseline conditions. Four different outdoor materials were proposed: pavement, grass, pavement with grass, and grass with trees. The results of data analysis (Figure 2.19) showed that temperatures of selected green areas (trees and grass) were lower than for sunlit pavements in all cases; particularly, combined grass and trees showed a mean reduction of 0.79 °C–1.3 °C. On the other hand, different configurations had no significant impact on wind conditions. Taking into consideration that site coverage carries the most important impact on area of outdoors spaces available for landscaping, and therefore reduction of outdoor temperature, this study concluded that the best outdoor thermal comfort was provided by a site coverage of 40%, the most compact building form configuration, and outdoor space covered with a mixed grass and trees softscape. Meanwhile, site coverage of 60% also with the most compact configuration covered by mixed grass and trees softscape had the lowest thermal performance.

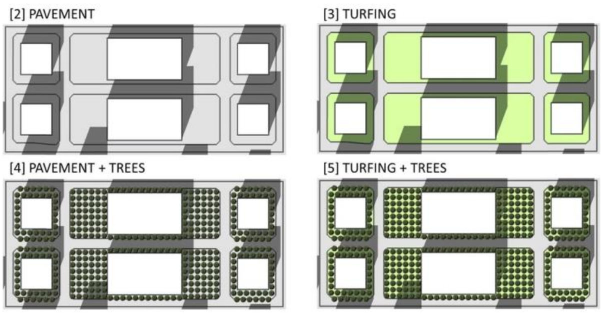
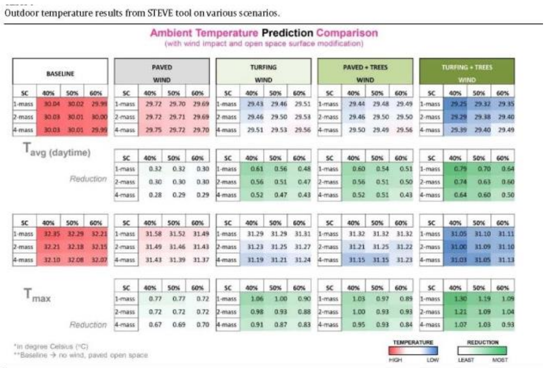


Fig. 7. Open space modifications which will be applied on each design iteration to observe its impact on ambient temperature.



Outdoor temperature results from STEVE tool on various scenarios.

Ambient Temperature Prediction Comparison
(with wind impact and open space surface modification)

$T_{avg\ (daytime)}$

SC	BASELINE 40%	50%	60%	PAVED WIND 40%	50%	60%	TURFING WIND 40%	50%	60%	PAVED + TREES WIND 40%	50%	60%	TURFING + TREES WIND 40%	50%	60%
1-mass	30.04	30.02	29.99	29.72	29.70	29.69	29.43	29.46	29.51	29.44	29.48	29.49	29.25	29.32	29.35
2-mass	30.03	30.01	30.00	29.72	29.71	29.69	29.46	29.50	29.53	29.46	29.50	29.50	29.29	29.38	29.40
4-mass	30.03	30.01	29.99	29.75	29.72	29.70	29.51	29.53	29.56	29.50	29.49	29.56	29.39	29.40	29.49

Reduction

SC	PAVED 40%	50%	60%	TURFING 40%	50%	60%	PAVED + TREES 40%	50%	60%	TURFING + TREES 40%	50%	60%
1-mass	0.32	0.32	0.30	0.61	0.56	0.48	0.60	0.54	0.51	0.79	0.70	0.64
2-mass	0.30	0.30	0.30	0.56	0.51	0.47	0.56	0.51	0.50	0.74	0.63	0.60
4-mass	0.28	0.29	0.29	0.52	0.47	0.43	0.52	0.51	0.43	0.64	0.60	0.50

T_{max}

SC	BASELINE 40%	50%	60%	PAVED WIND 40%	50%	60%	TURFING WIND 40%	50%	60%	PAVED + TREES WIND 40%	50%	60%	TURFING + TREES WIND 40%	50%	60%
1-mass	32.35	32.29	32.21	31.58	31.52	31.49	31.29	31.29	31.31	31.32	31.32	31.32	31.05	31.10	31.11
2-mass	32.21	32.18	32.15	31.49	31.46	31.43	31.23	31.25	31.27	31.21	31.25	31.22	31.00	31.09	31.10
4-mass	32.10	32.08	32.07	31.43	31.39	31.37	31.19	31.21	31.24	31.15	31.15	31.23	31.03	31.05	31.13

Reduction

SC	PAVED 40%	50%	60%	TURFING 40%	50%	60%	PAVED + TREES 40%	50%	60%	TURFING + TREES 40%	50%	60%
1-mass	0.77	0.77	0.72	1.06	1.00	0.90	1.03	0.97	0.89	1.30	1.19	1.09
2-mass	0.72	0.72	0.72	0.98	0.93	0.88	1.00	0.93	0.93	1.21	1.09	1.04
4-mass	0.67	0.69	0.70	0.91	0.87	0.83	0.95	0.93	0.84	1.07	1.03	0.93

*in degree Celsius (°C)
**Baseline → no wind, paved open space

TEMPERATURE: HIGH – LOW; REDUCTION: LEAST – MOST

Figure 2.19: Outdoor temperature results from STEVE tool on various scenarios (Ignatius, Wong & Jusuf 2015, pp. 127, 131).

A Swiss study conducted by Allegrini, Dorer, and Carmeliet (2015) focused on investigating the impact of general urban morphology on outdoor thermal comfort. This study was conducted through computational simulations by CFD (computational fluid dynamics) and building energy simulations for six generic urban morphologies, as shown on Figure 2.20. The heat fluxes through the boundaries of the urban areas were analysed. This study had the advantage of having highly spatially-resolved temperature and flow fields, and therefore was able to determine heat fluxes. The results showed the importance of wind conditions to remove heat from urban areas, particularly at the top of buildings or in a downstream direction. Buildings are considered as obstacles to wind. Although with higher obstacles more heat can be removed through the top plane and therefore a smaller part of the heat is transported downstream by convection, air temperatures are higher for urban areas with higher blockage due to lower wind speeds.

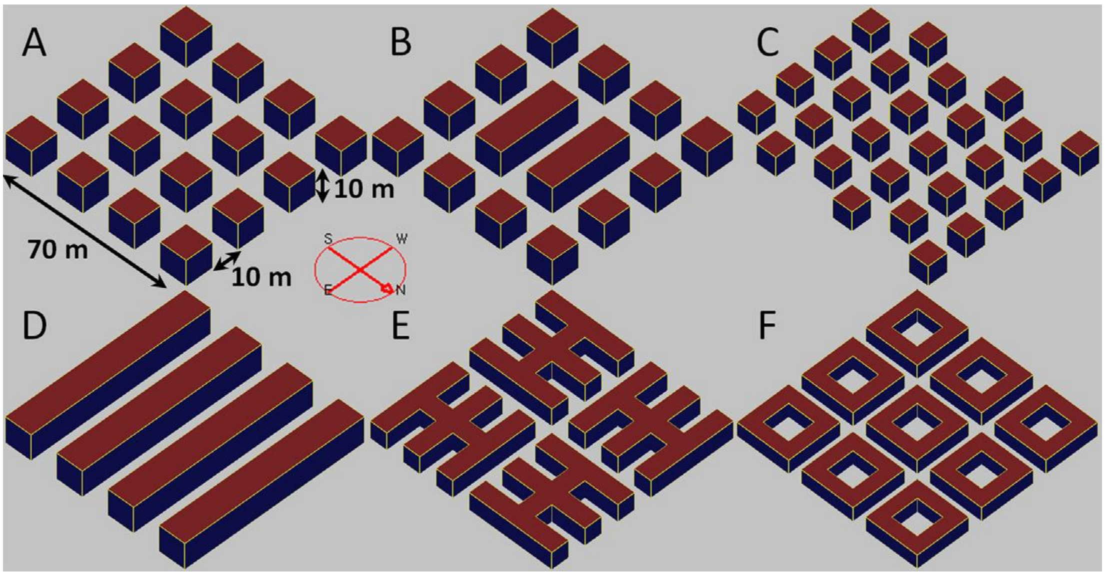


Figure 2.20: The layout and orientation of the six urban scenarios (Allegrini, Dorer & Carmeliet 2015, p. 387)

A full view of impact of building shape on energy efficiency and thermal comfort was undertaken by Okeil (2010) and followed by Taleghani et al. (2015). The papers sought to take investigate the potential of a holistic approach to energy-efficient building forms. Three urban configurations were investigated: two conventional configurations (linear form, and block form) and new urban form which was named residential solar block (RSB), as shown in Figure 2.21 The RSB form was designed as an L-shape building to improve the aesthetics and functionality of a conventional residential building shape, with overshadowing restrictions on site considered to provide almost the exact shade for the open space during summer.

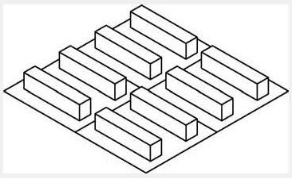
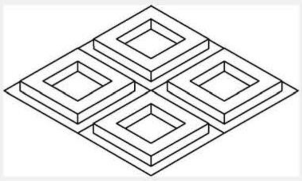
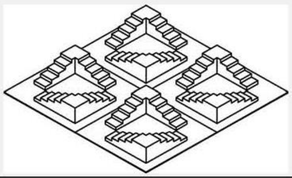
Module parameters		Layout (2 × 2 modules)
Urban form: linear		
Module size: 76.8 m × 76.8 m Building length: 60 m Building height: 15 m Street width: 26.4 m, 16.8 m Foot print/module: 1440 m^2 Surface area/volume: 0.28	Total area: 5898 m^2 Building width: 12 m Court: 60 m × 26.4 m Orientation: 0°, 45°, 90° Floor area ratio: 1.2	
Urban form: block		
module size: 76.8 m × 76.8 m Building length: 60 m Building height: 9 m Street width: 16.8 m Foot print/module: 2304 m^2 Surface area/volume: 0.2	Total area: 5898 m^2 Building width: 12 m Court: 36 m × 36 m Orientation: 0°, 45° Floor area ratio: 1.17	
Urban form: RSB		
Module size: 76.8 m × 76.8 m Building length: 60 m Building height: 3–15 m Street width: 16.8 m Foot print/module: 1840 m^2 Surface area/volume: 0.31	Total area: 5898 m^2 Building width: 12 m Court: 36 m × 36 m Orientation: 45° Floor area ratio: 1.1	

Figure 2.21: Main parameters of urban forms studied for incident solar radiation (Okeil 2010, p. 1440).

In this research, photo-voltaic (PV) panels were integrated for heated water, where maximising solar exposure during winter was a desirable effect; however the proposed RSB also attempted to reduce heat gain during summer. The computer tool CITY SHADOWS was developed to look at overshadowing and solar exposure within certain climate conditions for the three variable forms shown in Figure 2.21. ENVI-met was used to simulate airflow. Six different orientations were examined:

- Linear form at 0°, long sides aligned north-south
- Linear form at 45°, long sides aligned north east–south west
- Linear form at 90°, long sides aligned east–west
- Block form at 0°, sides facing north, east, west, south
- Block form at 45°, sides facing north east, south east, south west, north west
- RSB at 45°**,** sides facing north east, south east, south west, north west

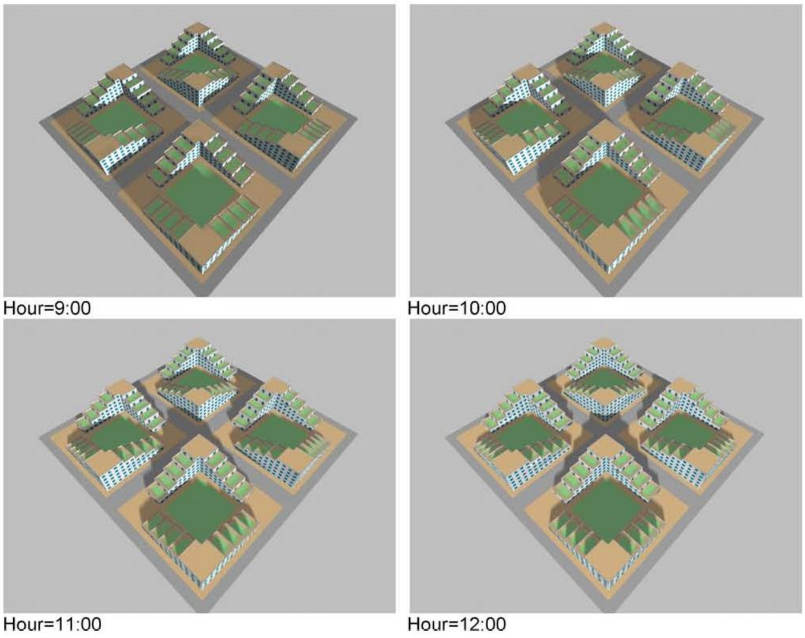


Figure 2.22: Main range of shadows 9:00–12:00pm in December for an RSB optimised for latitude 48.00. (Okeil 2010, p. 1439).

The ENVI-met simulation revealed that the courtyard created by an RSB L-shape configuration results in better thermal comfort due to enhanced air flow. The RSB form increased solar radiation in winter compared to the two other forms. According to Okeil (2010), a holistic approach to building forms had a significant effect on energy efficiency and thermal comfort.

Another study focused on investigating the mitigation of UHI and the impact of organic and structured urban configurations on temperature variations in Dubai (Taleb & Abu-Hijleh 2013). This study was conducted through simulation with the ENVI-met tool to examine the impact of three different urban configurations on temperature variations. Urban density was studied along with building geometry and street canyons. A model of Dubai's Bastakiyah district was selected to represent the old traditional organic urban configuration, and two structured configurations represented in perpendicular and linear configurations for a new part of Dubai. Simulation input data was 32 °C temperature, and wind speed variable between 0.1 m/s, 3.6 m/s, and 7 m/s, subject to season.

Figure 2.23 shows the results of ambient air temperature in Bastakiyah and linear at 14:30 in June. The results reveal that organic urban configurations have lower temperatures in summer compared to an urban structure in a new part of Dubai, however temperature differences in other seasons were minimal. In contrast, linear configurations had higher wind speeds, which did not influence temperature values.

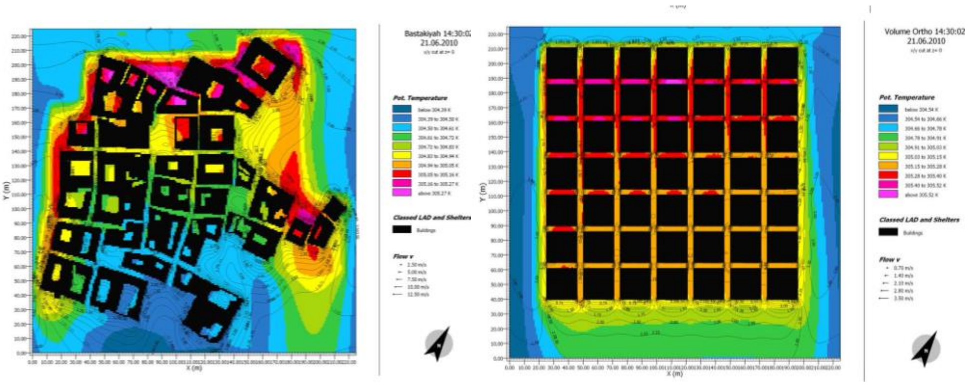


Figure 2.23: Temperature gradient in Bastakiyah and perpendicular configurations at 14:30 in June (Taleb & Abu-Hijleh 2013, p. 112).

According to ENVI-met simulation results as shown in Figure 2.24, the three different configurations had a significant effect on wind speed, and Bastakiyah, as an organic, urban design, provided the best outdoor thermal comfort.

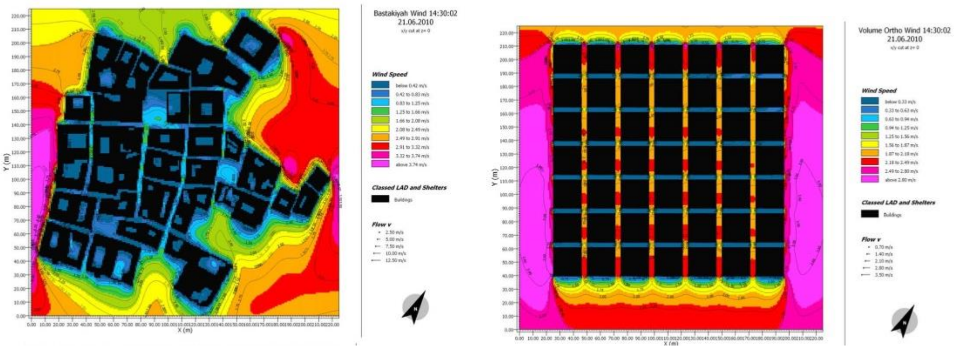


Figure 2.24: Wind contours in Bastakiyah and perpendicular configurations at 14:30 in June (Taleb & Abu-Hijleh 2013 p. 114).

Some researchers have focused on the role of urban morphology, particularly the impact of urban design parameters on outdoor thermal comfort. Chatzidimitriou and Yannas (2016) believe that the effectiveness of urban parameters and their impact on the urban micro climate must be investigated simultaneously, hence comparative assessment was provided. In this study, three computational software tools—ENVI-met, RadTherm, and Fluent—were used to evaluate overall microclimate, radiant temperature, and air movement, respectively. Due to the complexity of actual urban environment, the results of this simulation were then compared to measured data of the selected points (in Thessaloniki) in the summer period for validation, as well compared with numerous studies in the literature. Their study found 80% of the results were identical for the majority of parameters addressed. Two common urban configurations were chosen: the first was a square of 400 m^2, adjacent to buildings of 20 m height (h/w =2.0) and 10 m street width. The second urban configuration was a 20 m x 20 m courtyard, and building height was 20 m. For both areas, the simulation was conducted to comprise bigger urban space that the exact area of research for accurate results, as shown in Figure 2.25.

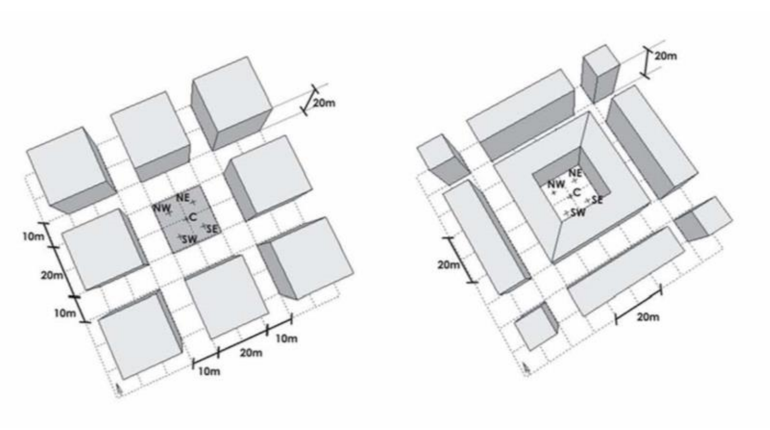


Figure 2.25: Geometric form of the base case of the two different configurations (Chatzidimitriou & Yannas 2016, p. 30)

The results of this study revealed that the mean radiant temperature (MRT) in the courtyard was lower than the square due to extra shading, and that doubling the H/W from 1 to 2 influenced the MRT, with a reduction of 3.5 °C – 4.5 °C for both the square and courtyard, respectively. Shading canopies improved the outdoor thermal comfort, with the simulation from Fluent showing a 5 °C reduction of PET on the two selected forms. Moreover, air velocity was significantly increased under the canopies due to channelling, as shown in Figure 2.26.

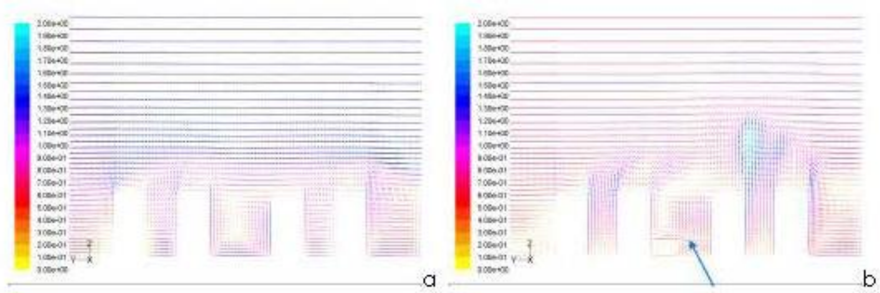


Figure 2.26: Comparison of air velocity between baseline and courtyard fully covered by shading canopy (Chatzidimitriou & Yannas 2016, p. 35)

The results of this study revealed that an increment of albedo from 0.5 to 0.8 improved outdoor thermal comfort by lowering the surface temperature by 5 °C. Also, the effect of hardscape material on PET was a reduction of 2.5 °C where hard pavements were replaced by grass, while the effect on square configurations was 4 °C, as illustrated in Figure 2.27.

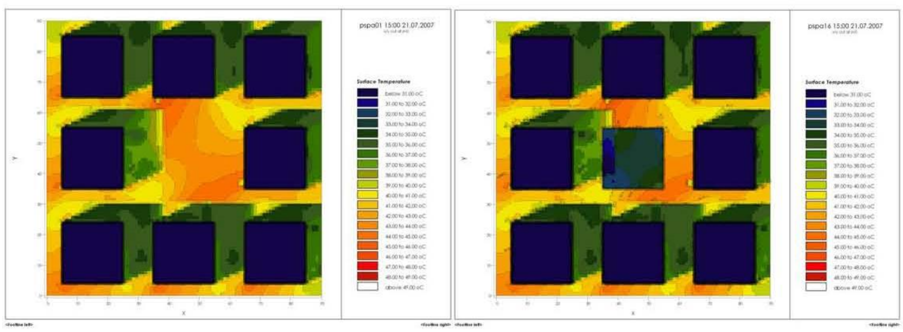


Figure 2.27: Square surface temperature—comparison of the baseline with 100% grass cover (simulation results by ENVI-met) (Chatzidimitriou & Yannas, 2016, p. 36)

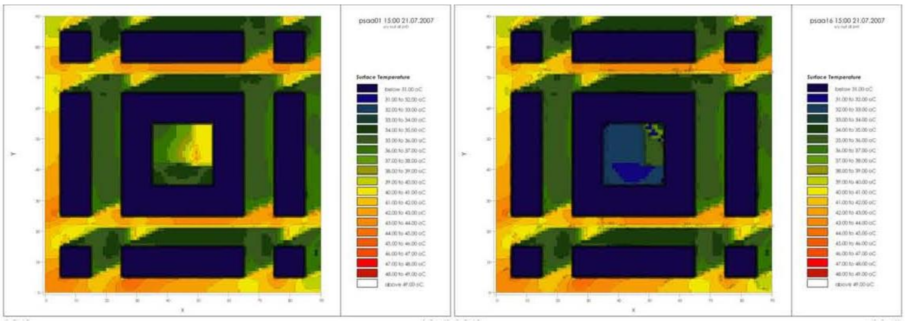


Figure 2.28: Courtyard surface temperature, comparison of the baseline with 100% grass cover (simulation results by ENVI-met) (Chatzidimitriou & Yannas, 2016, p. 36)

It was observed that the impact of H/W ratio was more significant on the courtyard configuration than on the square. In contrast, the effect of shading canopies was trivial to slight on the microclimate of the courtyard compared to the square. In this study, the importance of urban features—such as built form and street geometry, trees, vegetation, water elements and pavement materials—was graded on how they shaped the microclimates of open spaces and influence pedestrian thermal comfort and the use of these spaces by pedestrians as illustrated in Figure 2.28.

The importance of canyon direction and its influence on mean radiant temperature was raised by Targhia and Dessel (2015). In this research, the variation of outdoor thermal comfort conditions affected by urban configurations was explored. The impact of urban geometry and form on the microclimates of open spaces was assessed by simulating the MRT and PET in four different urban configurations in Worcester, Massachusetts, in the United States.

The study area was medium density, with five–storey buildings, and street canyons in north–south and east–west orientations. The urban area was selected to examine different configurations, H/W ratios, SVFs, and orientations as illustrated in Table 2.2 and Figure 2.29. Streets materials were asphaltic, with side pathway covered with concrete tiles. Moreover, façade treatment was considered as glass and brick.

Table 2.2: Urban geometry, SVF and H/W ratio for areas of the study (Targhia & Dessel 2015, p. 1157)

Study area	SVF	H/W	Major surface material
Location 1 (E-W canyon)	0.34	2.00	Pavement: asphalt Building facades: glass and brick
Location 2 (N-S canyon)	0.52	1.75	Pavement: asphalt Building facades: light grey stone, brick
Location 3 (urban square)	0.75	0.5	Pavement: asphalt and grass Building facades: light grey stone, brick
Location 4 (surface parking)	0.68	0.16	Pavement: asphalt Building facades: brick

Figure 2.29: Study locations in downtown Worcester: 1- East-west canyon, 2- North-south canyon, 3- Urban square and 4- Surface parking.

Three computational tools were used to investigate the impact on outdoor thermal comfort—ENVI–met 3.1, RayMan 1.2, and Urban Modeling Interface (UMI). ENVI–met was used to calculate outdoor thermal comfort aspects such as air temperature (°C), relative humidity (%), wind velocity (m/s), vapour pressure, and MRT (°C) of the area. RayMan was used to simulate the short- and long-wave radiation fluxes densities, sunshine duration, shadow spaces, and thermo-physiological parameters, including for the adjacent area. The third software, UMI, was developed by the author to provide operational and embodied energy use, walkability, and delighting potential of neighbourhoods and cities (Targhia & Dessel 2015).

To validate data, measurements were taken during June and July 2015 at the four existing points for global radiation and MRT conducted using an FLIR infrared camera to measure surface temperature and an HOBO weather station to measure air temperature.

Simulation results examined thermal comfort conditions at 1.6 m from 8 am to 8 pm to represent daytime hours during the hottest day of the year, which was July 2, 2015. As illustrated in Figure 2.30, there was no impact on MRT in the morning between the four configurations, while the three configurations other than the north–south canyon began to move into the discomfort zone from 12 pm. The east–west orientation was the worst case in terms of thermal comfort,, but the north–south orientation was relatively more comfortable than the other three locations, and began to warm from 15:00 to 20:00 during which 65.4 °C was the peak temperature. On the other hand, the east–west orientation reached its highest MRT (74.8 °C) at 15:00.

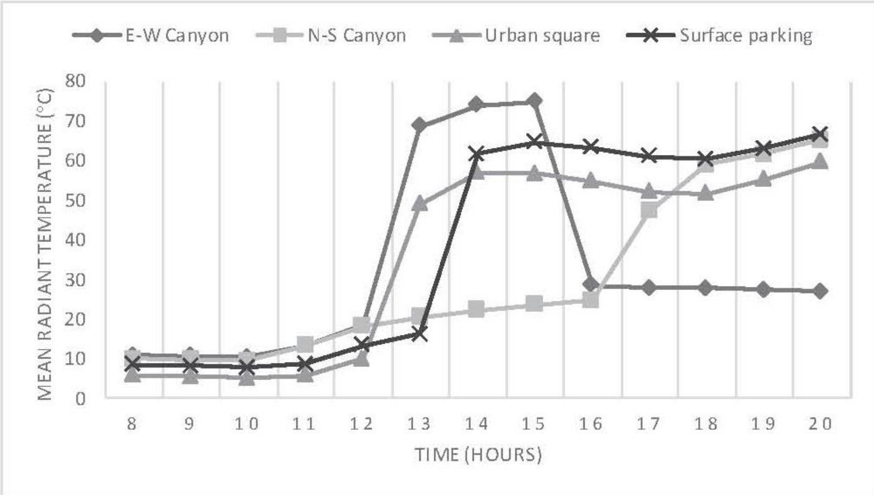


Figure 2.30: MRT (°C) at specific points in four locations from 8:00 h to 20:00 h on July 2, 2015. (Targhia & Dessel 2015, p. 1159).

PET measures were taken from 08:00 h to 20:00 h in four locations. The graph in Figure 2.31 highlights the discomfort zone which was significant in the east–west case, while the north–south case performed better, particularly from 12:30 h to 20:00 h. The urban square and surface parking cases were relatively similar, with discomfort beginning after 14:00 h.

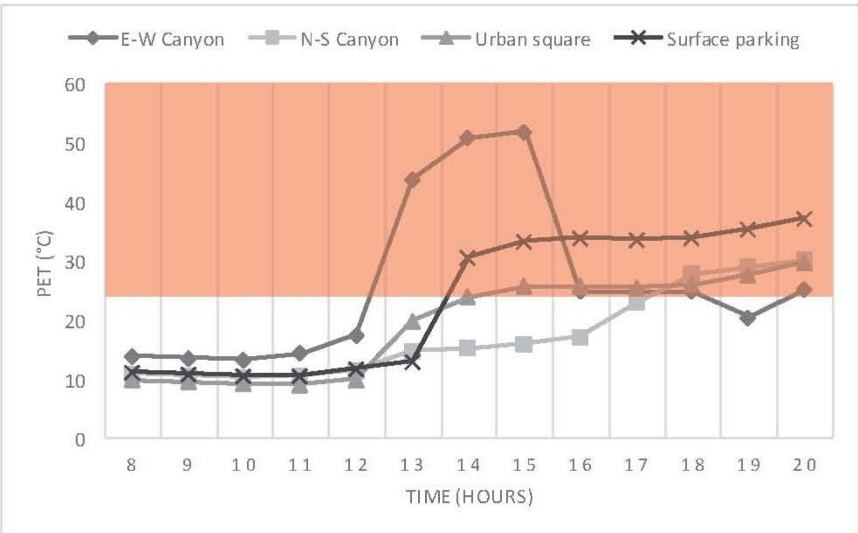


Figure 2.31: PET (°C) at specific points in four locations from 08:00 h to 20:00 h on July 2, 2015. (Targhia & Dessel 2015, 1159).

A recent study conducted by Algeciras, Consuegra, and Matzarakis (2016) agrees that the duration and time of day of high thermal stress within a street canyon depends strongly on aspect ratio (H/W) and street orientation. They assessed different urban configurations and their impact on microclimate outdoor thermal comfort, particularly MRT and PET in the historical urban centre of Camagüey, the largest in Cuba. They used the RayMan modelling software to examine the relationship between solar access, urban street configurations, and SVF to assess pedestrian outdoor thermal comfort.

Simulations were performed in summer and winter for different canyons orientations—north—south, east–west, north east–south west, and south east–north west—for five points in the hot-humid climate of Camagüey, Cuba. The selected canyon was 380 m long and 9 m wide. Ratios for H/W from 0.5 to 5.0 were examined, with results finding that the east-west orientation gained more solar radiation in summer and no beam radiation in winter, however the north–south orientation was highly comfortable. It was seen that intermediate orientations of north east–south west and south east–north west behaved similarly to the north–south orientation.

Figure 2.32 shows PET values for simulations conducted for summer during the night, where the north–south orientation generated the highest PET value. The east-west orientation indicated extreme discomfort at an H/W ratio less than 1.5 with increased heat stress and substantially reduces PET values, while PET values of approximately 35 °C was achieved at an H/W ratio higher than 1.5. Further, an H/W ratio higher than 2.0 provided more shaded area up to 14:00 h, and became the most comfortable situation during summer. This study revealed that an H/W ratio of 2.0 and a north–south orientation can achieved the best comfort in the critical hot hours of summer (Algeciras, Consuegra & Matzarakis 2016).

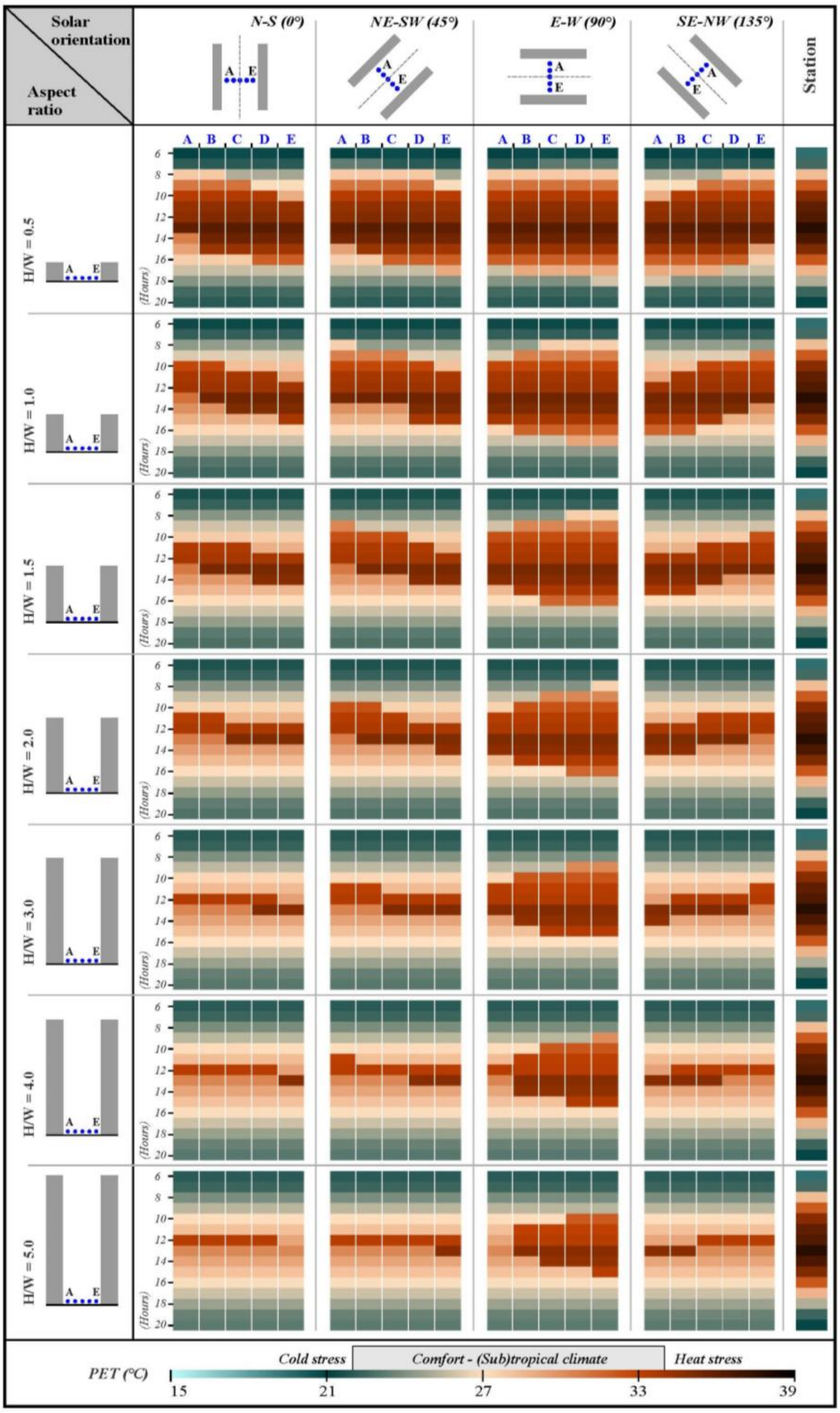


Figure 2.32: Values of PET (°C) for urban canyons with different aspect ratios and street orientations (Algeciras, Consuegra & Matzarakis 2016, p. 94).

A review by Taleghani et al. (2015) examined the impact of five different urban configurations on outdoor thermal comfort in the Netherlands. Singular, linear, and courtyard forms on east–west and north–south orientations were analysed to evaluate thermal indicators, and were divided into hot climate and cold climate factors, with the most prominent indicator in hot climate being the duration of sun radiation, which was effected by urban typology.

ENVI-met was used to generate mean radiant temperature, air temperature, and relative humidity during the most extreme hot day of the Dutch in summer (June 19, 2000 with a maximum 33 °C air temperature) and calibrated through measurement data for similar days of the computational simulation, then these data were entered into RayMan to calculate the PET using SVF in the centre point as shown in Figure 2.33.

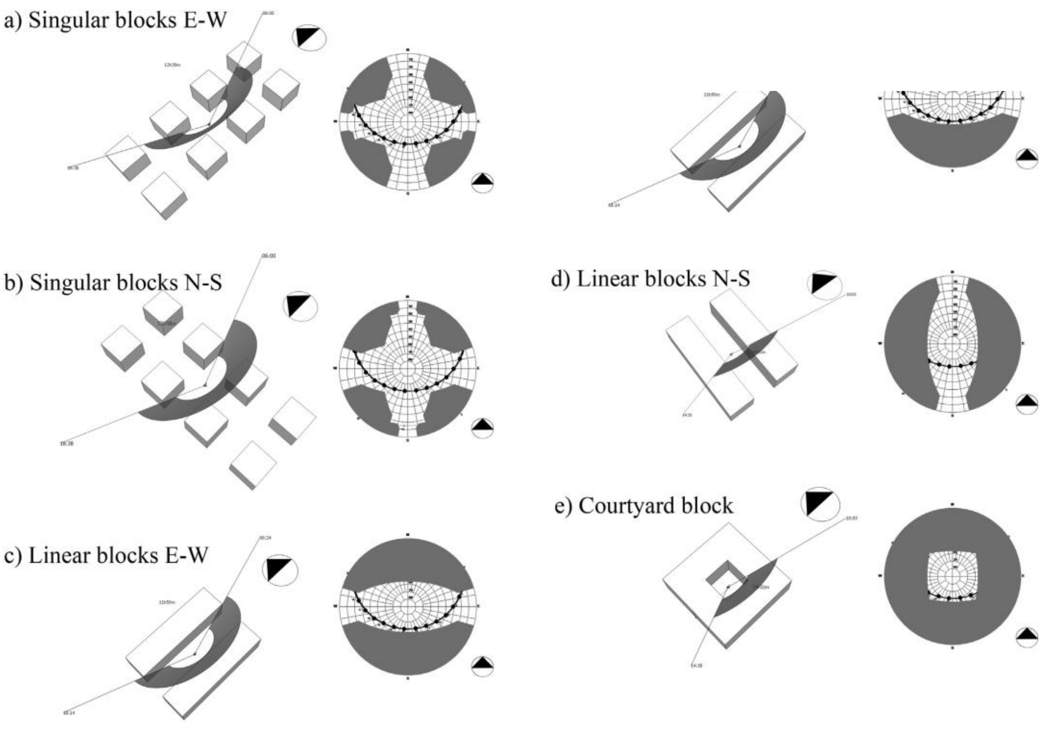


Figure 2.33: Isolation of the models and sky views from the reference points (adapted from Taleghani et al. 2015, p. 73)

The results revealed that outdoor thermal comfort differed according to urban configurations and compactness. Thermal behaviour—particularly air temperature and wind velocity—for the singular module (east–west) and (north–south) was approximately similar, with more exposure to the sun than in the linear and courtyard models. In terms of duration of direct sun, the linear east–west model had the highest heat stress, especially between 11:00 h to 14:00 h, with the remainder of the day similar to the singular forms. On the other hand, the linear and courtyard north–south models had better thermal behaviour, and temperature increased slowly between 10:00 h to 14:00 h. Wind velocity at this orientation decreased for all models, varying from 2.6 m/s to 0.2 m/s. Orientation played an important role influencing air movement, with east–west blocking wind while the north–south configuration allowed for wind penetration at the centre point. Figure 2.34 highlights the comfort zone using PET figures obtained from RayMan simulation, showing the courtyard had the longer comfortable hours compared to singular and linear configurations. This paper also showed that the courtyard provided the most comfortable microclimate in the Netherlands in June compared to the other studied urban forms (Taleghani et al. 2015).

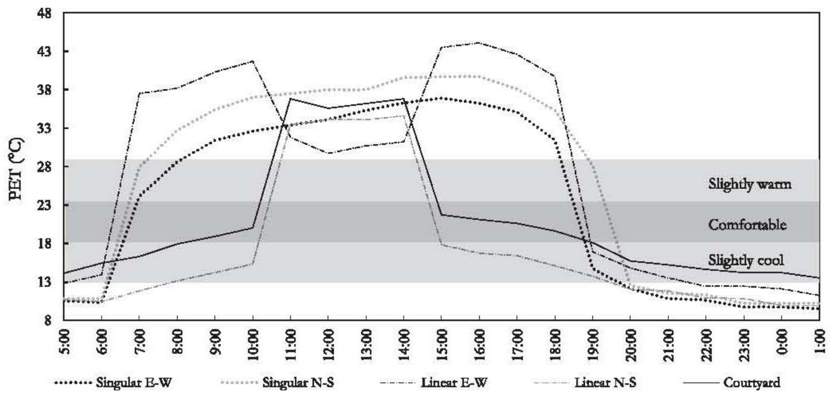


Figure 2.34:. PET at the reference points (the comfort range is highlighted with grey) Taleghani et al. 2015, p. 76)

2.5.2 Studies on the Impact of Urban Configurations Parameters – Open Space and Courtyard

In the second part of literature review, papers addressing the impact of an open courtyard—both shaded and unshaded—on outdoor thermal comfort in hot, arid climates will be reviewed, In this regard, some researchers investigated the role of an open courtyard in mitigating UHI. However, some papers focused on the impact on microclimate, and have adopted courtyards as an urban design strategy to be considered. Some papers provide qualitative and quantitative assessment of courtyards using computational software or field measurements. A recent study by Amirhosein Ghaffarianhoseini, Berardi, and Ali Ghaffarianhoseini (2015) demonstrated the influence of different design configurations and scenarios of unshaded courtyards in improving outdoor thermal comfort in Kuala Lumpur, Malaysia, by using computational simulations. Two software programs were used—ENVI-met 3.1 and RayMan—to calculate and the predicted mean vote (PMV) and PET, respectively. To calibrate software results, measurement of meteorological data dry-bulb temperature in Kuala Lumpur was compared to predicted hourly data from ENVI-met, and the difference was negligible. The PMV values derived from ENVI-met simulation were subsequently compared with PET values obtained from RayMan calculations to ensure consistency in the findings.

Kuala Lumpur has a hot, arid climate, and climatic data input comprised mean air temperature of approximately 27 °C, whereas the monthly mean maximum air temperature ranges from 33.5 °C–31.9 °C and the monthly mean of minimum temperatures ranges from 23.1 °C–24.3 °C. Relative mean humidity ranges between 70% and 90%, with maximum average daily levels as high as 94%.

Different urban configurations were considered for a courtyard of 24 m x 24 m surrounded by a single storey building (60 m x 60 m). Parameters for the study were open space orientation, the height of the wall enclosure, reflectance of wall enclosures, and vegetation to evaluate performance of different configurations of courtyards. As illustrated in Figure 2.35, the microclimate parameters evaluated to study outdoor thermal comfort included ambient temperature, relative humidity, wind speed, and mean radiant temperature. Five different courtyard orientations were examined: opening facing north, south, east, and west, and a version with a central courtyard.

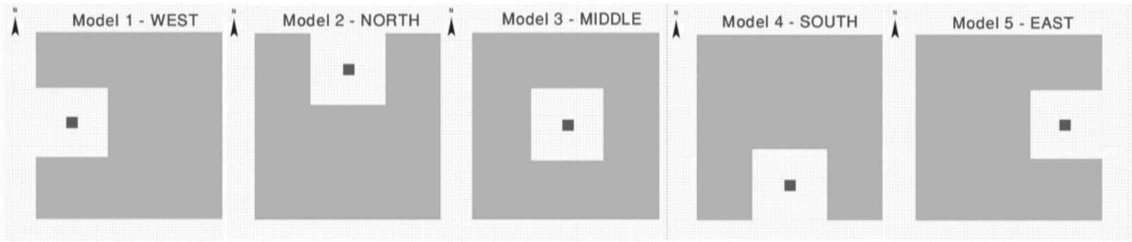


Figure 2.35: Different orientations of courtyard (Ghaffarianhoseini, Berardi & Ghaffarianhoseini 2015, p. 159)

The influence of location and orientation of courtyards towards determined microclimate parameters, the difference in temperature was significantly high, but temperature at courtyard facing north and east orientation was lower by 0.5 and had higher level of humidity, heat stress occurred at the courtyard facing west particularly from 10:00 h to 17:00 h as shown in Figure 2.36. This study revealed that long durations of direct solar radiation, high levels of temperature and humidity, and a lack of shading made all five orientations thermally uncomfortable.

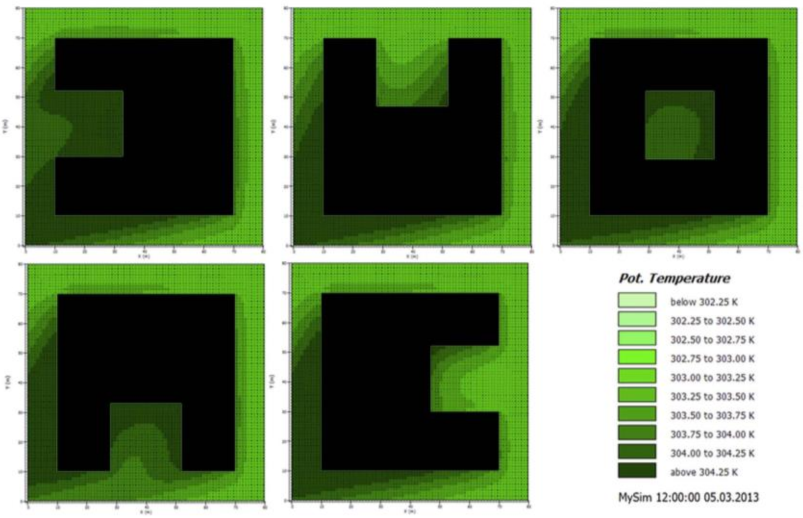


Figure 2.36: Simulated spatial distribution of air temperature in the courtyard models at 12:00 h, at 2 m height (Ghaffarianhoseini, Berardi & Ghaffarianhoseini 2015, P. 160)

Ratios of H/W were examined through three different heights of wall enclosures, at ratios of 6:1, 2:1, and 1:1, giving 4 m (one storey), 12 m (three storeys), and 24 m meter (six storeys) as shown in Figure 2.23.

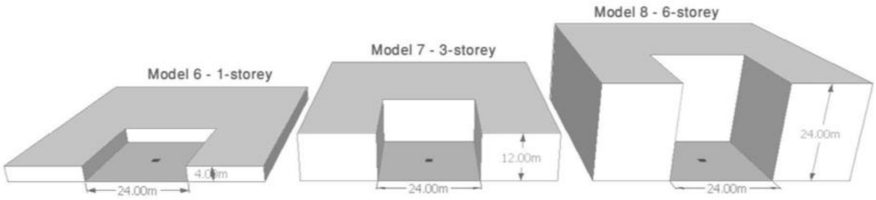


Figure 2.37: Different H/W ratios (Ghaffarianhoseini, Berardi & Ghaffarianhoseini 2015, p. 161)

The results showed that a higher wall enclosure around the courtyard provided better thermal behaviour, The six-storey scenario lowered the temperature by 1 °C due to receiving less direct solar radiation from 11:00 h to 17:00 h. The average daily temperature was lowest at six-storey height and most uncomfortable in one-storey height, even during the morning. After 10:00 h, once the PMV distribution of outdoor context was above 4, heights more than 12 m were reported as comfortable.

This study also looked at the impact of albedo of the wall enclosures, finding that increasing the albedo affected outdoor thermal comfort negatively. Similarly, and albedo of 0.93 (highly reflective plaster) increased radiant temperature by 12 °C compared to an albedo of 0.3 (brick). Three scenarios were developed. The study also explored whether using vegetation could improve outdoor thermal comfort, confirming that grass groundcover decreased air temperature by 0.13 °C during the morning compared to bare ground. In terms of the relationship between trees and thermal comfort, the most prominent correlation was recorded in unshaded areas that had a high level of discomfort, where it was found that a 3.3 °C reduction of air temperature at 20:00 h could be achieved by converting the courtyard to include 75% trees. On the other hand, relative humidity increased by 10.5% due to the reduction of air movement and wind speed.

Some of the studies in this area focus on other characteristics of H/W ratios on courtyards, and the influence of H/W on total energy consumption. Al-Masri and Abu-Hijleh (2012) compared the energy consumption of a rectangular building block to a courtyard block, of midrise buildings in the hot, arid climate of Dubai, UAE. An optimised courtyard model was explored by studying different parameters including number of storeys, type of glazing, wall thickness, and insulation type and thickness. Their study was also followed by Ghaffarianhoseini, Berardi, and Ghaffarianhoseini (2015).

Results showed a 54.25% reduction in solar gain of the courtyard compared to the rectangular building block. However, the court yard increased external conduction gain by 54.15% because more of the façade area was exposed to the sun, and therefore heat transfer was higher for the courtyard compared to the rectangular building block. As illustrated in Figure 2.38, the results confirmed the capability of the courtyard design to reduce total energy consumption, in this case by 6.9%,. considering cooling load as the most prominent cost actor in hot, arid climate, and other building systems such as lighting were assumed to be constant. Apart from during summer, the impact of courtyard design on energy consumption was noteworthy for the rest of the year.

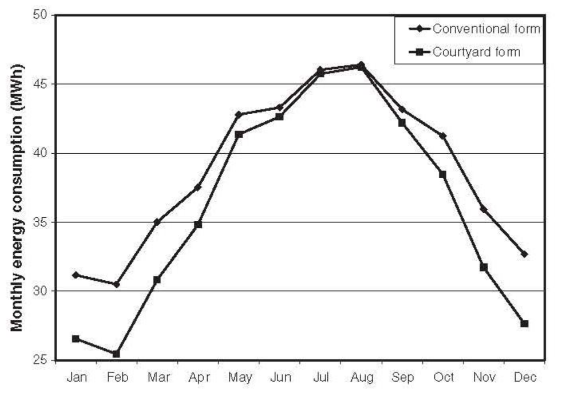


Figure 2.38: Monthly energy consumption of conventional and courtyard models (Al-Masri & Abu-Hijleh 2012).

In terms of total energy consumption, the study recommended that a six-storey building was the optimum building height. Increments of building height from eight storeys to ten storeys affected total energy consumption by 0.34%, as seen in Figure 2.39.

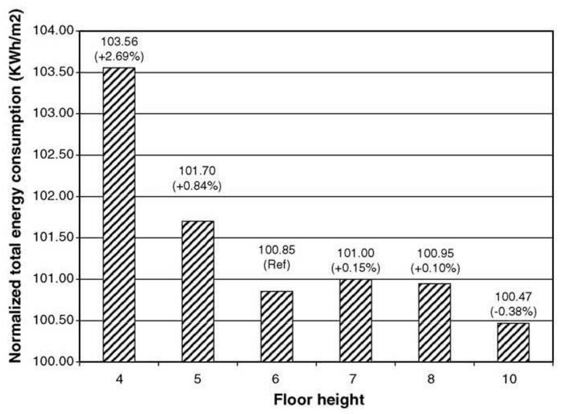


Figure 2.39: Normalised total energy consumption of the selected heights of the courtyard model (Al-Masri & Abu-Hijleh 2012, p. 1896).

Based on the results, an optimised model of courtyard was achieved in a six-storey courtyard building having triple glazed "low-e" windows, 40 cm wall thickness, and cellular polyurethane with 10 cm thickness. This optimised model achieved a total energy reduction of 11.16%. Considering the key elements of pedestrian comfort, Ragheb, El-Darwish, and Ahmed (2016) agreed that the key elements of road configuration, H/W ratio, and softscaping and hardscaping material influenced the microclimate of urban open space, and formed the unique local climate for each neighbourhood in a city.

The study, conducted in Alexandria, Egypt, examined human comfort in an old historical district to the south known as Kom Al Shoqafah, and highlighted the importance of design parameters of relative humidity, air movement, and air temperature, which strongly impact outdoor thermal comfort.

ENVI-met software was used to simulate the different design parameters mentioned earlier for three different urban configurations. The first is the current urban space, and the other two are proposed designs—proposal 1 with 13 m height, and proposal 2 with 36 m height, having 55% and 60% coverage, respectively. As seen in Figure 2.40, the simulation was run in four selected areas: open space, secondary street level, street level, and pavement level.

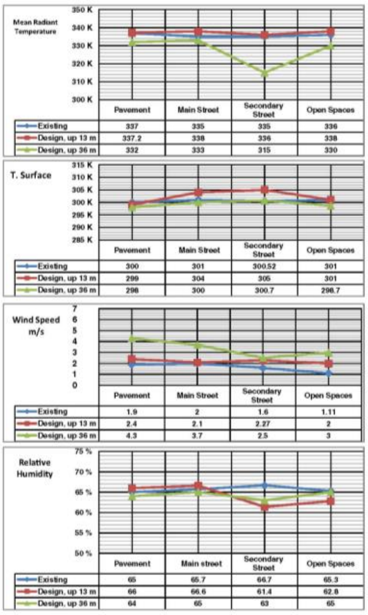


Figure 2.40: Comparing proposed designs 1 and 2 (10 m and 36 m height) to current conditions results (Ragheb, El-Darwish & Ahmed 2016, p. 166)

Study	Climate	The key findings

The results revealed that the impact of three scenarios of open space, street level, and pavement level were similar. A building height of 13 m improved air movement and decreased relative humidity by 0.90, or 2.5%, compared to current situation, but had a minimal impact on MRT (2–3 °C increment), however the open space of the proposed 35 m height increased MRT by 3 °C–6 °C, and decreased relative humidity by 0.70, or 2.5%, compared to the current situation. On the secondary street, increasing building height to 35 m influenced outdoor thermal comfort significantly with a 20 °C reduction in MRT and 5.3% in relative humidity compared to the current situation.

The Ragheb, El-Darwish, and Ahmed study concluded there were three main climatic functions for the courtyard: firstly, and taking into consideration correct orientation, it could play multifunctional roles as sun collectors and protectors. Secondly, wind circulates between exterior spaces and inside the courtyard, in addition to ventilating the interior building with courtyard air; in tropical regions where the temperatures outside and inside a courtyard building are close to each other, the courtyard is used for refreshing interior air. The third function of a courtyard is to increase humidity. Humidity is needed in arid areas to achieve comfort by increasing the relative humidity of the air.

Table 2.3: Summary of the results of recent studies into strategies for improving the outdoor thermal comfort in urban environments

Study focus	Climate	Key findings
Impact of the geometry of an urban street canyon on outdoor thermal comfort in a Mediterranean subtropical climate – Tunis.	Mediterranean subtropical climate	The most favourable H/W ratio is 4, higher buildings provide more shaded area. A north-south orientation was the best scenario. Younsi & Kharrat 2016.
Achieving sustainability through the management of microclimate parameters in Mediterranean urban environments during summer.	Mediterranean subtropical climate	H/W ratio has significant influence on east–west orientation only, a higher H/W ratio on east–west orientation could significantly decrease the air temperature by 1.70 °C Tsitoura, Michailidou & Tsoutsos 2016.
Urban microclimate analysis with consideration of local ambient temperature, external heat gain, urban ventilation, and outdoor thermal comfort in the tropics.	Tropical climate	Site coverage of 60% had the least heat gain compared to 20% site coverage. There was no significant impact of different configuration on wind conditions. Ignatius, Wong & Jusuf 2015.
Coupled CFD, radiation and building energy model for studying heat fluxes in an urban environment with generic building configurations	Moderate with no excessive heat, cold or humidity	Buildings are considered as obstacles to wind. The higher the building, the more heat can be removed through the top plane and the better the outdoor thermal conditions Allegrini, Dorer, and Carmeliet 2015.
A holistic approach to energy-efficient building forms.	Hot arid climate	The court created by innovated RSB L-shape results in better thermal comfort due to enhanced air flow. RSB increased solar radiation in winter compared to linear and block. Okeil 2010.
Urban heat islands: Potential effect of organic and structured urban configurations on temperature variations in Dubai, UAE.	Hot arid climate	Organic urban configurations have lower temperatures in summer compared to urban linear structural configurations. In contrast, Perpendicular and linear configurations configurations had higher wind speed which did not, however, influence temperatures. Taleb & Abu-Hijleh 2013.
Microclimate design for open spaces: Ranking urban design effects on pedestrian thermal comfort in summer.	Temperate climate	MRT was lower in courtyards than in squares due to shading. Increasing the H/W ration from 1 to 2 results in a reduction of MRT by 3.5 °C and 4.5 °C for square and courtyard, respectively. Further, canopies improve wind conditions due to channeling. Chatzidimitriou & Yannas 2016.
The potential contribution to outdoor thermal comfort by urban developments. Worcester, Massachusetts, USA.	Warm, temperate, and cold climates	East–west orientation was the worst case in terms of thermal comfort, particularly from 12:30 to 20:00. It was observed that the impact of H/W ratio is more significant on courtyard configurations than for squares. Targhia & Dessel 2015.
Spatial-temporal study on the effects of urban street configurations on human thermal comfort in the world heritage city of Camagüey, Cuba	Tropical wet and dry	PET results found that an east–west orientation gained more solar radiation in summer and led to extreme discomfort, while a north–south orientation was highly comfortable. An H/W ratio more than 2.0 provided more shaded area up to 14:00 h, and became the most comfortable situation during summer. Algeciras, Consuegra & Matzarakis 2016.
Outdoor thermal comfort within five different urban forms in the Netherlands.	Temperate maritime climate	The thermal behaviour of singular modules aligned east–west and north–south were approximately similar, with more exposure to sun than the linear and courtyard models. The linear east–west had the highest heat stress, especially during peak time. Orientation allowed an east–west to block the wind, and allowed wind penetration of north–south alignment. Taleghani et al. 2015.
Thermal performance characteristics of unshaded courtyards in hot and humid climates.	Hot arid climate	The best orientation was north, achieving air temperature reductions of 300 K at 8:00 h and 305 K at 15:00 h. Further, an H/W ratio of 1:1 was best, improving outdoor thermal comfort by blocking intense solar radiation and providing more shaded areas. Ghaffarianhoseini Berardi & Ghaffarianhoseini 2015.
Courtyard housing in midrise buildings: An environmental assessment.	Hot arid climate	Courtyard design reduced total energy consumption by 6.9 % compared to rectangular block, and a 6-storey height of courtyard achieved a total energy reduction of 11.16%. Al-Masri & Abu-Hijleh 2012.

Microclimate and human comfort consideration in planning an historic urban quarter.	Hot arid climate	A building height of 13 m decreased relative humidity by 0.90 (2.5%) but had minimal impact on MRT (2 °C –3 °C increment). A 35 m building height increased MRT by 3 °C –6 °C and decreased relative humidity by 0.70 (2.5%) compared to current situation. On a secondary street, increasing building height to 35 m influenced outdoor thermal comfort significantly with 20 °C reduction in MRT and 5.3% of RH compared to current situation. Ragheb, El-Darwish & Ahmed 2016.

2.6 Research Limitation

After review for the available research papers in the field of urban configurations and outdoor thermal comfort, some limitation might be identified. The lack of holistic view of urban configurations including urban elements of building form, open space proportion, height, and orientation and their influence of outdoor thermal comfort. These elements were studied to provide strong evidence and findings limited to single relationships separately but not simultaneously.

It can be seen in relevant research that researched linked the suitable urban design to mitigation strategy of UHI; particularly in hot arid climate. Another main finding from the literature review is that many researchers concentrate the research to address the impact of softscape on outdoor thermal conditions. These efforts have been recognized to be of utmost importance in defining the measure for outdoor thermal comfort. Regardless the comfort zone, air temperature, wind speed and humidity were the key findings. These thermal indicators help to identify whether or not the urban configuration serves well in terms of outdoor thermal comfort. Many paper have addressed the hot arid climate recently, however, few paper focused on gulf region and no paper addressed military camps in Abu Dhabi in particular. This research attempts to bridge this gap in micro-climatic research related to urban design and analyse the relationship between wind conditions and air temperature of different urban configurations.

2.7 Hypotheses

VII. Use of bioclimatic approach in the urban design enhances the outdoor thermal behaviour, particular air temperature and wind speed in military camps in climate of Abu Dhabi, UAE.

VIII. Application of the most favourable urban configuration of building form, open space proportion, height and orientation will improve outdoor thermal conditions in military camps in climate of Abu Dhabi, UAE.

3 METHODOLOGY

3.1 Introduction

In this section, a detailed explanation of the steps and procedures followed to carry out the current study will be reviewed. The tools, methods, and techniques used in each stage of research will be identified and justified critically. The complexity of physical urban modeling and the variable parameters involved and affecting each other led to delays in studies addressing the holistic approach of urban design from a microclimatic point of view; however, in the past few years urban planning professionals began to use this approach, with the literature review showing that researchers used variety of methodologies because of the complexity of parameters affecting outdoor thermal comfort and microclimatic variables of certain urban areas. Each parameter interacts with another, and a cumulative impact takes place; therefore, sophisticated tools and software were required to evaluate these microclimatic variables. Generally, the need for new studies increases with an incident that triggers a few queries in need of an answer, and then the research process begins instinctively and deepens gradually until it reaches the stage where aims are established through setting goals in planning, achieved through research objectives. Each and every research study has its own methodology, where all contribute to one goal. Scientific research methods adopted need to be based upon earlier attempts in similar investigations.

3.2 Methodologies Used for Similar Topics

Through earlier investigations conducted to assess outdoor thermal comfort—particularly air temperature and wind speed indicators—it has been found that several methodologies were used depending on simplifying the complexity of variable parameters affecting thermal comfort depending on each study’s research resources. It is essential to obtain 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 in Chapter 2, when trying to understand the various parameters of outdoor thermal behaviour of different urban configurations, there are two main approaches used to investigate the interact relationship between different urban morphologies and outdoor thermal comfort. The first approach is observation, which is field measurement, which has been used mainly for validation and collaboration. The second approach is simulation, which has been used extensively for similar topics. A simulation approach comprises two tools: the ENVI-met model, and estate environment evaluation (STEVE), which means creating real conditions of urban configurations that influence the outdoor thermal comfort. Other methodological tools such as social surveys, experimental methods, field measurements, and computer simulations were rarely adopted for outdoor parameter investigations. Each of the mentioned methodologies will be clarified separately, justifying the selected method for the current investigation.

3.3 Methodology Literature Review

This section aims to present a literature review of the different research methodologies approaches relevant to the topic of investigation, based on different urban morphologies, and their impact on outdoor thermal comfort. The pros and cons of each approach and methodology will be discussed to justify selection of the most favourable tool for this study.

3.4 Observation Approach – Field Measurements

In this section, field measurements, the most widely used approach for validation, is discussed in more detail through sample papers that employed field measurement as a tool as part of their methodology. In situ data gathering is 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 complementary yet essential addition 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 a method is used for the investigation of a case, it follows that thermal comfort records are expected to cover all various climatic conditions (thus, all seasons of the year). The time intervals required to study certain phenomena are rather long. When testing thermal comfort in outdoor urban spaces, climatic records must be measured with precision. Therefore the in situ survey becomes essential and requires high levels of accuracy. The time intervals of data recorded in each case study must be long enough to obtain valid measurements. The presence of a number of dependent and independent variables in the field requires great awareness on the part of the researcher of how each variable can affect readings. Field measurements investigating complex outdoor parameters have always been combined with social surveys or simulation methods.

Several studies used field measurement as an aiding tool to their main methodology, which was computer simulation. Field measurements were the source of input data required for simulations. The concept of measurements taken for input in computer software makes the results more realistic than having to insert absolute measurements. Studies undertaken by Taleghani, Tenpierik & Dobbelsteen (2014) used field measurement to evaluate different criteria in designing a comfortable and energy-efficient courtyard building for the temperate climate of the Netherlands. In their research, field measurement was used to validate the results obtained from their main methodology tool, which was Design Builder. Their monitoring was conducted when the courtyard house was in free-running mode to avoid the impact of heating or cooling when measuring the air temperature of the internal rooms of the existing courtyard building, as shown in Figure 3.1.

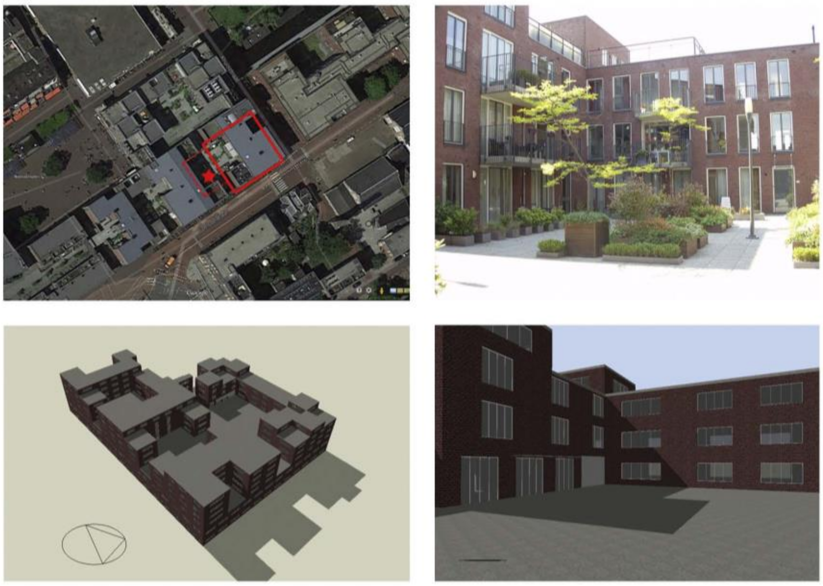


Figure 3.1: The location and a view of the courtyard building (Taleghani, Tenpierik & Dobbelsteen 2014).

Moreover, experimental tool was used, in this context; sun is typically defined as the nominal full sunlight intensity on a bright clear day, which measures 1000 W/m^2. Thus, a 1000 W tungsten halogen light was used as the heat source, and a 22 W desk fan was used to generate wind. The fan blew air to the model from the south-west to simulate the prevailing wind in the Netherlands as shown in Figure 3.2.

Figure 3.2: Top left: the scale model experiment with the halogen light and fan. Top right: the sensors placed in the four sides of the model. Bottom, from left to right: black cardboard, gravel, grass, and white cardboard. (Taleghani, Tenpierik & Dobbelsteen 2014).

3.5 Simulation Approach—Numerical Model Tool

The numerical simulation of the BES City Sim, a simulation tool that models energy fluxes in a city of sizes ranging from a small neighborhood to an entire city, was employed in recent study by Allegrini, Dorer and Carmeliet (2015). They used BES to evaluate urban heat fluxes for six different urban morphologies for the climate of Zürich (Switzerland). The available version of City Sim cannot consider convective heat transfer coefficients (CHTC) therefore CFD simulations cannot not be conducted using CitySim. The cons of using BES is the limitation of number of buildings of each morphology for available computational resources needed for the CFD simulations. However, this tool has the advantage of having highly spatially-resolved temperature and flow fields and, therefore, is able to determine heat fluxes. Turbulent and convective heat fluxes are considered. The results show the importance of buoyancy for low wind speed cases, and the strong influence of buildings upstream on heat fluxes and temperature.

Nevertheless, numerical simulation is too difficult for educated non-scientists to understand, and therefore the benefits of studies employing this tool is limited to the academic domain only; however, the involvement and support of scientists is required to help urban planners. On the other hand, simulation results acquired from computational software is simple and easy to understand. The most important programs used for this topic are ENVI-met and STEVE.

3.6 Simulation Approach—Computer Simulation Tool

3.6.1 The ENVI-met Software

ENVI-met is a three-dimensional microclimate model designed to mimic the correlation between surface–plant–air in an urban environment, including application of landscape, architectural and urban areas. The basis of the predictive modeling of ENVI-met is the fundamental laws of fluid dynamics and thermodynamics. As illustrated in Figure 3.3, this software is capable of carrying out simulations of bioclimatology, the impact of softscaping and hardscaping of the local microclimate, air ventilation around and between buildings, and building physics. As well as calculating heat exchange processes at ground surface and at building walls, the software is able to examine heat and mass exchanges related to other surfaces. Over the past 20 years, more than 4000 simulations have been conducted using ENVI-met within 145 different countries (Bruse et al. 2016).

Researchers have been using this software to analyze outdoor thermal comfort parameters, where values of air temperature, mean radiant temperature, relative humidity, and solar radiation were validated against values experimentally measured in the field.

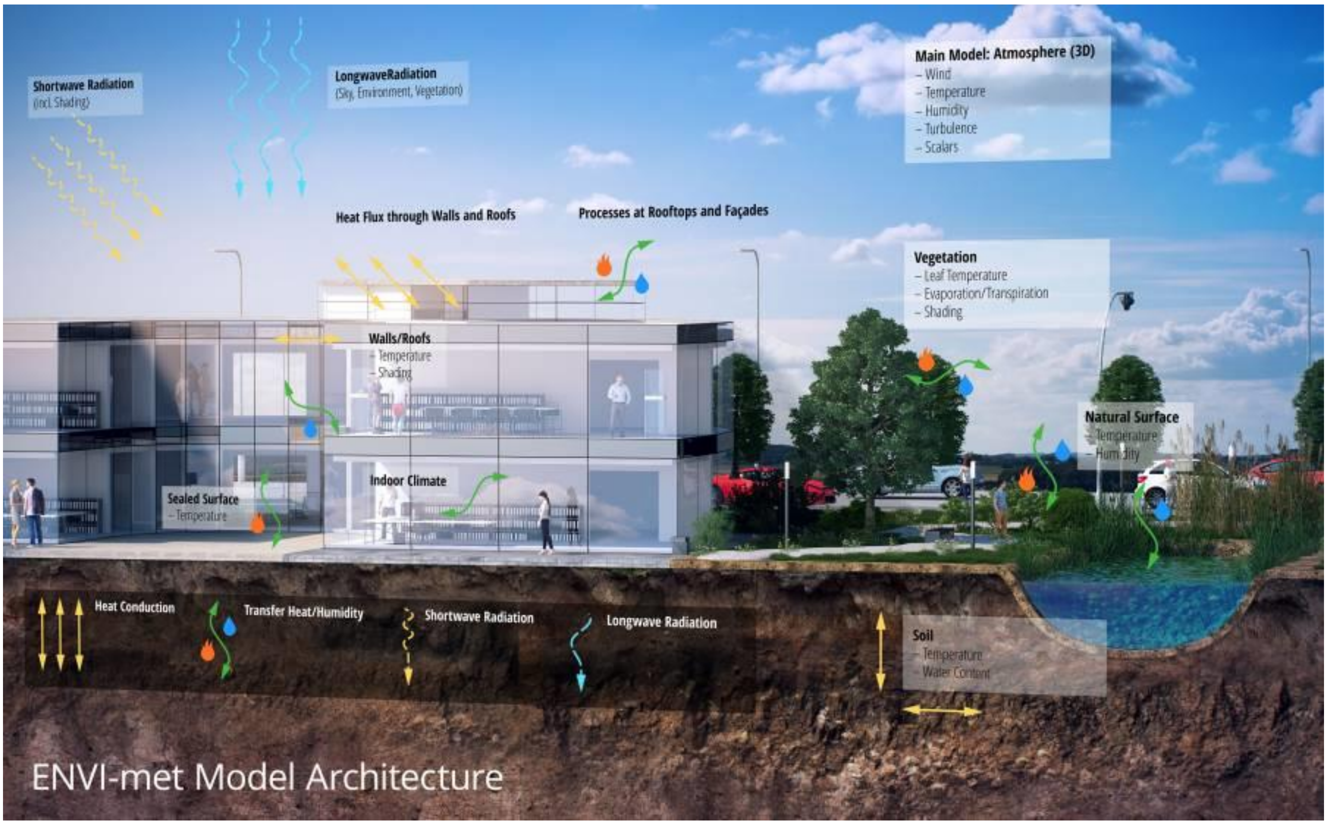


Figure 3.3: ENVI-met – a holistic microclimate model (Bruse et al. 2016, p. 1).

Calculations of ENVI-met are influenced significantly by the size of the grid (x, y) and nest area, where the specified grid distance will determine the resolution required for analysis of small or large-scale interactions between individual buildings, surfaces, and plants. ENVI-met is characterized by two sets of applications: core applications and helper applications. The first application set comprise of Headquarter, ENVI-met Core, Spaces, LEONARDO, and BioMet. These applications are time-consuming to build the main model. The second application set contains DB Manager, Albero, Project Wizard, Eagle Eye, Manage Workspaces, and Projects Organize. These are smaller applications compared to the first set, but nevertheless very important for simulation work (Bruse et al. 2016)

This software has been used in many studies to evaluate microclimate conditions and outdoor thermal comfort. It is important to note that this software was used extensively to assess landscape and greenery in particular; for example, it is capable of examining the amount of water absorbed by different types of trees and the impact of the soil balance. However, apart from landscape studies, other morphological features have been examined using ENVI-met.

In the Netherlands, Taleghani et al. (2015) used ENVI-met to reveal that different urban forms created different microclimates, and led to diverse in outdoor thermal comfort zones accordingly. As shown in Figure 3.4, the simulation results of ENVI-met was used to evaluate outdoor air temperature, mean radiant temperature, wind speed, and relative humidity for five different urban forms: singular east-west and north-south, linear east-west and north-south, and a courtyard. The researchers also used RayMan modeling software to convert these data into physiological equivalent temperature (PET).

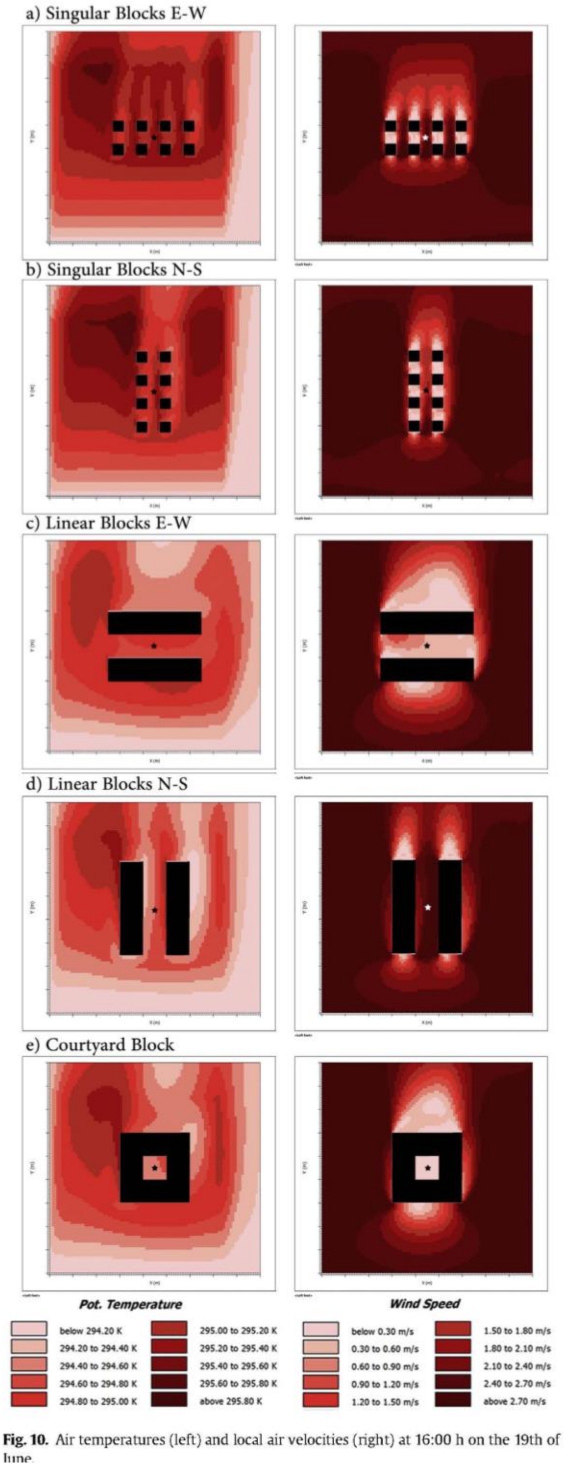


Figure 3.4: Values achieved for five urban forms for air temperature and wind speed (Taleghani et al. 2015)

Ignatius, Wong, and Jusuf (2015) believed that addressing the effectiveness of physical density and form of urban configurations on surface ambient temperature, urban ventilation, and external heat gain and outdoor thermal comfort would provide a comprehensive investigation into urban microclimate analysis. Their study concentrated on commercial office buildings in an urban area in Singapore, with a plot area of 9 ha, comprised of six buildings with a total area 63,000 m^2. The maximum plot ratio was set at 10 to comply with local authority guidelines, and four different hypothetical buildings configurations having five different site coverages (20%, 30%, 40%, 50%, and 60%) were proposed on an empty block as shown in Figure 4. In order to simplify the analysis, the height of buildings was unified within each configuration, and variable densities were addressed by splitting buildings into two, four, and six smaller sizes. Also, SVF was calculated for each urban configuration.

3.7 Improvement of Newly-Developed ENVI-met 4.0

While considering developments in this field of study, it must be specified that recently the ENVI-met version 4.0 has been introduced and, even if it is actually in the last beta configuration (beta II, to be precise), it presents some improvements over previous versions. For example, it is now possible to obtain a more accurate representation of architectural elements, setting different materials for each facade, ground, or roof element, with 3D representations of the different buildings configurations (Salata et al. 2016).

The latest version of ENVI-met has been launched, and some improvements are noticeable. In terms of quality of architectural presentations, the facade treatment of properties is improved and based on wall assembly nodes (inside, middle, outside of wall) to consider thermal behaviour and heat transfer for building envelopes. Apart from variations to atmospheric boundary conditions (forcing), the program's "project wizard" or configuration file is basically similar to previous versions of the software. "Forcing" is an added feature allowing specific meteorological scenarios for air temperature and relative humidity.

Figure 3.5 reports the discrepancy between the results provided by ENVI-met 3.1 and ENVI-met 4.0 for similar 3D models for air temperature and MRT respectively. The differences between the values of the two versions revealed that the older version of the software seems to report values of air temperature slightly higher during mornings at the coldest periods of the day. However, during afternoon hours, ENVI-met 3.1 provides values which are approximately 2–3 K lower than the latest version. It is important to note during this research that the latest version, 4.1, overestimates air temperature during afternoon hours and underestimates it in the morning (Salata et al. 2016).

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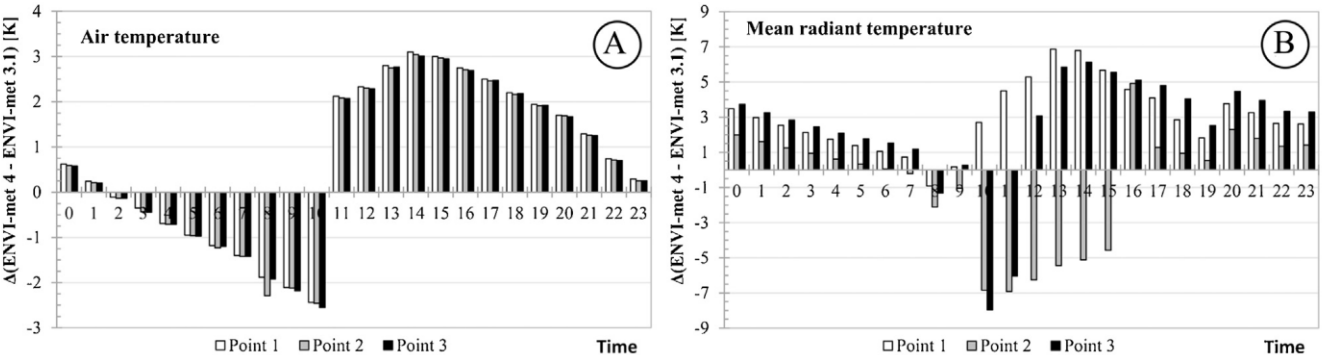

Figure 3.5: Comparison between the values of air temperature and MRT predicted through ENVI-met 4 and ENVI-met 3.1 (Salata et al. 2016).

3.7.1 Estate Environment Evaluation (STEVE) model

Sketch Up software has been improved with the addition of an urban analysis tool named STEVE (which stands for screening tool for estate environment evaluation) which simulates urban areas to calculate temperature maps and profiles. These maps consider various parameters such as solar radiation, ambient air temperature, wind speed, softscape and hardscape, building density, greenery, and albedo.

The software uses a geographic information system (GIS) as the database to produce temperature maps.

STEVE is a web application specific to an estate, and it calculates the average of temperatures of the point of interest for existing conditions and future conditions (such as a proposed master plan) of an estate. Temperatures at any particular point are a result of the surrounding environment within a buffer zone. Output data from STEVE uses the GIS database) to produce a raster map of temperature differences within an estate based on the stored values of the surrounding environment (Hien et al. 2012).

The STEVE model has been developed through trial and error to predict air temperature at the estate level of Singapore based on climate conditions and urban morphology characteristics. Prediction models have been validated with field measurement in Singapore at various locations. As shown in Figure 3.6, the most important advantage of STEVE is simplicity: it is a user-friendly tool for urban planners, allowing understanding of the impact of microclimate conditions while they developing urban design concepts. In addition, STEVE can analyze thermal behaviour for specific locations due to surroundings by creating section lines to generate temperature profiles. (Tan et al. n.d.)

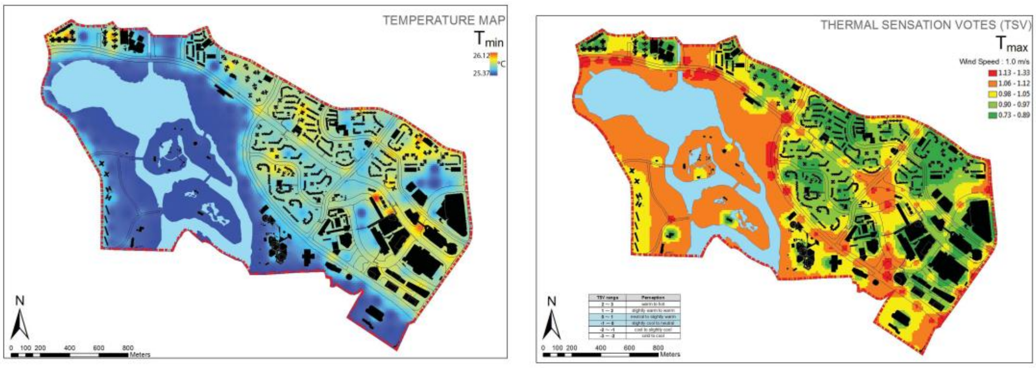

Figure 3.6: Temperature map and thermal sensation votes for empirically-developed models in Singapore (Tan et al. n.d.)

Another study used the STEVE tool to demonstrate a more comprehensive micro climate analysis on a precinct by looking at several components. Firstly, thermal load models were used to predict the energy performance and external heat gains.

Then, STEVE was used to analyze outdoor temperature and greenery implementation. Meanwhile, urban ventilation analysis was conducted by using the ventilation ratio (VR) method, observing the urban geometric condition to determine wind speed conditions at the pedestrian level. The results were then combined with outdoor temperatures, which in the end affected the overall energy performance of buildings.

This study explored the effect of urban texture, characterized by its physical density and form, on the receivable external heat gain, ambient temperature, urban ventilation, and outdoor thermal comfort. Addressing these aspects would provide a more comprehensive methodology on urban microclimate analysis, rather than being conducted separately. Hence, analyzing building performance should look not only at a stand-alone (isolated) setting, but also consider the "neighborhood" approach, where urban environment has a significant effect on the energy performance of individual buildings. A series of hypothetical building arrangements were put into an empty block in a dense urban area, where each of scenarios went through a series of microclimatic analyses. In the end, this parametric study narrowed down design options which had favourable microclimate condition and acceptable district energy performance.(Hien et al. 2012).

3.7.2 Comparison of ENVI-met and STEVE

There are two computational software programs to predict temperature and outdoor thermal comfort for points of interest of certain urban settings within buffer zones: STEVE and ENVI-met.

Output data from STEVE is based on GIS data to produce a raster map of temperature difference within a location of interest. ENVI-met uses a computational fluid dynamics (CFD)-based micro-climate and local air quality model to calculate temperatures within interval times for 1–2 days. The main differences are related to climate context variables such as wind speed and surface temperature. STEVE calculations consider wind speeds as constant within a specific day, while ENVI-met considers it inconstant. In terms of map quality, the raster maps generated are based on grid pixels from ENVI-met, as a better resolution compared to STEVE maps which are generated based on a buffer zone with specified diameter). Another difference is that ENVI-met calculates air temperature at different heights, while STEVE only calculates temperature at human eye level (Hien et al. 2012).

Table 3.1: Comparison of key factors of STEVE and ENVI-met.

Factors	**STEVE**	**ENVI-met**
Base	GIS	Computational Fluid Dynamics (CFD)
Wind speed	Considered as a constant	Wind speed within specific day is inconstant
Map output	Low resolution raster map, based on buffer zone with specified diameter	High resolution raster map
Height of air temperature readings	Based on pedestrian eye-height only	Generated for different heights
Validation	With field measurements in Singapore	With field measurements in 24 different countries

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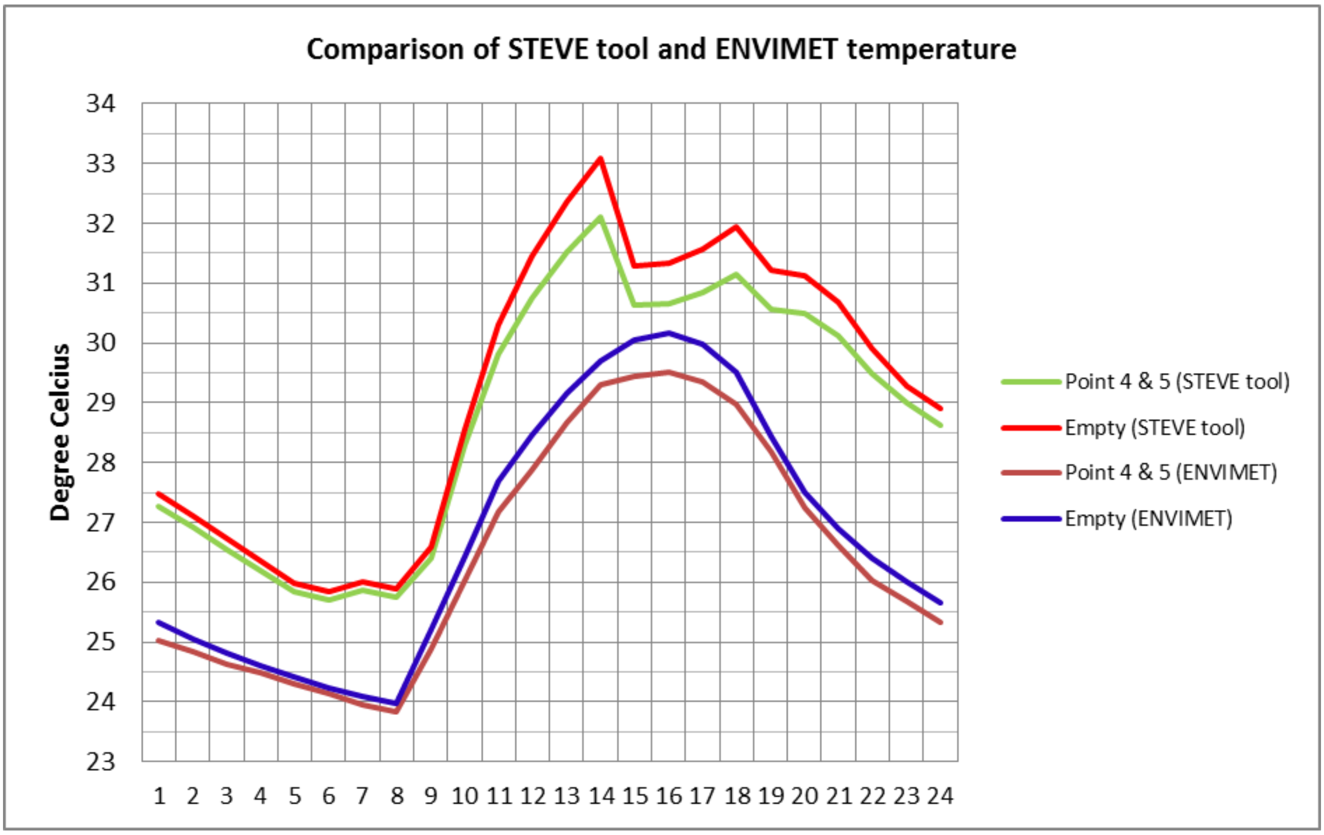


Figure 3.7: Values achieved by STEVE and ENVI-met for air temperature (Hien et al. 2012).

In Figure 3.7, a comparison of results achieved from STEVE and ENVI-met revealed that ENVI-met has better quality of maps. Results showed that predictive temperatures from STEVE were always higher compared to the ENVI-met tool, even for the empty land indicated in red and blue colors for both programs, respectively. The discrepancy can reach as much as 3.77 °C maximum, and 2.38 °C average. However, the two programs provided similar tendency of temperature profile. Ultimately, adjustments to the ENVI-met temperature profile by raising initial temperature 2-3 °C could achieve a mostly similar temperature profile (Hien et al. 2012).

3.8 Methodology Selection and Software Selection

As mentioned at the end of the previous chapter, the main aim of this research is to investigate the impact of six different urban configurations on outdoor thermal comfort in military camps at Abu Dhabi and Dubai. According to the comparison between different methodologies as discussed in the previous section, computer simulation is selected as the main study approach in this research. The methodology of this research is divided into two main stages: the first is software validation using modeling with applications followed by a simulation process to obtain the predicted results. The second stage analyses the acquired data. In this section, the question of why simulation is the preferred methodology will be discussed, and software will be validated to ensure the capability and accuracy of ENVI-met as the main simulation tool.

Given the increasing concern of the international scientific community towards microclimate and outdoor thermal comfort, this paper focuses on the software ENVI-met. It is a holistic three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions, and is often used to evaluate urban environments and assess the microclimate deriving from different urban morphologies. (Salata et al. 2016).

3.9 Methodology Justification

Computer simulation is preferred to investigate the impact of different urban configurations on outdoor thermal comfort, due to time and efficiency factors. This research proposes design strategies to examine the optimal urban configurations in terms of thermal behaviour for six different configurations; one is an existing military camp referred as the “base case”, and five other urban configurations are designed on a hypothetical basis according to literature review recommendations. Field measurement for such approach is not practical, as it needs to be conducted over long periods of time, different locations, and the six different existing urban configurations need to be found; moreover, this research investigated different urban configurations located in on existing site in order to reach valuable results.

Further, a second factor is the cost impact: field measurement equipment and human resources for a data collection stage have a cost impact which is not applicable for the scope of this academic research.

Because of the complexity of parameter involved in evaluating the outdoor thermal comfort, methodologies such as numerical approaches and over-simplified models are not applicable with the proposed urban configurations.

On the other hand, computer simulation enables the research to develop a more realistic model of the potential conditions and focus on the effect of multiple variables simultaneously. Further, computer simulation provides a faster and cheaper means to study the effect of urban greenery, and is a suitable solution of methodology with respect to resources available for this research.

In order to acquire valuable and efficient results within a time frame of 16 weeks with limited resources, the main selected methodology is computational tool. ENVI-met- version 4 is used to simulate the six different urban configurations to analyze the outdoor thermal parameters influencing human comfort, particularly in a hot, arid climate.

On the other hand, an experimental measurements process is costly and takes time to obtain valuable results, while numerical models require simple parameters to build mathematical equations; therefore, three-dimensional computational simulation is considered the most appropriate and preferred methodology to investigate urban design parameters simultaneously (Salata et al. 2016).

The existing urban area selected for this research is located in Abu Dhabi, the capital city of the United Arab Emirates. Summer climatic conditions are selected to perform the simulation as it is the most uncomfortable period in hot, arid regions.

It is important to note that, field measurement and numerical models have been used extensively to validate results from the ENVI-met models.

3.10 Methodology Validation

Some previous studies have tested the validity of ENVI-met software by comparing the simulation results obtained from the software against measured values for a similar time and location of input data for simulation. A recent validation of ENVI-met software was conducted by Salata et al. (2016), with results obtained for different micrometeorological parameters and predicted mean vote (PMV) from ENVI-met validated against experimental values measured in the field at different locations and times. A selected mesh grid for 2 x 2 m^2 was accurate with no significant deviations; for example, the biggest difference reported of global radiation was approximately 10%, MRT was 0.9%, and air temperature 0.6%, while differences in relative humidity values were negligible. It is important to highlight that the software executes the simulation considering the ideal situation of cloudless sky (Salata et al. 2016).

Furthermore, the software's capability of evaluating outdoor thermal comfort is examined, with results compared to a field survey performed with random sample of people answering a structured questionnaire in addition to personal questions about their thermal perceptions. The interviewees were standing within 3 m of existing points selected to conduct this survey, and micro-meteorological measurements were performed at a height of 1.1 m. Following an ASHRAE 7-point scale used for PMV by ENVI-met, the scale ran from cold (−3), to cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2) and hot (+3). This unified scale is shown in Figure 3.8, making the comparison easy to understand (Salata et al. 2016).

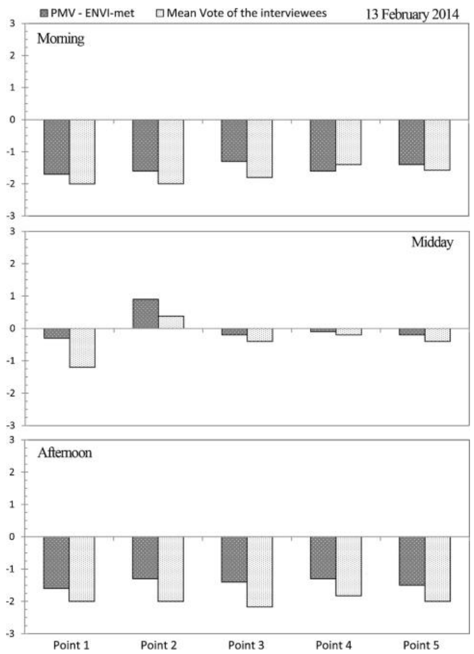


Figure 3.8: Comparison between the PMV values provided by ENVI-met and the mean value of the votes given by interviewees during the field survey on 13 February 2014. (Salata et al. 2016).

For the five points, the thermal comfort was examined for a precise hour (not the whole day) for 13 February, 2014. For three points, the PMV reported by interviewees was higher compared to values obtained from the software, indicating a higher discomfort level. The reason could be that body temperature can better adapt to heat conditions rather than cold conditions by natural processes through vasodilatation and vasoconstriction for the two conditions respectively (Salata et al. 2016).

On the other hand, Priyadarsini et al. (2008), in their study of the key factors contributing to the urban heat island in Singapore, attempted to validate the results of CFD simulation and real condition data from a wind tunnel experiment and field measurements. Figure 3.4 shows the results of the comparisons of wind tunnel experiment and field measurements with CFD simulations; as shown in the figure, the CFD simulation has the same profile as the real condition data.

Despite the fact that the data do not match completely, and that there is a level of discrepancy, the authors relied on the overall distribution and profile of the data. Since some factors in the real conditions that contribute to thermal data are absent in simulation condition (in the case of this research, anthropogenic heat is one these factors), it is not possible to gain results that are completely consistent with the real condition.

Even though ENVI-met has been verified in some of the previous studies, the accuracy of the software is required to be reconfirmed for the purpose of this study. In order to validate ENVI-met, thermal images of Dubai were acquired from the Dubai municipality environmental studies section. Figure 3.5a shows an urban block located in the Deira area which is considered as a part of old and dense urban area in Dubai. Figure 3.5b shows the infrared image of the same urban block, taken a few hours after sunset during early December, 2009 (Zacarias, 2011).

3.11 Site Selection

A residential area which is part of existing military camp has been chosen for demonstrating different the urban configurations. A 1.6775 ha accommodation area is located at the Mahawi camp, Abu Dhabi city, United Arab Emirates. The existing precinct comprises six accommodation blocks of four storeys, and a total GFA of 19200 m^2. Based on local guidelines, the maximum FAR has been set at 1.14, and site coverage percentage (SC) at 28.6%. The site is located adjacent to Alain Abu Dhabi Road 37, as shown in Figure 3.9.The climate conditions of this site have been explained in Chapter 1.

Figure 3.9: Selected Site. (Google Earth 2016).

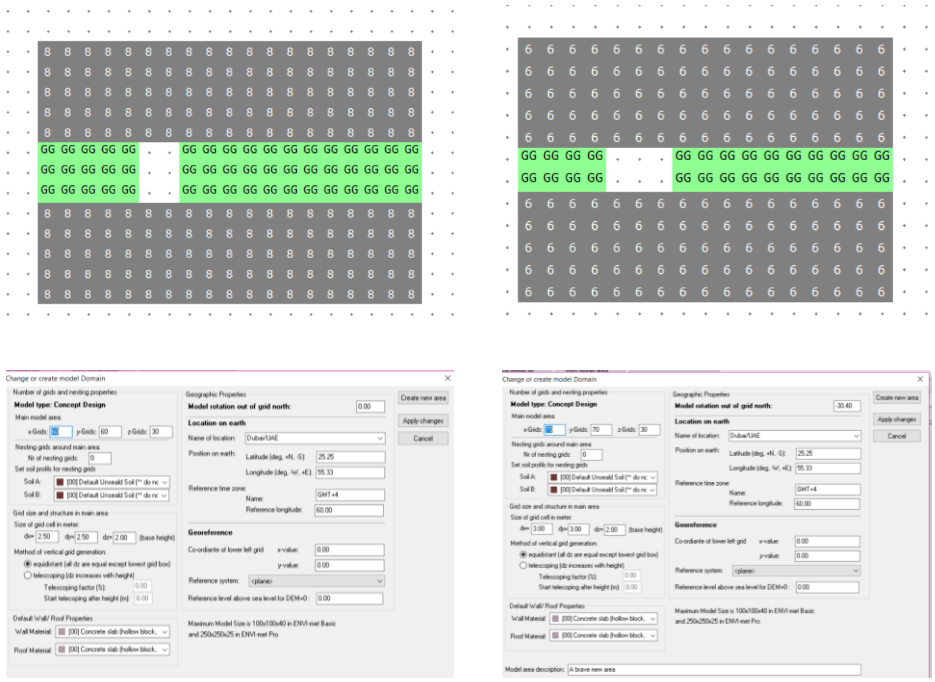
4 COMPUTER MODEL APPLICATION

4.1 Introduction

The investigations of the impact of urban configurations in this research are conducted by dividing the research into three main phases. Phase One of this research aims to identify the optimal urban configuration in terms of outdoor thermal behaviour through investigation of six different proposed urban configurations, with varying building forms and courtyard proportions; therefore all other parameters are considered constant. While Phase Two will use the results acquired in the earlier phase to determine the most favourable building height in terms of outdoor thermal comfort, with three different heights to be tested. Ultimately, Phase Three will investigate the impact of different orientations using the optimal urban configuration and height identified in the first two phases. This chapter discusses the selection of the parameters and their variables, as well as detailed explanation of the process of microclimate modelling using the ENVI-met 4 application. In addition, a quick trial validation of the software at the beginning of this section will be generated, followed by further validation in more detail at the end of Chapter 5 through a review of supportive literature.

4.2 Trial Validation

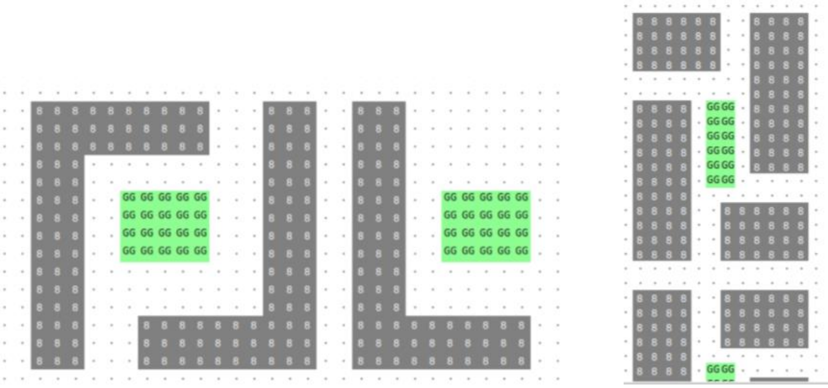
As mentioned in Chapter 3, ENVI-met is the preferred tool for this investigation, and was recommended throughout the literature reviewed. However, to ensure the software is capable of generating valuable results, trial simulation runs were performed using ENVI-met. This trial was performed for the existing urban configurations (the base case) from 10:00 till 16:00. Figure 4.1 represents each of the simulation results obtained at 12:00. Two parameters were examined; air temperature and wind flow, with the simulation results showing differences in temperature and wind flow. The trial verified that the software takes into account form, height, and orientation variations in thermal and wind calculations.



Trial different heights and orientations	Air temperature	Wind speed
Base case G+3	33.8	1.66
Base case G+2	32.38	1.66
Base case (North west –South east)	33.8	1.66
Base case (North –South)	31.72	1.53

Figure 4.1: ENVI-met model results for different heights and orientations for the base case

The detailed validation of simulations runs were intended to verify that ENVI-met depicts the outdoor thermal behaviour of different building forms, heights, and orientations. Simulations were performed for two sets of model applications for the developed linear configuration and L shape proposed configuration. The results depict that there are differences in the readings of thermal comfort corresponding to the forms, heights, and orientations of urban configuration. This certified the accountability of ENVI-met for different urban configuration as shown in Figure 4.2 below.



Trial different forms	Air temperature	Wind speed
L shape (G+3)	32.71	1.63
Linear developed shape (G+3)	31.95	1.91

Figure 4.2: ENVI-met model results for two different building forms

Research by Taleb (2011) recommended a finer grid of 1:1 scale model to obtain high quality temperature readings, meaning each grid axis represents one metre. In this research, three grid size were investigated: 1:1, 1:3, and 1:6. Due to the large size of the area of study (180 x 180 metre) a 1:3 grid size is preferred.

4.3 Parametric Analysis Research Matrix

A parametric analysis is a method to make several simulations runs on different urban configurations to examine only single parameter, considering others are constant. The effect of design variables on outdoor thermal conditions will be investigated by varying one variable at one time. This study's scope is to determine the optimal urban configuration's potential influence on outdoor thermal comfort, and it argues that various urban configurations proposals with reference to climate conditions may result in different outdoor thermal comfort conditions for each design proposal (Allegrini, Dorer & Carmeliet 2015).

To achieve the goal of this research, three parameters of urban configuration on outdoor thermal comfort will be investigated. As listed in Table 4.1, the first parameter— building form and courtyard proportions—is the most important parameter and is the base of this study. Building height is the second parameter, and the final (and least important) parameter is orientation. These three parameters are investigated throughout simulation runs performed in three phases using the ENVI-met software.

Phase 1 investigates the impact of urban configuration including building forms, and courtyard proportions (L/W and H/W ratios). Other parameters such as block area (buildable), maximum floor area ratio (FAR), maximum gross floor area (GFA), footprint, gross site coverage (GSC), site coverage (SC), and orientations are kept constant. The selected urban configurations—with designs inspired by the literature review—are listed in Table 4.1 (the letter denotes the configuration in later modelling):

A: Existing linear building form and deep shallow courtyard, referred to as urban configuration.

B: Proposed fortress with square courtyard.

C: Proposed fortress with rectangular courtyard.

D: Proposed U-shape building with square courtyard.

E: Proposed L-shape building with square courtyard.

F: Developed linear blocks with rectangular courtyard.

Phase 2 uses the result acquired at the end of Phase 1 to investigate the impact of different building heights of 3 storeys, 4 storeys and 6 storeys, and consequently the H/W ratio will be tested. In Phase 3, the impact of two different orientations will be tested for the most variable urban configuration. The selected two orientations were recommended by literature review as per Table 2.1 in the end of Chapter 2: Axis 1 as north west–south east, and Axis 2 as north–south. The research phases are explained comprehensively in Chapter 5.

Table 4.1: The six proposals of different urban configurations

Configuration code	Building form	Courtyard proportion
A	Linear	54:8 = 7:1
B	Fortress	12:12 = 1:1
C	Fortress	24:12 = 2:1
D	U shape	32:28 = 1:1
E	L shape	28:28 = 1:1
F	Developed linear	24:12 = 2:1

For each one of the three parameters, a range of variables was determined. It can be seen that the highlighted variables (in grey) are used as default values, which are constant values when testing other parameters. The research matrix is developed as illustrated in Table 4.2 below.

Table 4.2: Selected parameters and variables

Parameters	Variables	Constants (urban texture variables)
P1 – Building form & courtyard proportion	(A) Existing linear blocks with deep courtyard (B) Fortress blocks with square courtyard (C) Fortress blocks with rectangular courtyard (D) U-shape with square courtyard (E) L-shape with square courtyard (F) Developed linear blocks with rectangular courtyard	Block area m^2 = 16771.5 FAR = 1.14 GFA m^2 = 19200 GF m^2 = 4800 (GSC) = 0.4 SC = 28.6%
P2 – Building height	Six storeys (24 m) H/W = 24/12 = 2.0 Four storeys (16 m) H/W = 16/12 = 1.5 Three storeys (12 m) H/W = 12/12 = 1.0	
P3 – Orientation	Axis 1: North West–South East Axis 2: North–South	

These tests will be applied on a simplified urban block designed to determine the effect of each individual parameter as shown in Table 4.3 to 4.5. In the next sections, the variables and the simplified model are explained in more detail.

Table 4.3: Phase 1: Trials investigating the impact of building forms and courtyard proportion

Trial	**P1 – Variable parameters** Building forms & courtyard proportion	**P2 – Fixed parameter** Building height	**P3 – Fixed parameter** Orientation
P1-1	Existing linear blocks, rectangular courtyard	16 metre (four storeys)	Axis 1: North West–South East
P1-2	Proposed fortress blocks, square courtyard	16 metre (four storeys)	Axis 1: North West–South East
P1-3	Proposed fortress blocks, rectangular courtyard	16 metre (four storeys)	Axis 1: North West–South East
P1-4	Proposed U-shape blocks, square courtyard	16 metre (four storeys)	Axis 1: North West–South East
P1-5	Proposed L-shape blocks, square courtyard	16 metre (four storeys)	Axis 1: North West–South East
P1-6	Proposed developed linear blocks, rectangular courtya	16 metre (four storeys)	Axis 1: North West–South East

Table 4.4: Phase 2: Trials investigating the impact of building height (H/W ratio)

Trial	**P2 – Variable parameter** Building height	**P1 – Fixed parameter** Building form	**P3-Fixed parameter** Ordination
P2-1	(G+2) Three storeys = 12 m	The most favourable of Phase 1	Axis 1: North West–South East
P2-2	(G+3) Four storeys = 16 m		Axis 1: North West–South East
P2-3	(G+5) Six storeys = 24 m		Axis 1: North West–South East

Researchers have linked orientation to microclimate conditions, and orientation plays an important role on outdoor thermal comfort. In this research, orientation is less important than building form, courtyard proportions, and building height, as it has already been tested comprehensively. The most unfavourable orientations are eliminated, for example previous studies revealed that an east–axis provides higher cooling load. There is considerable fluctuated cooling load data of manipulated, extended building shapes at different orientations. Data calculations indicate the percentage difference between building forms in hot-humid orientations shows a difference of only 1% to 3% in cooling load (Taleghani, Tenpierik & Dobbelsteen 2014).

Table 4.5: Phase 3: Trials investigating the impact of building orientation

Trial	**P3 -Variable parameter** Ordination	**P1 – Fixed parameter** Building form	**P2 – H/W ratio**
P3-1	Axis 1: North West–South East	The most favourable of Phase 2	2
P3-2	Axis 1: North West–South East		1
P3-3	Axis 2: North–South		1

The descriptive diagram of the research matrix in Figure 4.3 showcases the research map which will be discussed in detail in next sections.

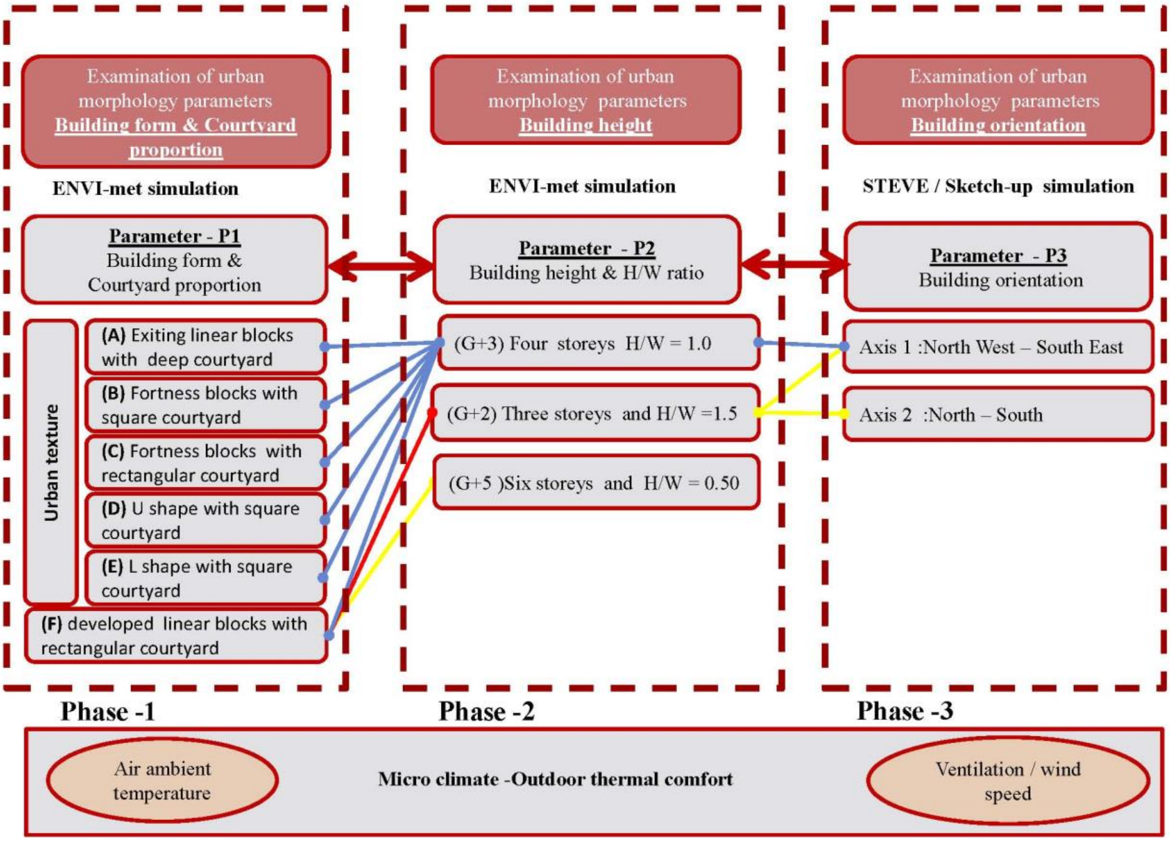


Figure 4.3: Descriptive diagram of the research matrix

4.4 Microclimate Variables

The numbers of variables that influence outdoor thermal comfort are many and interconnected. Every variable has its own impact and also interacts with variables, creating create complexity in this research. To simplify, in this research some variables have been applied as constants and acknowledged as core factors, an approach supported by the literature review and earlier research results presented in earlier chapters. In general the modelling variables can be divided into three groups: fixed variables, independent variables, and dependent variables which change when independent variables change. It is important to identify these three types of variables and parameters before commencing the simulation process.

Fixed variables are kept constant to highlight the importance of the three main variables affecting urban configurations; however, some of this study's fixed variables have been considered as changing variables in other studies. For example, the hardscape and softscape area and properties are approximately fixed in the six urban configurations.

Those constant variables are part of the input data that does not change in any of the simulation runs. Fixed variables remain fixed throughout simulation performance to ensure result and outcomes focus on the selected independent variables without interference from other varying conditions or factors. The dependent variables are fixed for the simulations as shown in Table 4.6, but can be varied according to season, place, and date. These are climatic data such as wind speed, wind direction, average temperature, and relative humidity, which depend on simulation day and time setup. The albedo and heat transmission values of walls and roofs and the inside temperature of the buildings are also kept fixed in all simulations.

Table 4.6: Dependent (fixed) variables for all simulation runs

Wind speed (m/s)	Wind direction (degrees)	Initial temp (K)	Specific humidity in 2500m (gWater/kg air)	Relative Humidity in 2m (%)	Inside temp of buildings (K)	Heat trans. walls [W/m²K]	Heat trans. roofs [W/m²K]	Albedo walls & roofs
3.6	325	305.15	7	60	300	2	1	0.1

The independent parameters were selected to achieve the goal set for this research. The six selected urban configurations are simple urban forms and designed to investigate the individual parameters. The three variables P1, P2, and P3, listed in Table 4.2, play a significant role in the interface between urban configuration and outdoor thermal comfort. The latest version of ENVI-met 4 modelling software is capable to considering the interconnected variables contributing to this interface.

Based on the developed descriptive diagram of the research matrix shown above, the selected parameters are simulated. It is important to note that all simulation runs were conducted during summer at the hottest day of July 2, 2016. All values for fixed variables as listed in Table 1 are considered as input data for the software, and the average of hours selected to run simulation was 24 hours from 07:00 to 07:00. As illustrated in Figure 4.4, the basic settings for model domain are identical for all trials, main model area grid measures of 70 x, 70 y, 30 z, and grid cell size of 3 m (dx), 3 m (dy), and 2 m (dz).

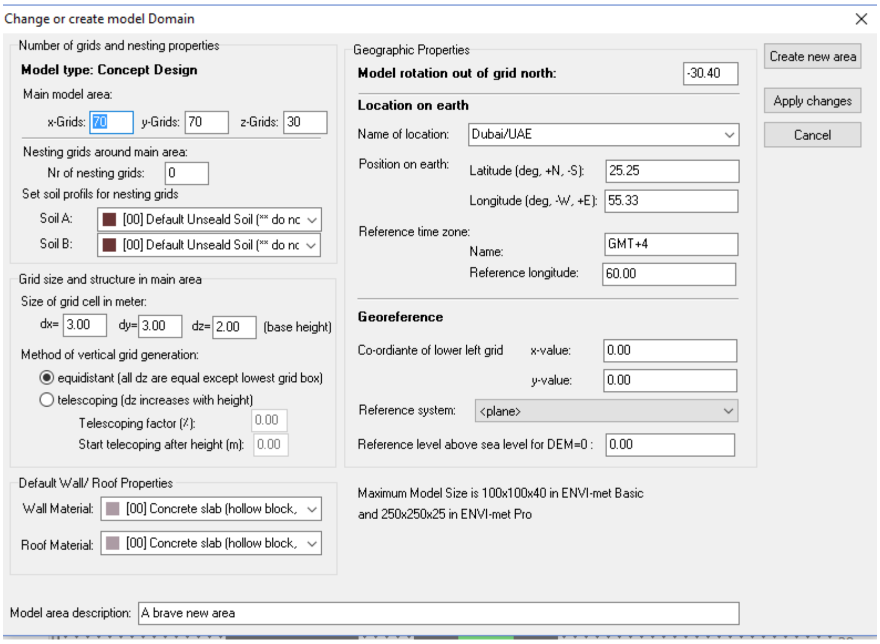


Figure 4.4: Basic setting for the ENVI-met model domain

Taleghani et al. (2015) listed the main four microclimatic parameters most often considered during simulations as air temperature, mean radiant temperature, air velocity, and relative humidity. This research tends to deepen knowledge of the impact of urban configuration on outdoor thermal comfort, specifically building form and H/W ratio. Primarily, ASHRAE has outlined six points that will influence and used in the outdoor thermal comfort: building characteristics, building configuration, outdoor design conditions, indoor design conditions, operating schedules, and date and time (Rashdi & Embi 2016).

4.5 Urban Texture Variables

The form and density of urban precinct is characterised by several urban texture variables which significantly influence building physical parameters within urban space. These variables are listed in Table 4.1 for the six selected different urban configurations.

The parametric design approach was selected, setting a FAR of 1.14 and site coverage of 28.6% as constants to comply with the local UAE building code for low density urban design, while the floor BUA is variable from 800 to 1200 m^2 square to achieve the maximum gross floor area (GFA) of 19,200 m^2 for the different number of buildings: six buildings for the existing urban configuration (A) and four buildings for proposed urban configurations B and C.

Ignatius, Wong, and Jusuf (2015) defined the gross site coverage ratio (GSC) as "the ratio of the total building footprint to the remaining open space of a studied area". In this research, the GSC is maintained as 0.4 for all six urban configurations. Every building has been set to have the same height for all different iterations. Within this parametric approach, as the site coverage rises, the building height lowers to meet the maximum floor area restriction. In this particular study (as shown in Table 1), the number of blocks in each iteration varies from 4–16, but the site coverage and gross floor area are kept constant.

The next design iteration process is designed to examine the impacts of building height. Since the FAR has been fixed for the whole precinct, every iteration process affects the number of buildings and surface area slightly. This can be seen from Table 3, which indicates that as the urban configuration becomes more compact, the total building surface area becomes smaller. In this case, becoming more compact by maintaining the FAR means the buildings become lower and the footprint becomes larger.

There are numerous alternative design layouts of urban configurations, and accordingly many ways to determine the building form and courtyard proportion considering variable options and dimensions of height, length, and span. Building volume is influenced by GFA and FAR. It is important to note that two different buildings may have a different GFA, which influences the surface area of sun exposure, but both buildings may have similar FAR if a different number of storeys is considered. In this research, all selected building forms and urban configurations are purely simple geometry that is commonly found in urban design field.

Table 4.7: Urban texture variables values for P1, all with the following common parameters: 4 storeys, Total GFA m^2 of 19,200, building height of 16m, GSC of 0.4, and occupancy loading of 164.0

	No. of buildings	Footprint GF/m^2	Courtyard width/m	Courtyard length/m
P1-1	6	800	8	54
P1-2	4	1200	12	12
P1-3	4	1200	12	24
P1-4	8	600	28	32
P1-5	8	600	28	28
P1-6	16	300	12	24

4.6 Model Application for Simulation Runs Investigating the Impact of Building Form and Courtyard Proportion—P1

The study investigates the manipulation of the basic urban configurations of low density of an existing urban area in a hot arid climate. The existing urban configuration plus five different proposals will be tested to assess the main parameter affecting outdoor thermal comfort throughout parametric analysis, which has been explained in earlier sections. The six urban configurations considered in this research were derived from recent research studies undertaken by Ratti, Raydan and Steemers (2003), Okeil (2010), Taleghani, Tenpierik and Dobbelsteen (2014), Taleghani et al. (2015), Allegrini, Dorer and Carmeliet (2015), and Rashdi and Embi (2016). These studies were reviewed and analysed critically in Chapter 2.

The study scope is to explore which of six proposals holds the optimal urban configuration to provide the best outdoor thermal comfort. The concept design for these six urban configurations were being created in Autodesk 2014 Revit and AutoCAD 2013, and simulated in ENVI-met as the core software. Required data input for Revit is considered constant for all six proposals, and the same information entered in the software as shown in Table 4.7. Such data are operation schedules, regulations, space usage, desirable temperature, occupancy, and other operational parameters.

Throughout the simulation stage, Ecotect2011 has been used as supportive software to provide climatic data. The six urban configurations are manipulated; however urban texture variables such as maximum FAR, GSC, and SC, in addition to softscape and hardscape properties, are set as constants.

Based on the literature review, two typical forms of urban configuration that are recommended in many papers are taken as the generic cases for this research: the first is *linear urban* for the A configuration, and the second is *fortress* for the B and C configurations. The proposed designs for D, E, and F configurations are extended urban forms based on experimentation and the literature review. These two typical forms of urban configuration, linear and fortress, were taken from the six different generic urban morphologies investigated by Allegrini, Dorer, and Carmeliet (2015) in Switzerland to study the impact of general urban morphology on outdoor thermal comfort. Recent studies by Ignatius, Wong, and Jusuf (2015) have reported on a larger high density urban area of 9 ha where building heights vary between 17 and 50 storeys and courtyards were square with variable areas ranging from 400 m^2 to 2000 m^2.

In this research, the fortress urban form is divided into two: fortress with a rectangular courtyard and fortress with a square courtyard, with these referenced as forms B and C, respectively. Form A represents the existing accommodation in precinct urban area, while Form B represents the proposed urban configuration of a fortress with a square internal courtyard of 12 x 12 m, Form C represents a fortress with rectangular internal courtyard of 12 x 24 m as, while forms D, E, and F represent the extended urban forms described in detail in the coming sections of this chapter.

The number of buildings of each configuration is limited by local building code to maintain total buildable area of 19,200 m^2. The distance between buildings is a minimum of 8 m in order to unify the H/W ratio of 2.0. For the three different configurations, the floor area is quite small, varying from 300–1200 m^2, but are quite typical in their geometries with common proportions and H/W ratios, as illustrated in Table 4.7.

Figure 4.17 and 4.18 indicate the proposed urban configurations from A to F respectively, where Form A is the existing design—which is considered as the "base case"—and the remaining forms B to F are design proposals. Once the simulation of the configurations is completed, the two main parameters influencing outdoor thermal comfort—air temperature, and wind speed—will be tested to determine the most favourable urban configuration. All six models share the same amount of grass and trees despite differences in the form of buildings, and greenery and values of parameters of building height (P2) and orientation (P3) are constant. The results obtained from all tests investigating the three parameters will be evaluated based on average hourly surface temperatures and wind speed. For each parameter, air temperatures obtained from different tests will be displayed in the same graph for further comparison and analysis. The next chapter will focus on the analysis of data and discussion of the results.

4.6.1 Existing Urban Configuration (Form A)—Base Case

The existing urban configuration referred to as Form A is considered to be the base case. The trapezoid plot has sides of 151 m, 133 m, 146 m, and 96 m. The existing accommodation zone is part of an existing military camp, as explained in Chapter 3, and comprises six residential buildings.

In order to standardise the urban textures and direct all the focus on the different forms and courtyard proportion, a simplified existing urban configuration was selected for this research. Figure 4.7 shows the ENVI-met model of the simplified urban block; the model area is developed on a 70 x 70 grid of points each measuring 3 m x 3 m. As listed in Table 2, the existing urban textures were used as standard for the other five proposals. In the base test, all landscape is designed to reflect the simplicity and functionality of actual site treatment of military camps (MC), the courtyards are green turf, and the parking areas have the albedo of asphalt. The base-test is manipulated according to the values of three parameters for each individual test in tables 1 to 4. These models will be explained independently later in this chapter. Beside the input model for running a simulation, ENVI-met also requires a “project wizard” file where values of fixed variables, timing details, and input and output information are set. Figure 4.2 shows snapshots of the ENVI-met configuration files. The values of different variables are based on values in Table 4, and the simulation runs to calculate conditions of a full day (24 hours).

The open spaces surround six buildings as illustrated in Figure 4.5, which are blocks 14.8 m x 53.7 m each with a height of 16 m (4 storeys). The receptor (the point considered for thermal comfort) is located in the centre of the courtyard at a height of 1.40 m.

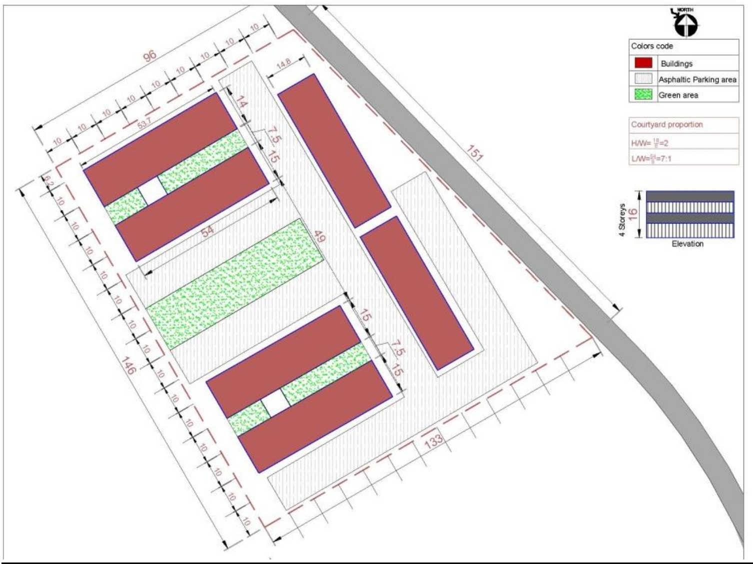


Figure 4.5: The "base case" existing urban configuration layout (Form A)

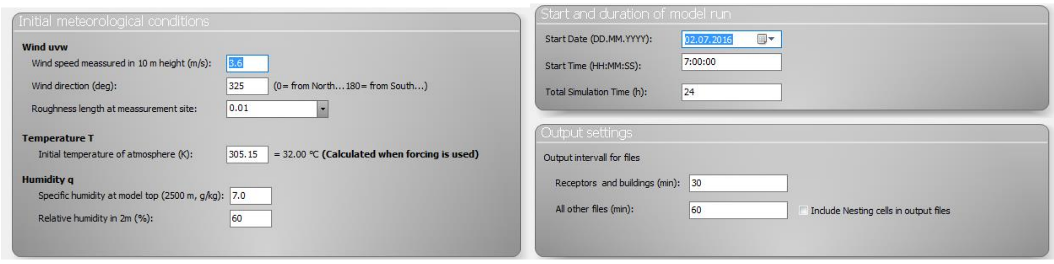


Figure 4.6: The project wizard with fixed input data to investigate ز

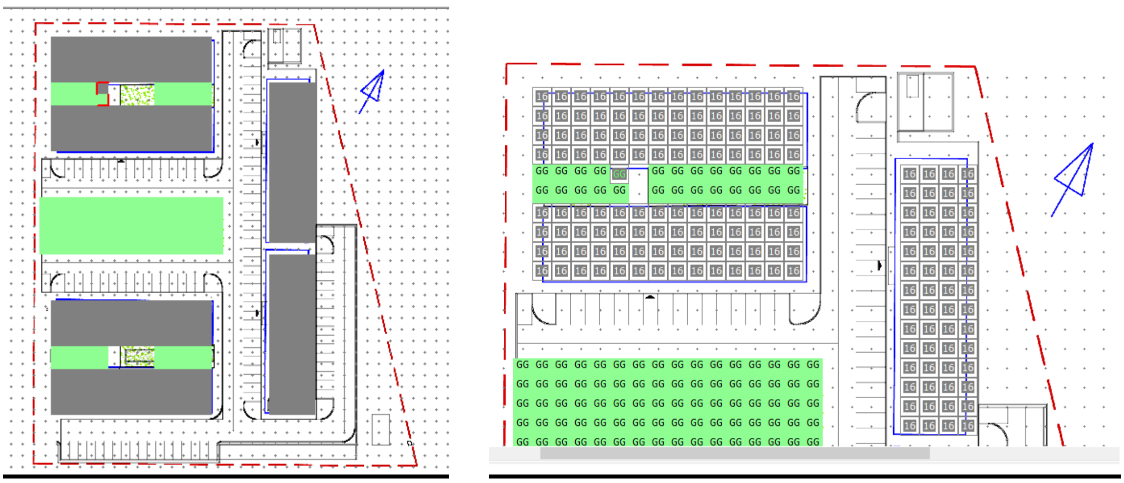


Figure 4.7: ENVI-met model of existing urban blocks, referred to as base case A, P1-1.

In order to maintain the SC as a constant 28.6%, the buildings cover 4800 m^2 out of 16771.50 m^2. The H/W ratio kept as 2.0 and Axis 1 (North West–South East) is maintained for the three different configurations. It should be noted that asphaltic area and green areas are fixed on all simulation trials to examine parameter P1.

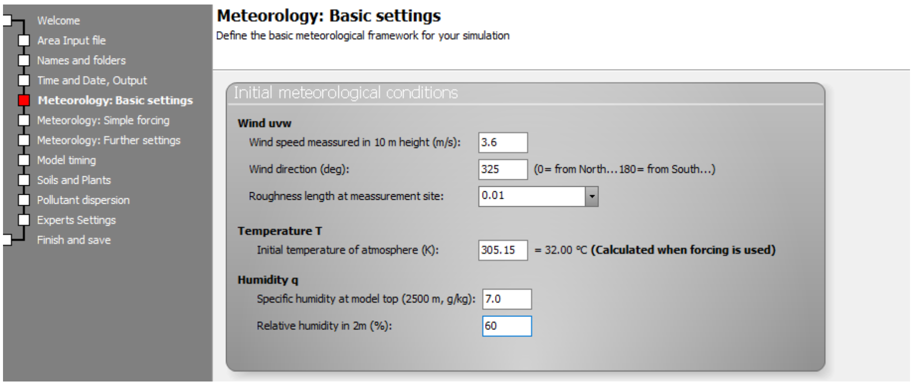


Figure 4.8: Meteorology basic setting for all simulation runs

In addition to the input model for running a simulation, it is important to fill the project wizard file with initial basic meteorology conditions such as wind speed, wind direction, initial temperature of atmosphere, and relative humidity. Eventually the simulation runs to calculate conditions of a full day (24 hours) as shown in Figure 4.8 above.

4.6.2 Proposed Urban Configurations B and C

Urban configuration proposal plans B and C are archetypal forms of Taleghani, Tenpierik, and Dobbelsteen (2014), who concluded that a courtyard configuration led to a more favourable micro-climate because of more favourable environmental variables (such as surface to volume ratio, and shadow density). The thermal behaviour of courtyards has been studied widely in hot arid climates, where courtyards are used as a passive design strategy to provide shading and for better natural ventilation—the main character of the courtyards due to stack effect—and consequently courtyards cool down the microclimate. In general, courtyards have been used extensively in austere climates. For example, they are used in hot climates to provide better shading, in humid climates for better natural ventilation and air movement, and in temperate and cold climates to protect pedestrians from winds and storms.

As shown in Figure 4.9, 18 urban configuration blocks were examined with varying proportions for courtyard models, and four main orientations were tested. Outcomes revealed that a north west–south east orientation is more comfortable among the rotated courtyards (Taleghani, Tenpierik & Dobbelsteen 2014).

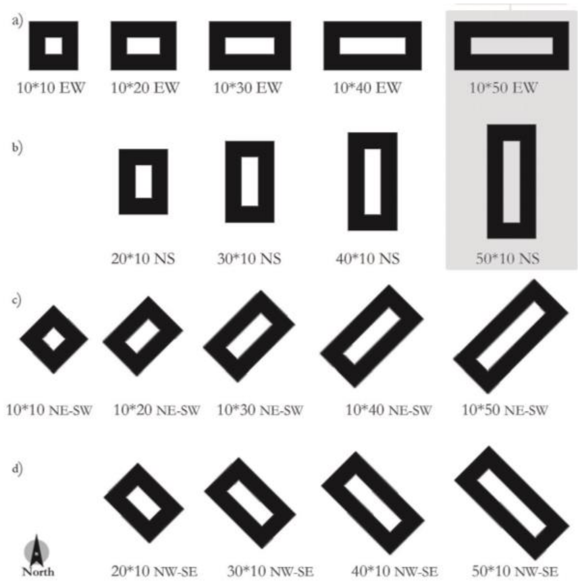


Figure 4.9: Different orientations and proportion for the examined courtyards (Taleghani, Tenpierik & Dobbelsteen 2014)

Furthermore Taleghani et al. (2015) compared courtyard buildings with different urban layouts (linear and singular blocks with the same floor area). They courtyard configurations have the least hours of summer discomfort. The comprehensive urban study undertaken by Ratti, Raydan, and Steemers (2003) reveals that the courtyard building form has the best thermal behaviour among the different five forms studied.

Refer to Figure 4.10 and 4.11, the proposed Plan B design comprises square courtyard for the fortress, while Plan C contains a rectangular courtyard, a shallow plan form, and narrow spaces for shade which improves thermal comfort despite an increased heat island. For design Plan B, the fortress measures 37 m x 37 m, the width of the buildings surrounding the courtyard is 25 m. This means that the dimension of the courtyard is 12 m x 12 m. In the design proposal Plan C, the fortress measures 33 m x 45 m with rectangular proportions for the courtyard of 12 m x 24 m.

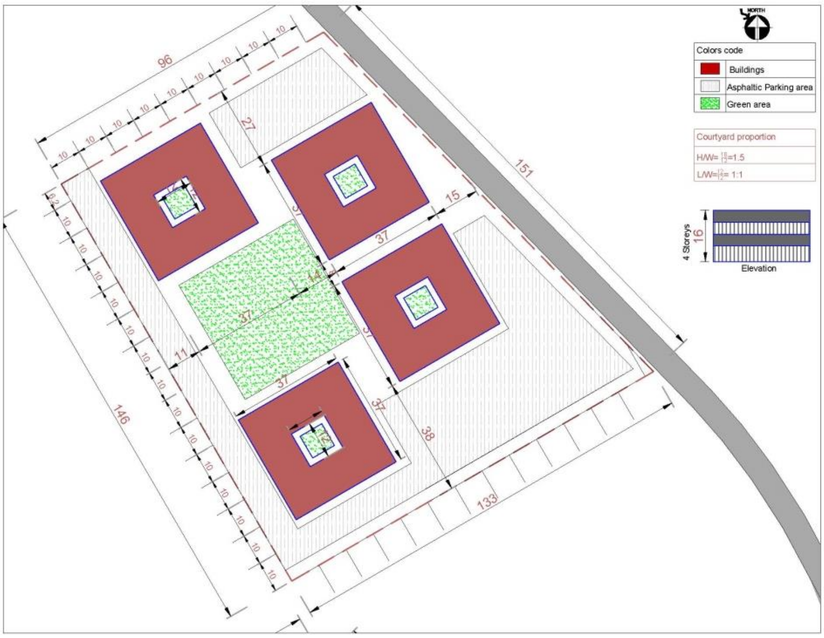


Figure 4.10: The proposed fortress blocks and square courtyard urban configuration layout of Plan B

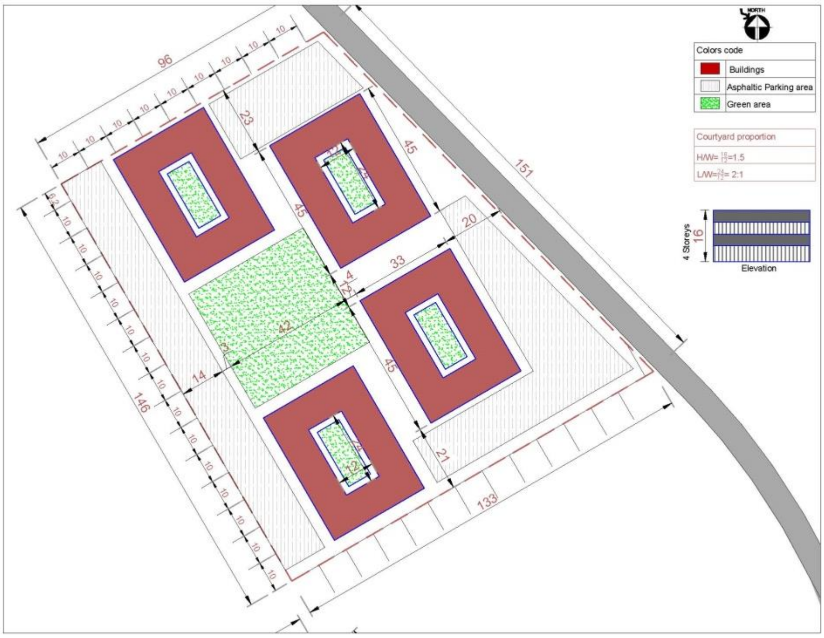


Figure 4.11: The proposed fortress blocks and rectangular courtyard urban configuration layout C.

4.6.3 Proposed Urban Configurations D and E

Refer to Figure 4.14 and 4.15, the design of urban configurations of D and E are simple forms representing U and L shapes respectively. These urban configurations can be considered to be extended manipulated forms from the original proposals of the rectangular and fortress plans, inspired by research done by Rashdi and Embi (2016), who investigated the optimal building form in terms of cooling load in Malaysia. Cooling load, and airconditioning in particular, makes the biggest demand of total energy consumption in hot climates, and constitutes 70% of total energy consumption per annum. Rashdi and Embi's study confirmed that designing a building form in an efficient way to cool itself (known as a passive cooling strategy) reduces the need for airconditioning. For example, a small saving in airconditioning use leads to considerably less energy consumption. Moreover, the impact of a building envelope's material was also highlighted. The results revealed that a more compact form with a lower surface to volume ratio significantly reduces cooling load. As represented in

Figure 4.12, the L shape (L2) and U shape (U3) provided a decrease in cooling capacity compared to other forms such as rectangular, square, and T-shape, ellipse, circle, courtyard, and box. The reason behind that is the compactness of form (Rashdi & Embi 2016).

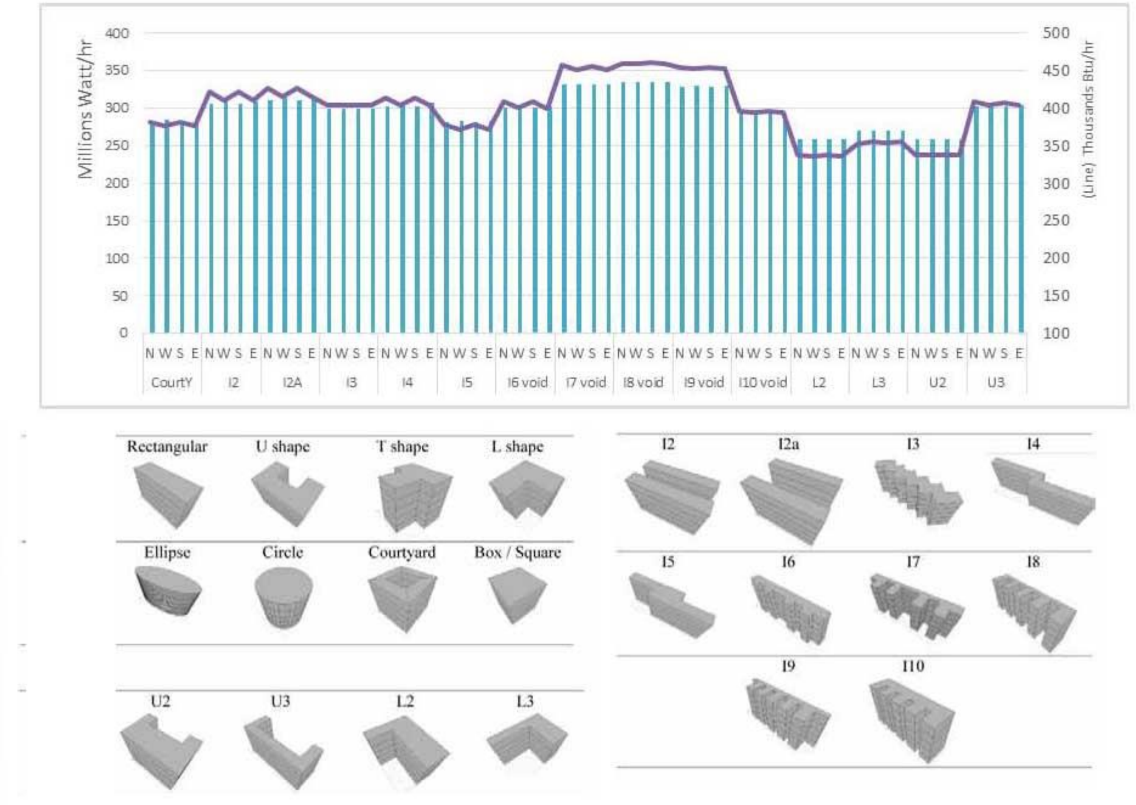


Figure 4.12: Different building forms and cooling load (Adapted from Rashdi & Embi 2016, p. 786, 789)

The results indicate that air temperature increases consequently within a loose shape, while the most compacted shape such as a courtyard or fortress shows lower air temperature. The graphs show the outdoor thermal comfort results are consistent with the surface to volume ratio relative to various basic forms. The lower the width to length ratio, the more compact the urban configuration becomes, and the lower its air temperature, thus less shade is needed to decrease heat.

This design proposal is inspired by a study conducted by Okeil (2010), where a residential solar block (RSB) form is used as preferred building form in terms of energy-efficient neighbourhood layout for a hot and humid climate. The study investigated three different urban forms: linear, block, and RSB. The preferred RSB form provides the best functional, spatial, social, and visual advantages compared to conventional linear form. As illustrated in Figure 4.13, the RSB form is created taking into consideration overshadowing restrictions on the site to reduce solar exposure. The concept design is based providing different heights for one building form by extruding the block high at the corner and low where the L-shape meets ground levels; this stepped concept for the form results in a full shaded area that fits almost exactly in the open spaces between buildings. Results revealed that the L-shape form also provides protection from sandstorms at pedestrian level.

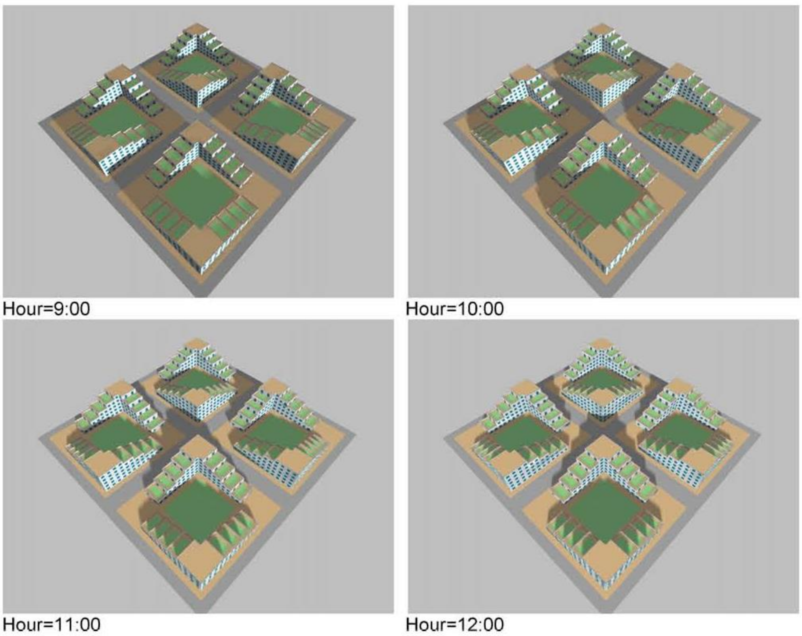


Figure 4.13: Different shadow areas during day time for an RSB (Okeil 2010).

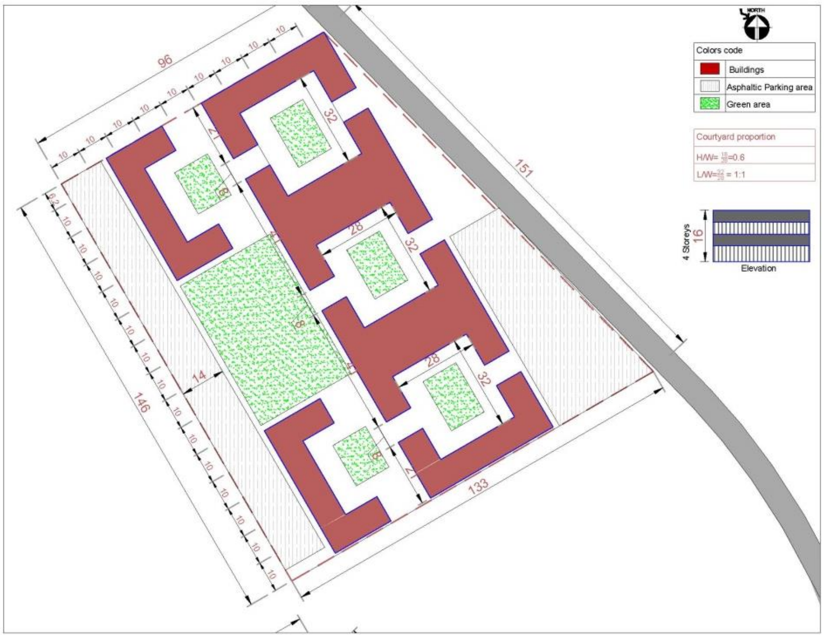


Figure 4.14: Proposed U-shape blocks and square courtyard urban configuration layout (Form D)

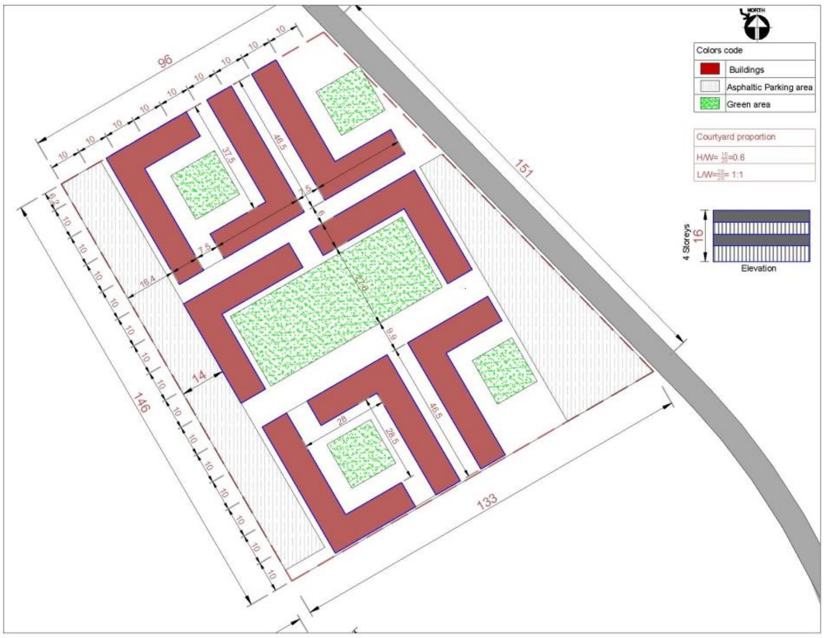


Figure 4.15: Proposed L-shape blocks and square courtyard urban configuration layout (Form E)

4.6.4 Proposed Urban Configuration (F)

The proposed urban configuration Form F is the extended urban form generated from the proposed design for Form C and Form E. The rectangular fortress is split into smaller linear forms; however the courtyard form is maintained as a rectangle of 24 m x 12 m as represented in Figure 4.16.

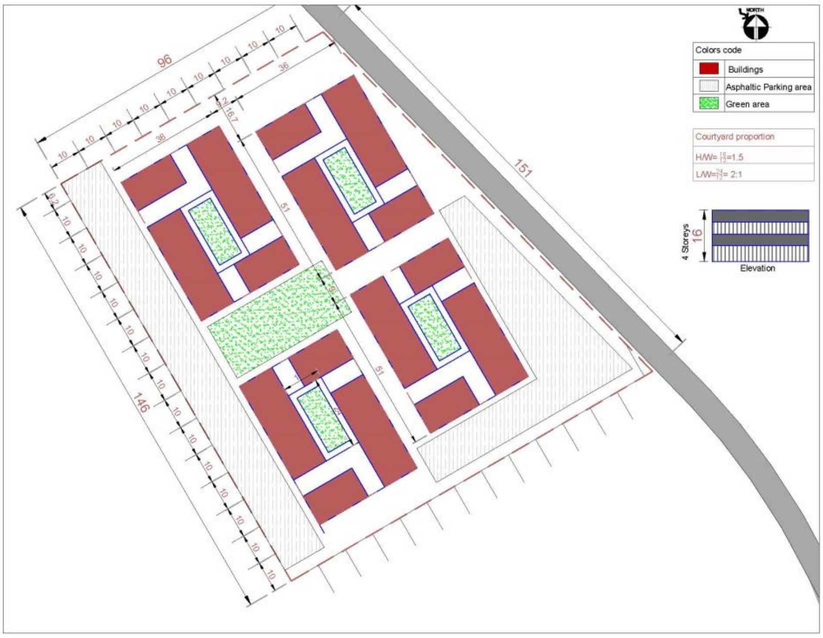


Figure 4.16: The proposed developed linear blocks with rectangular courtyard urban configuration Form F.

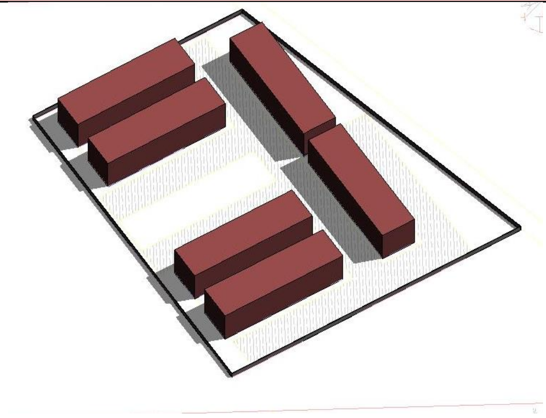
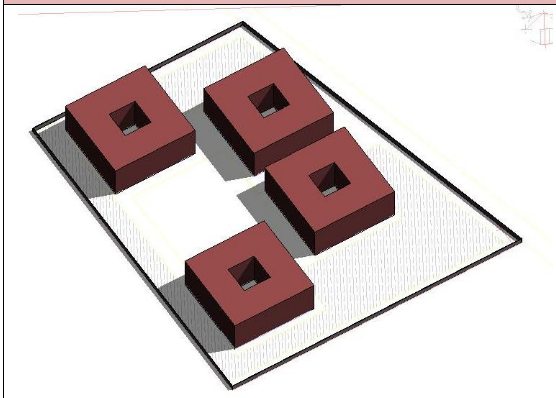
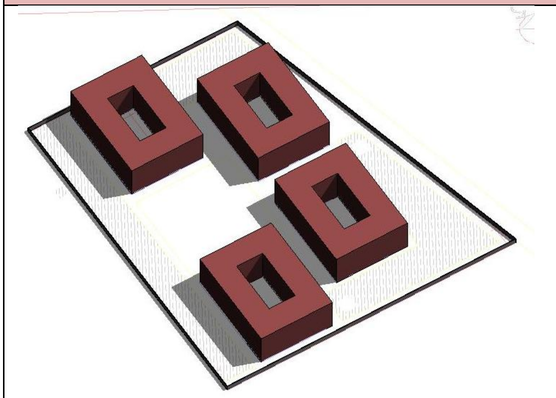
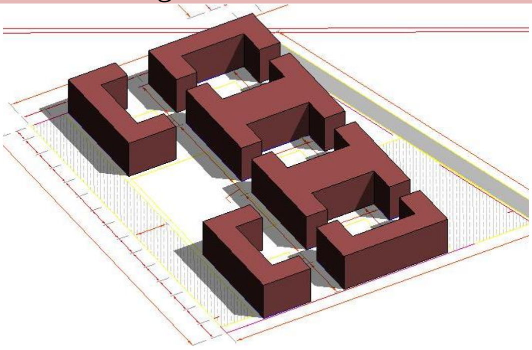
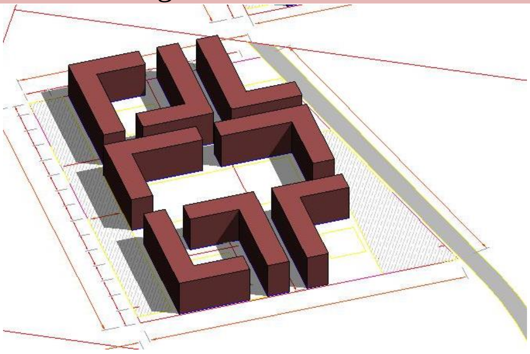
Urban configuration A: Trial P1–1	Existing linear blocks	
	Block area (buildable) /m^2	16771.50
	Asphaltic area / m^2	5819
	Grass area / m^2	1756
	Max floor area ratio (FAR)	1.14
	Max gross floor area (GFA) / m^2	19200
	Footprint /GF/ m^2	4800
	Gross site coverage (GSC)	0.40
	Site coverage (SC)	28.6%
	Number of storeys	4
	Number of buildings	**6**
	Internal courtyard dimension (m)	**54 m x 8 m**
	External courtyard dimension (m)	**45x49 M**
Urban configuration B: Trial P1–2	Fortress blocks with rectangular courtyard	
	Block area (buildable) /m^2	16771.50
	Asphaltic area / m^2	3980
	Grass area / m^2	2020
	Max floor area ratio (FAR)	1.14
	Max gross floor area (GFA) / m^2	19200
	Footprint /GF/ m^2	4800
	Gross site coverage (GSC)	0.40
	Site coverage (SC)	28.6%
	Number of storeys	4
	Number of buildings	**4**
	Internal courtyard dimension (m)	**12 x12 M**
	External courtyard dimension (m)	**50x50 M**
Urban configuration C: Trial P1–3	Fortress blocks with square courtyard	
	Block area (buildable) /m^2	16771.50
	Asphaltic area / m^2	4100
	Grass area / m^2	2080
	Max floor area ratio (FAR)	1.14
	Max gross floor area (GFA) / m^2	19200
	Footprint /GF/ m^2	4800
	Gross site coverage (GSC)	0.40
	Site coverage (SC)	28.6%
	Number of storeys	4
	Number of buildings	**4**
	Internal courtyard dimension (m)	**12 x24 M**
	External courtyard dimension (m)	**50x50 M**

Figure 4.17: The layout and urban texture variables of proposed urban configurations under investigation (P1)

Urban configuration D: Trial P1–4	Existing linear blocks	
	Block area (buildable) /m^2	16771.50
	Asphaltic area / m^2	3980
	Grass area / m^2	2090
	Max floor area ratio (FAR)	1.14
	Max gross floor area (GFA) / m^2	19200
	Footprint /GF/ m^2	4800
	Gross site coverage (GSC)	0.40
	Site coverage (SC)	28.6%
	Number of storeys	4
	Number of buildings	**6**
	Internal courtyard dimension (m)	**28 x 32**
	External courtyard dimension (m)	**28 x 67**



Urban configuration E: Trial P1–5	Fortress blocks with rectangular courtyard	
	Block area (buildable) /m^2	16771.50
	Asphaltic area / m^2	3912
	Grass area / m^2	1985
	Max floor area ratio (FAR)	1.14
	Max gross floor area (GFA) / m^2	19200
	Footprint /GF/ m^2	4800
	Gross site coverage (GSC)	0.40
	Site coverage (SC)	28.6%
	Number of storeys	4
	Number of buildings	**8**
	Internal courtyard dimension (m)	**28 x 28**
	External courtyard dimension (m)	**50 x 50**



Urban configuration F: Trial P1–6	Fortress blocks with square courtyard	
	Block area (buildable) /m^2	16771.50
	Asphaltic area / m^2	4000
	Grass area / m^2	1945
	Max floor area ratio (FAR)	1.14
	Max gross floor area (GFA) / m^2	19200
	Footprint /GF/ m^2	4800
	Gross site coverage (GSC)	0.40
	Site coverage (SC)	28.6%
	Number of storeys	4
	Number of buildings	**16**
	Internal courtyard dimension (m)	**12 x 24**
	External courtyard dimension (m)	**20x40**

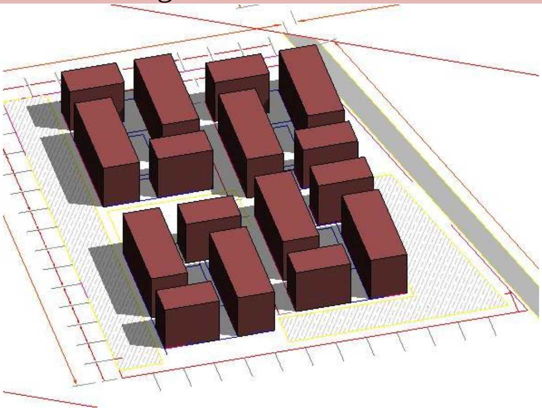


Figure 4.18: The layout and urban texture variables of proposed urban configurations under investigation (P1)

4.7 Model Application for Simulation Runs Investigating the Impact of Building Height—P2

Based on the results will be acquired from Phase 1, Phase 2 will explore the manipulation of building heights. Essentially, the impact of three different heights—three, four, and six storeys—will be tested, as shown in Table 4.18. The manipulation of building height is based on H/W ratio.

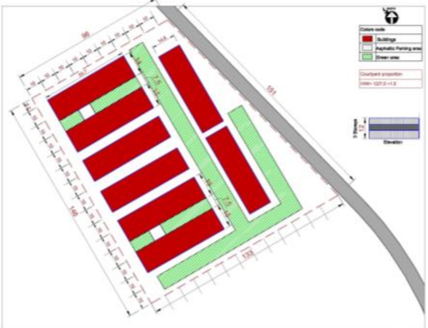
This parameter, the impact of building height, investigates the effect of the different building heights and accordingly the H/W ratio. Each trial under this parameter aims to measure one possible condition of the height, at 12 m, 16 m, or 24 m. Table 1 in Figure 6 shows three urban texture models that investigate the effects of the parameter. For example, in model P2–1, the building height is 12 m, while in model P2–2 and P2–3 the height is changed to 16 m and 24 m, respectively. In all the models investigating Parameter 2, values of the other two parameters are fixed, meaning the proposed urban configuration is set at as A and the optimal design for the second parameter (P2) and the urban form has the north west– south east orientation of Axis 1 for the third parameter (P3). Figure 4.19 shows the impact of changing the building height on other urban textures such as site coverage (SC), footprint. hardscape and softscape.

Table 4.8: Parametric design analysis for building height and H/W ratio

Simulation runs	Building form	Building height/mete	H/W ratio
P2–1	(A) Three storeys	12	12:7.5 = 1.5
P2–2	(A) Four storeys	16	16:12 = 1.5
P2–3	(A) Six storeys	24	24:48 = 0.5

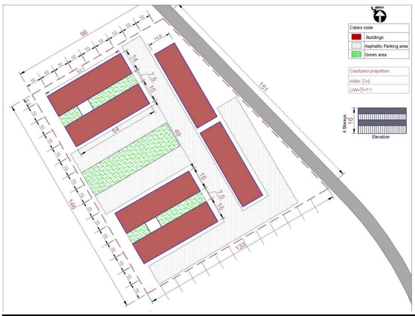
P2–4	Most favourable urban configuration of (P1)	12	12:12 = 1
P2–5	Most favourable urban configuration of (P1)	16	16:8 = 2.0
P2–6	Most favourable urban configuration of (P1)	24	24:18 = 1.5

Urban configuration A: Trial P2–1



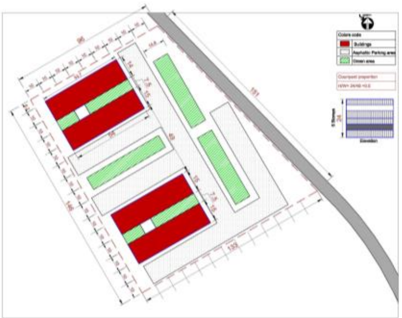
Block area (buildable) /m^2	16771.50
Asphaltic area / m^2	3400
Grass area / m^2	1200
Max floor area ratio (FAR)	1.14
Max gross floor area (GFA) / m^2	19200
Footprint /GF/ m^2	6400
Site coverage (SC)	38.16%
Number of storeys	3
Number of buildings	**8**

Urban configuration A: Trial P2–2



Block area (buildable) /m^2	16771.50
Asphaltic area / m^2	5819
Grass area / m^2	1756
Max floor area ratio (FAR)	1.14
Max gross floor area (GFA) / m^2	19200
Footprint /GF/ m^2	4800
Site coverage (SC)	28.6%
Number of storeys	4
Number of buildings	**6**

Urban configuration A: Trial P2–3



Block area (buildable) /m^2	16771.50
Asphaltic area / m^2	5719
Grass area / m^2	2267
Max floor area ratio (FAR)	1.14
Max gross floor area (GFA) / m^2	19200
Footprint /GF/ m^2	3200
Site coverage (SC)	19%
Number of storeys	6
Number of buildings	**4**

Figure 4.19: The layout and urban texture variables of proposed urban configurations under investigation (P2)

4.8 Model Application for Simulation Runs Investigating Impact of Orientation—P3

Thermal behaviour is not only influenced by a building's spatial layout "form", but is also significantly affected by orientation. Building size and orientation of the façade are the factors directly affected by the sun and which connect outdoor spaces to indoor spaces. Three trials were performed around the third parameter (P3), aiming to investigate the impact of the orientation on outdoor thermal comfort. In this research, two axes recommended by other studies are tested; Axis 1 and 2 representing south west–north east, and north–south, respectively. ENVI-met enables changing the orientation in the model, as shown in Figure 4. It is important to note that in this test the values of the other two parameters are fixed, meaning the proposed urban configuration is kept as A compared to the optimal urban configuration for first parameter (P1), and the urban form height is the favourable building height for second parameter (P2) compared to the existing base case.

Table 4.9 shows the sample model from all the tests investigating Parameter 3, which aims to measure the impact of the urban form orientation and outdoor thermal comfort through three different configurations.

Table 4.9: Bundle of simulation runs and their corresponding variables, investigating parameter 3 (P3)

Trial	P3 -Variable parameter – orientation	P1–Fixed parameter – building form	P2–H/W ratio
P3–1	Axis 1: north west–south east	Four storeys (A) base case	16:8=2
P3–1	Axis 1: north west–south east	Most favourable urban configuration of (P1)	Most favourable building height of (P2)
P3–2	Axis 2: north–south	Most favourable urban configuration of (P1)	Most favourable building height of (P2)

For the total 15 simulation trails investigating the three parameters as listed in Table 4.3,4.8 and 4.9, results for air temperature and wind speed would be acquired, analysed and evaluated based average hourly averages. For each parameter, air temperature and wind speed values obtained from different tests would be displayed in the same graph for further comparison and analysis. Next chapter would focus on the analysis of data and discussion of the results.

5 RESULTS AND FINDINGS

5.1 Introduction

After completion of simulation, outcomes were extracted using ENVI-met's LEONARDO 2014 beta software, and findings were categorised to analyse the results. In this chapter, the findings from Phase 1 are examined and discussed in more detail. Based on the results of Phase 1, one urban configuration from the six investigated models will be selected as the most favourable design proposal for further investigation of the impact of different building height (P2) and orientation (P3) on outdoor thermal comfort. This most favourable design proposal is selected based on outdoor thermal behaviour, which will be discussed later in this chapter through comparison of outcomes from six trials of simulation runs. Phase 2 concentrates on investigation of the impact of building height throughout six trials of simulation runs, followed by Phase 3 which focuses on the application of two different orientations to analyse its impact on outdoor thermal conditions. It is important to note that morphological analysis in this research involves three factors: building form, courtyard proportion, and building height and orientation. In order to concentrate on urban areas, surface temperature related to the buildings is ignored.

Figure 5.1 and 5.2 show visualisation samples of snapshots of simulated timeframes.

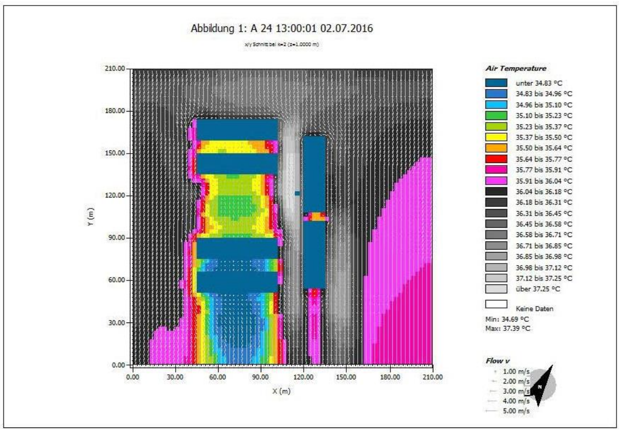


Figure 5.1: Visualisation of average air temperature for the base case (A)

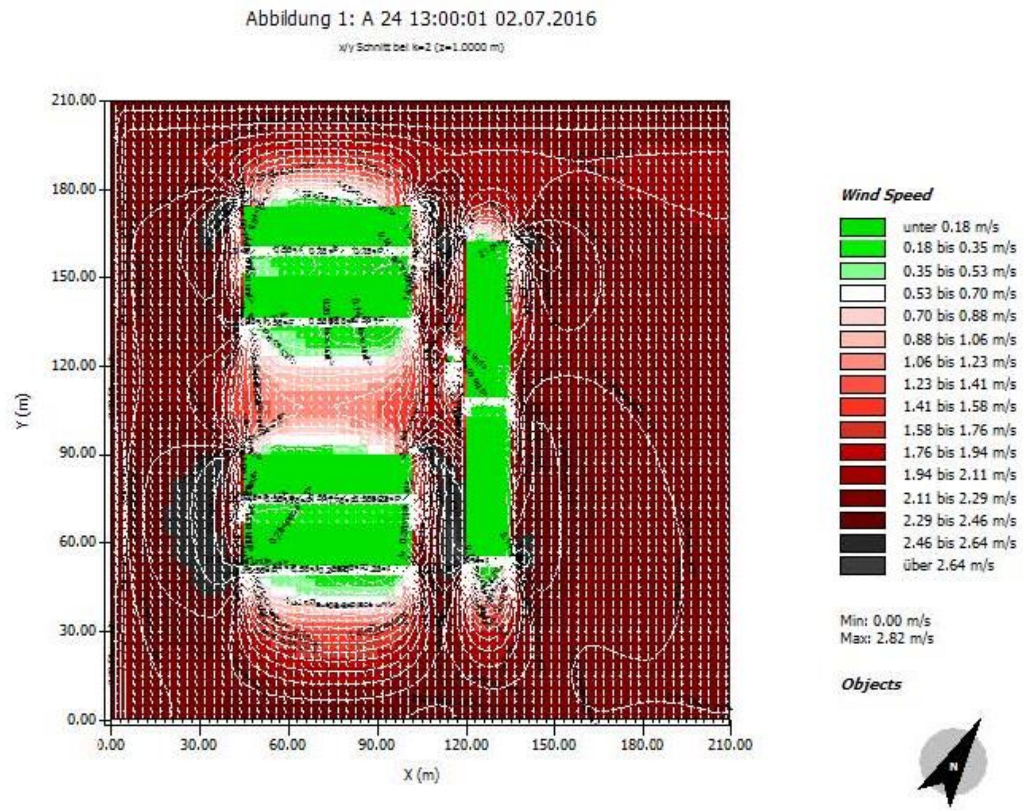


Figure 5.2: Visualisation of wind speed for the base case (A)

Temperature and wind speed variations are visualised in colour ranges in Celsius (◦C) and metres per second (m/s) respectively. For wind speed visualisation, vectors represent wind direction and contour isolines represent wind speed values, and colour ranges will enable the extracted visualisations to be more legible and easy to understand. The position of the view plane was 2 m above ground surface. Numerical data was extracted using Excel, with each simulated hour comprising more than 4900 coordinates (see Appendix A). This numerous data was simplified, reorganised, and the averages extracted for each timeframe, as shown in Figure 5.3. It is important to note that some errors occurred represented by unpredicted values or zeros; coordinates which had zero values (or approximately zero) were eliminated, and errors corrected by repeating simulation performance.

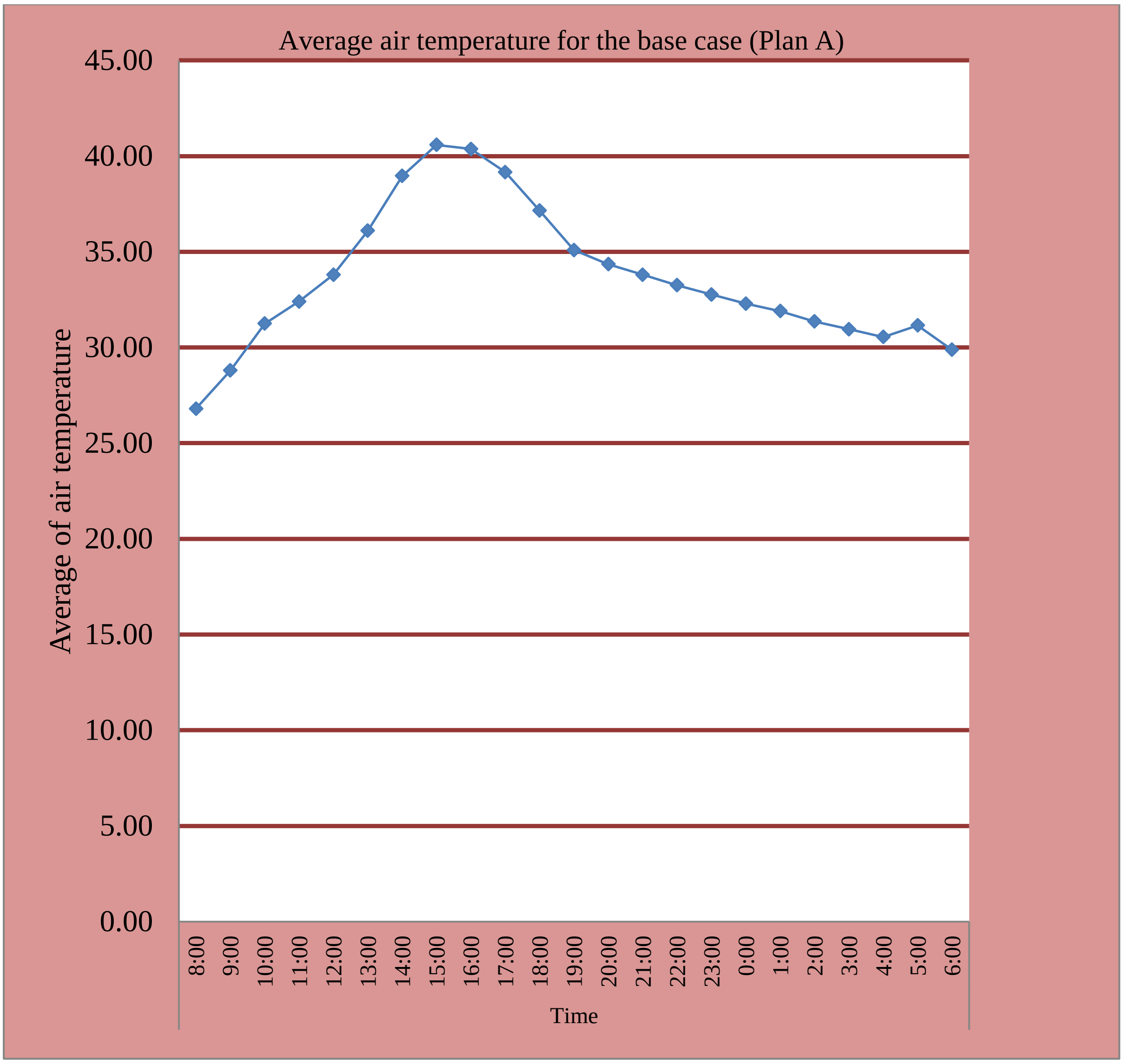


Figure 5.3: The average air temperature for the base case (Plan A) on July 2, 2016.

It should be noted all simulation trials are compared based on average hourly surface temperatures and wind speed. Due to the focus on the area of research, overheating of urban area related to buildings and envelope properties is not considered. Therefore, the results exclusively present the conditions of remaining space as a result of subtraction of building surfaces from the whole urban block.

5.2 Phase 1: Results and Discussion

Phase 1 comprises six different configurations of urban design to investigate outdoor thermal comfort indicators focusing on the impact of building form and courtyard proportion. Air temperature and wind speed will be tested and results will be compared to justify selection of the most favourable urban configuration to then be tested in Phase 2 and Phase 3. This optimal urban configuration will be recommended in Phase 3 of the research, which is discussed in later sections. Six different simulation runs were conducted to investigate the impact of this parameter.

5.2.1 Phase 1 : Results of Investigation into the Impact of Building Forms and Courtyard Proportion—P1

Six different urban configurations and their corresponding variables were assessed throughout six simulation runs as developed in Table 5.1. Each trial of these runs had different building form and courtyard proportions, as shown in Table 1. The H/W ratio particularly in this section of the research is the ratio between the height average of the building form (H) and the smallest width of the open space/courtyard area (W). Various design proposals with different H/W ratios—2, 1.5, and 0.6—were simulated for the six urban configurations. Further, courtyard proportion focuses on length to width ratio (L/W), and three different courtyard proportions—7:1. 2:1, and 1:1—were investigated for the six urban configurations.

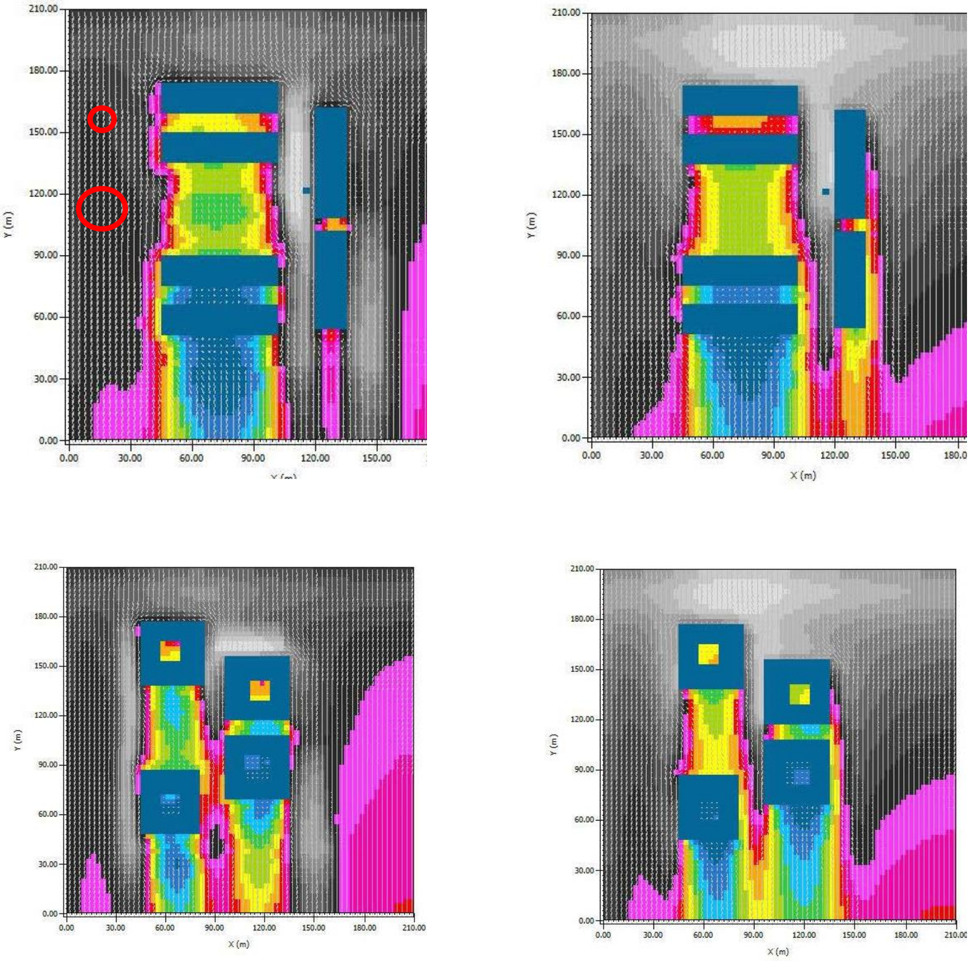
Table 5.1: Bundle of simulation runs and their corresponding variables investigating P1

Simulation runs	Configuration code	Building form	Courtyard proportion (L/W)	H/W ratio
P1–1	A 	Linear	54:8 = 7:1	16:8 = 2.0
P1–2	B 	Fortress with square courtyard	12:12 = 1:1	16:12 = 1.5
P1–3	C 	Fortress with rectangular courtyard	24:12 = 2:1	16:12 = 1.5
P1–4	D 	U-shape	32:28 = 1:1	16:28 = 0.60
P1–5	E 	L-shape	28:28 = 1:1	16:28 = 0.60
P1–6	F 	Developed linear	24:12 = 2:1	16:12=1.5

Figures 5.4 and 5.5 show visualisation snapshots for the air temperature for the six different configurations, including the base case. Meanwhile, Figure 5 shows a comparison of the average hourly air temperature on July 2, 2016 for the configurations. It can be seen that different configurations depict diverse behaviours and, further, the air temperature for all five proposed urban configurations was lower than the base case (the existing urban configuration). In addition, the critical time zone for solar radiation from 12:00 to 19:00 was the turning point for thermal behaviour, because solar radiation increased in these hours of the day.

At first glance to Figure 5.4 and 5.5, visualisation snapshots for air temperature reveal that the fortress urban configuration B and C have the same temperature variation trends throughout the day.

July data analysis shown in Table 5.2 confirms that the closed fortress urban configuration which registered the highest values of 32.59 and 32.47 (◦C) were the most unfavourable; likewise the U-shape and L-shape forms behave similarly, with registered high values of 32.30 and 32.18 (◦C), respectively. The difference in temperatures recorded for the proposed urban configurations B, C, D, and E was minor, as illustrated in simulation runs P1–2 to P1–5. On the other hand, the trial P1–6 reported that urban configuration F had the lowest air temperature, 2 ◦C lower than the base case (A).



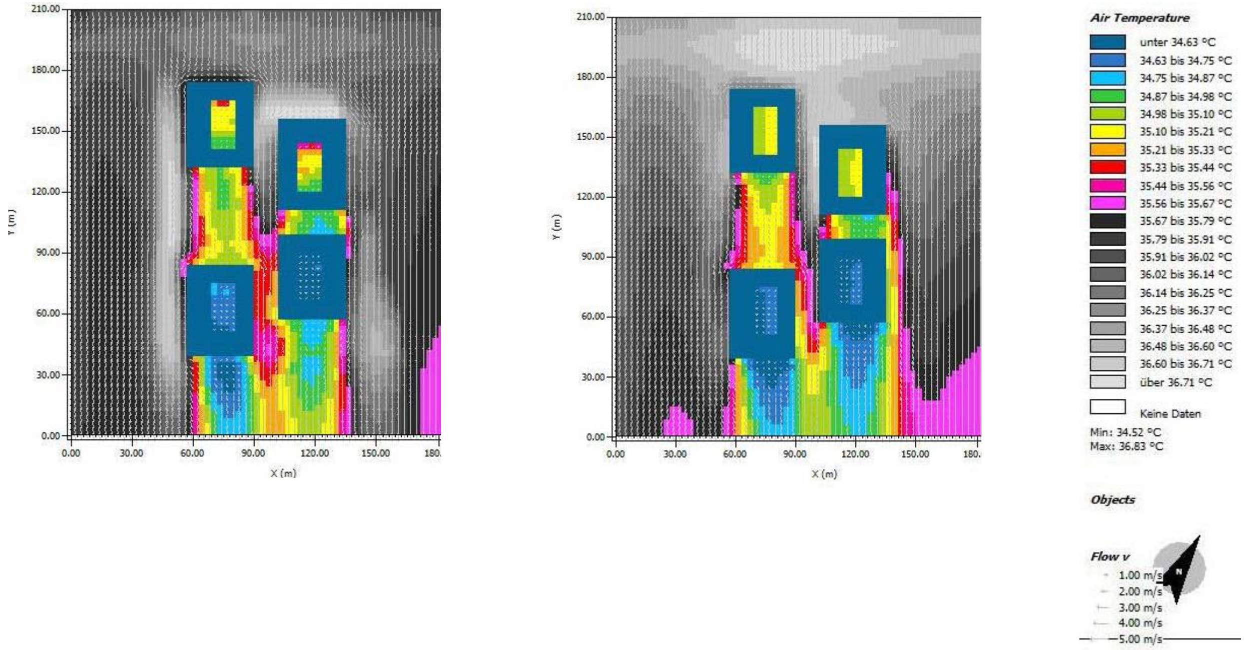
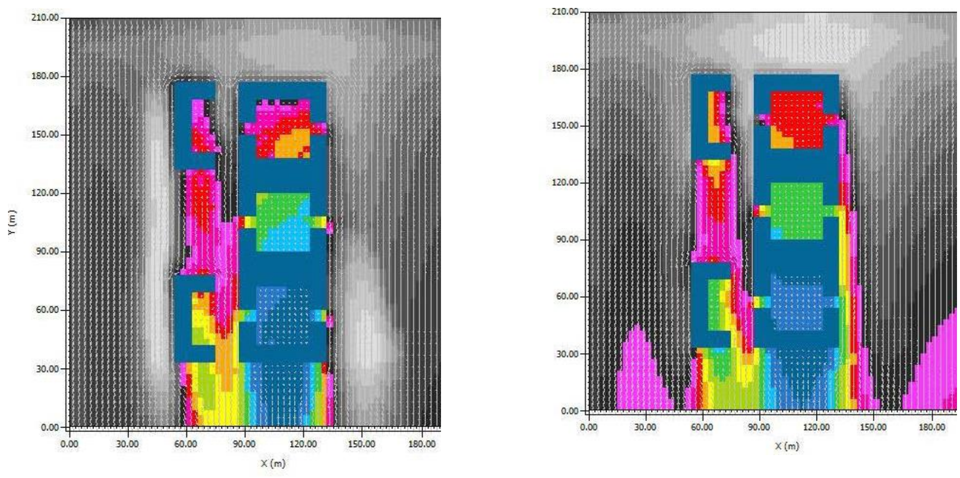


Figure 5.4: Air temperature for proposed urban configurations A (top), B (centre), and C at 13:00 h (left) and 16:00 h on July 2, 2016.



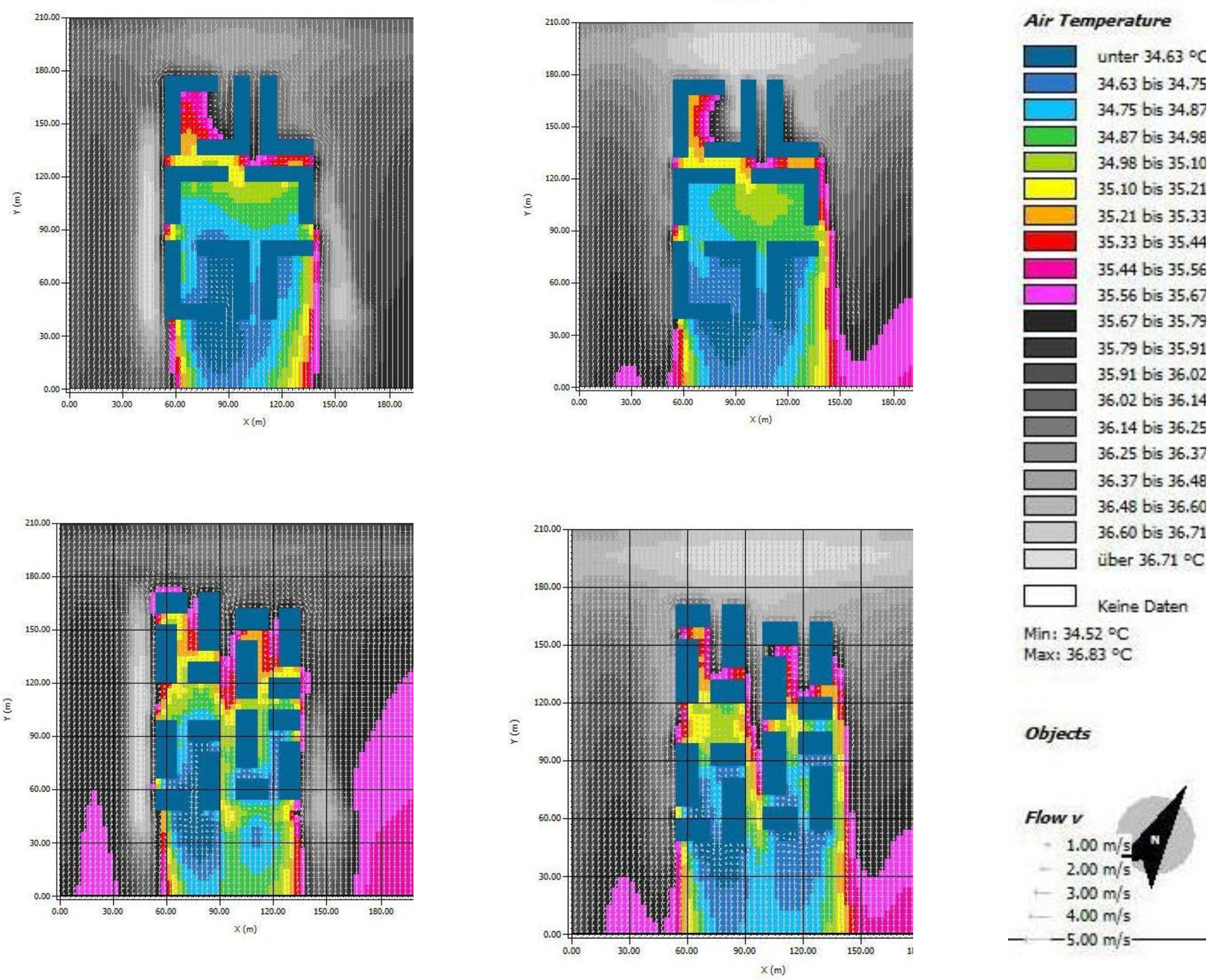
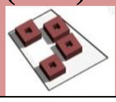
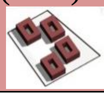


Figure 5.5: Air temperature for proposed urban configurations D (top), E (centre), and F at 13:00 h (left) and 16:00 h on July 2, 2016.

Table 5.2: Summary of numerical data extracted in Phase 1, average of air temperature for proposed urban configurations A to F on July 2, 2016.

Time	**Average of air temperature**					
	(P11) A 	(P1-2) B 	(P1-3) C 	(P1-4) D 	(P1-5) E 	(P1-6) F 
8:00	26.80	26.17	26.55	26.23	26.23	26.22
9:00	28.80	28.11	28.65	28.13	28.13	28.02
10:00	31.25	30.58	30.67	30.61	30.55	30.49
11:00	32.40	31.50	31.63	31.52	31.54	31.46
12:00	33.80	32.86	32.88	32.71	32.71	31.95
13:00	36.10	34.98	34.95	34.66	34.69	33.88
14:00	38.96	37.62	37.55	37.16	37.21	36.32
15:00	40.59	39.27	39.19	38.83	38.88	37.96
16:00	40.37	39.17	39.05	38.78	38.77	37.88
17:00	39.16	38.06	37.88	37.73	37.62	36.50
18:00	37.15	36.12	35.88	35.84	35.65	34.95
19:00	35.09	34.19	33.91	33.69	33.69	33.09
20:00	34.35	33.46	33.16	33.20	32.94	32.37
21:00	33.80	32.88	32.59	32.62	32.37	31.81
22:00	33.25	32.35	32.07	32.09	31.85	30.92
23:00	32.77	31.85	31.58	31.58	31.35	30.45
0:00	32.29	31.35	31.10	31.07	30.86	30.20
1:00	31.90	31.10	30.63	30.58	30.35	29.57
2:00	31.36	30.40	30.18	30.11	29.84	29.30
3:00	30.95	29.97	29.76	29.66	29.35	28.63
4:00	30.55	29.55	29.36	29.24	28.90	28.63
5:00	31.15	29.16	28.98	28.48	28.50	27.72
6:00	29.88	28.81	28.64	28.48	28.17	27.63
Average	**33.60**	**32.59**	**32.47**	**32.30**	**32.18**	**31.56**

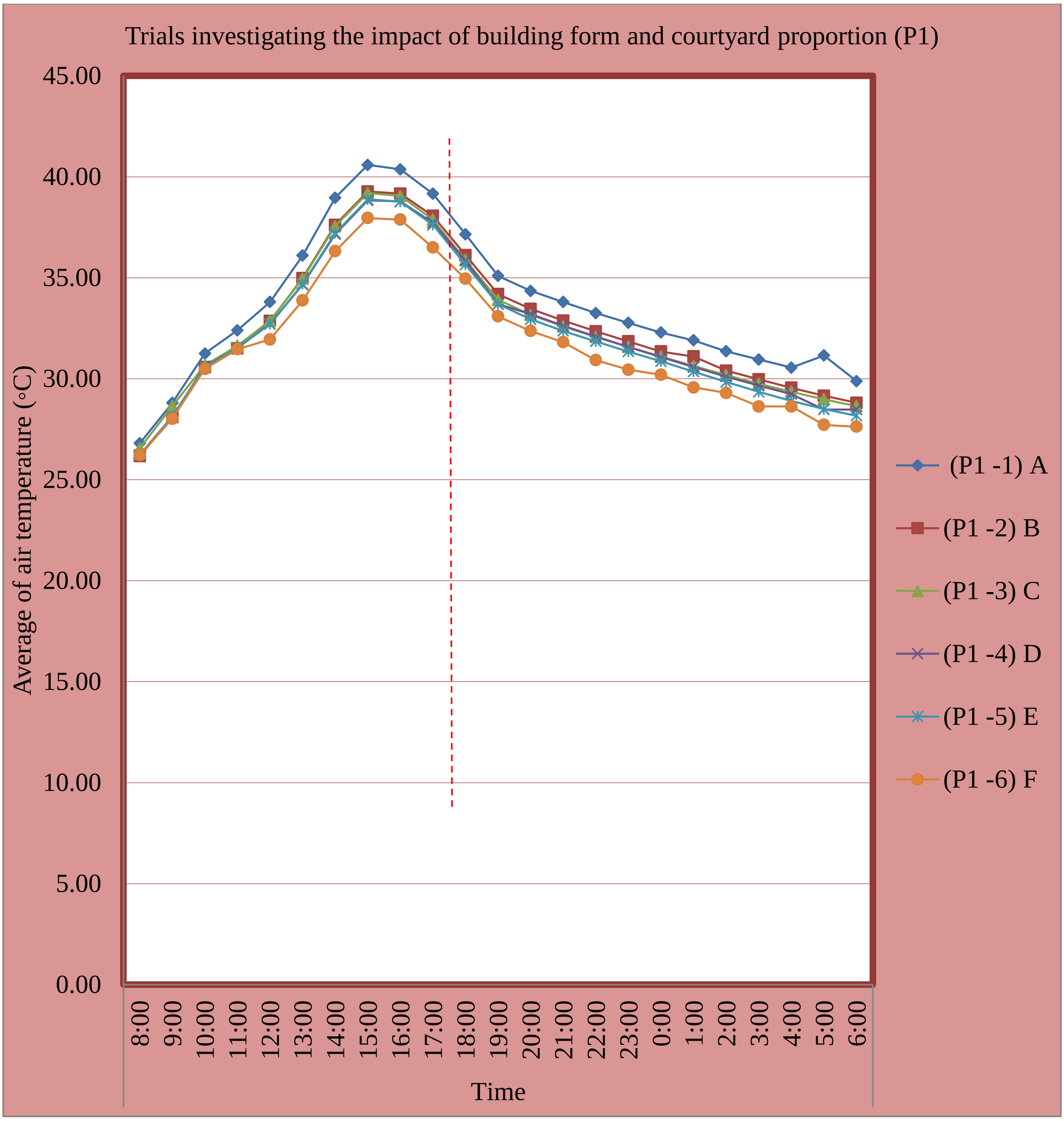


Figure 5.6: Average hourly air temperatures for six trials investigating the impact of building form and courtyard proportion **(P1)**

The different air temperature results in varying thermal environments mean urban forms and courtyard proportions influence the duration of direct sun and air temperature, and accordingly outdoor thermal comfort. In terms of air temperature, the base case (existing urban configuration) had the most uncomfortable external areas compared to the developed leaner form (F), which provided the most comfortable microclimate in this military camp in July compared to the other studied urban forms. Among all six urban configurations, the P1–6 trial, which is the developed linear building form with a courtyard proportion of 2:1 and H/W ratio of 1.5, had the lowest air temperature with average of 31.56 ◦C, particularly from 12:00 h to 18:00 h, revealing the duration of direct sun, an exposure influenced by building form and courtyard proportion which play the most important role in outdoor thermal comfort. The existing base case was the most unfavourable form, reporting an average temperature of 33.60 ◦C.

Considering the hours highlighted in red in Table 5.2 and Figures 5.6 show the air temperature between 13:00 h and 16:00 h for the six urban configurations. It can be seen in Figure 5.6 that all forms behaved similarly before 12:00 h, and the difference in air temperature was negligible. Extracted simulation outcomes and numerical data (in Table 5.2) for the fortress with a square courtyard (B), fortress with a rectangular courtyard (C), U-shape (D), and L-shape (E) reported air temperature averages of 32.59, 32.47, 32.30, and 32.18 ◦C, respectively. While courtyard proportions and H/W ratios were variables between these models, their impact on thermal comfort was minor. These findings of average air temperature do not appear to be influenced by wind conditions around the different configurations: The wind graph represented in Figure 5 registered similar trends across the six configurations. Taking a detailed view of trials P1–3 and P1–6 with the same L/W ratio of 2:1, it can be observed that air temperature results are consistent with the L/W courtyard proportion relative to different urban configurations, and thus the air temperature is higher by 1.0 ◦C for the fortress form than for the developed leaner form, regardless of the common L/W ratio.

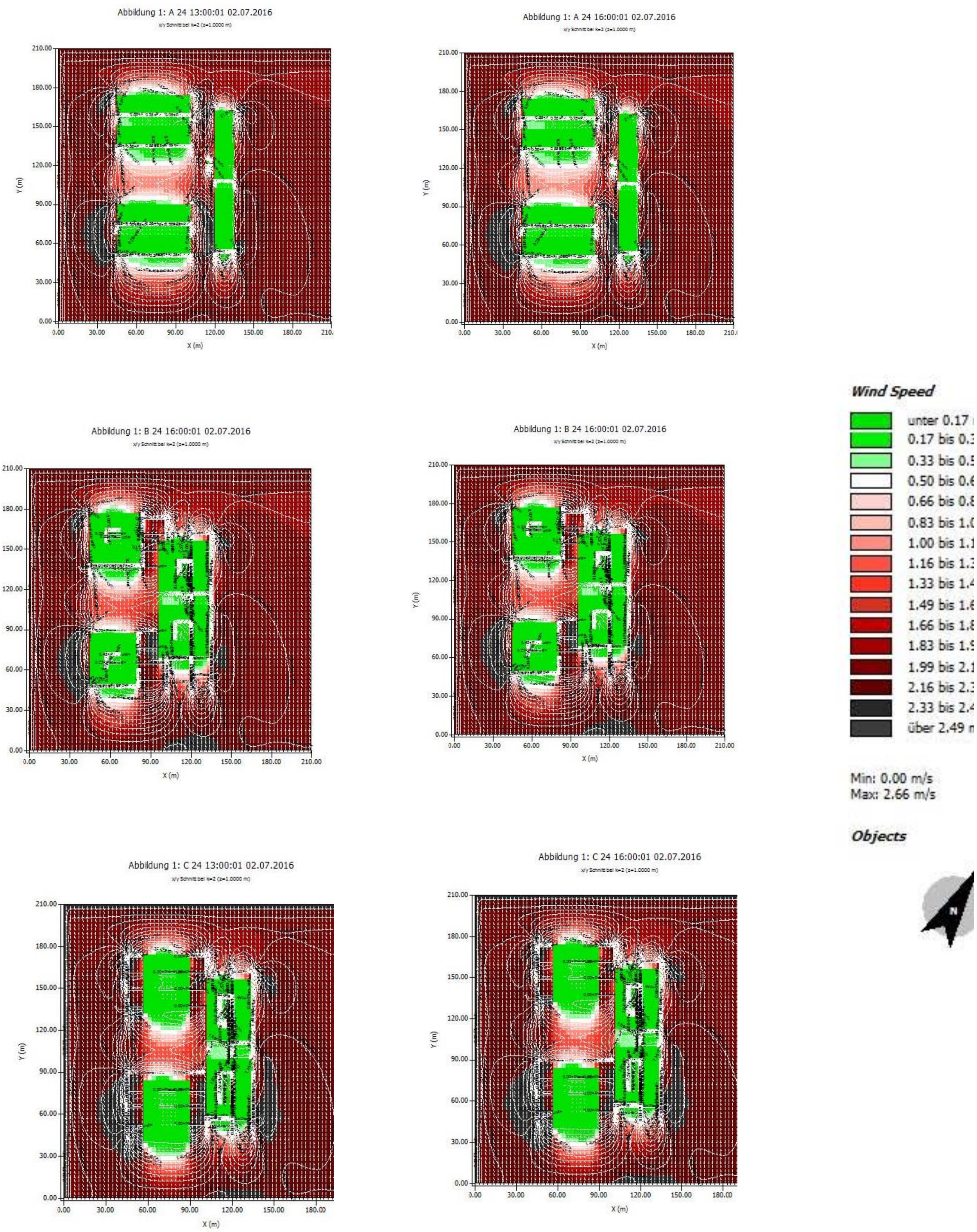


Figure 5.7: Wind speed for proposed urban configurations A (top), B (centre) and C at 13:00 h (left) and 16:00 h on July 2, 2016.

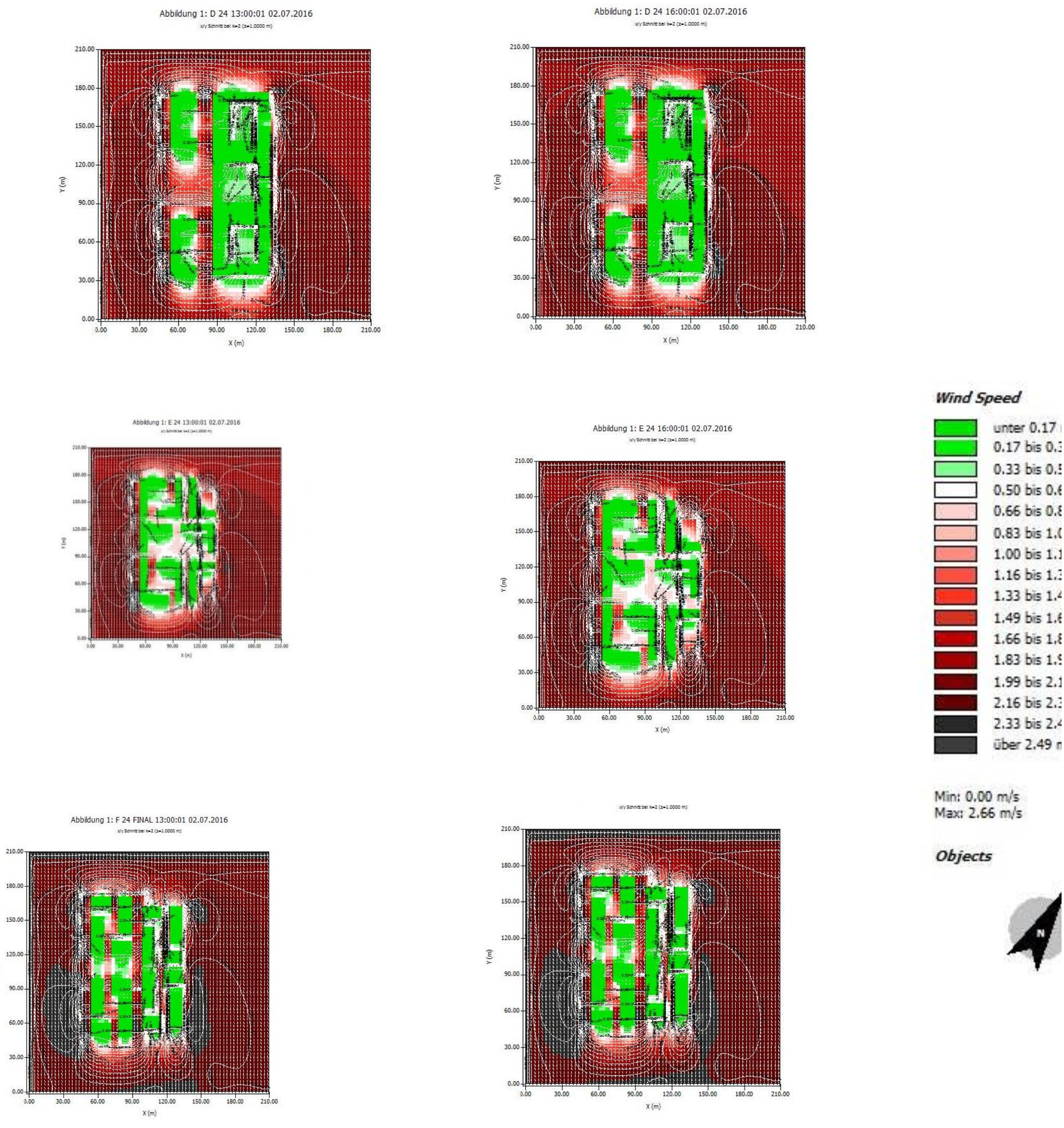
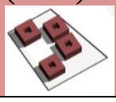


Figure 5.8: Wind speed for proposed urban configurations D (top), E (centre) and F at 13:00 h (left) and 16:00 h on July 2, 2016.

Table 5.3: Summary of numerical data extracted in Phase 1, average of wind speed for proposed urban configurations A to F.

Time	Average of wind speed					
	(P1-1) A 	(P1-2) B 	(P1-3) C 	(P1-4) D 	(P1-5) E 	(P1-6) F 
8:00	1.65	1.76	1.71	1.81	1.63	1.88
9:00	1.60	1.72	1.71	1.79	1.63	1.85
10:00	1.60	1.72	1.71	1.78	1.63	1.83
11:00	1.66	1.78	1.71	1.84	1.63	1.89
12:00	1.66	1.79	1.71	1.85	1.63	1.91
13:00	1.65	1.77	1.71	1.84	1.63	1.90
14:00	1.63	1.75	1.71	1.82	1.59	1.88
15:00	1.61	1.80	1.71	1.80	1.59	1.86
16:00	1.60	1.80	1.71	1.79	1.58	1.85
17:00	1.58	1.80	1.72	1.78	1.57	1.85
18:00	1.58	1.80	1.72	1.77	1.56	1.83
19:00	1.58	1.80	1.72	1.77	1.56	1.83
20:00	1.58	1.80	1.72	1.77	1.56	1.83
21:00	1.58	1.80	1.73	1.77	1.56	1.83
22:00	1.58	1.80	1.73	1.77	1.56	1.83
23:00	1.58	1.80	1.73	1.77	1.55	1.82
0:00	1.56	1.80	1.73	1.75	1.54	1.80
1:00	1.54	1.80	1.73	1.73	1.52	1.79
2:00	1.53	1.80	1.73	1.72	1.50	1.77
3:00	1.50	1.80	1.73	1.70	1.47	1.75
4:00	1.48	1.80	1.73	1.68	1.44	1.72
5:00	1.46	1.80	1.73	1.65	1.42	1.70
6:00	1.44	1.80	1.73	1.63	1.40	1.68
Average	1.58	1.79	1.72	1.76	1.55	1.82

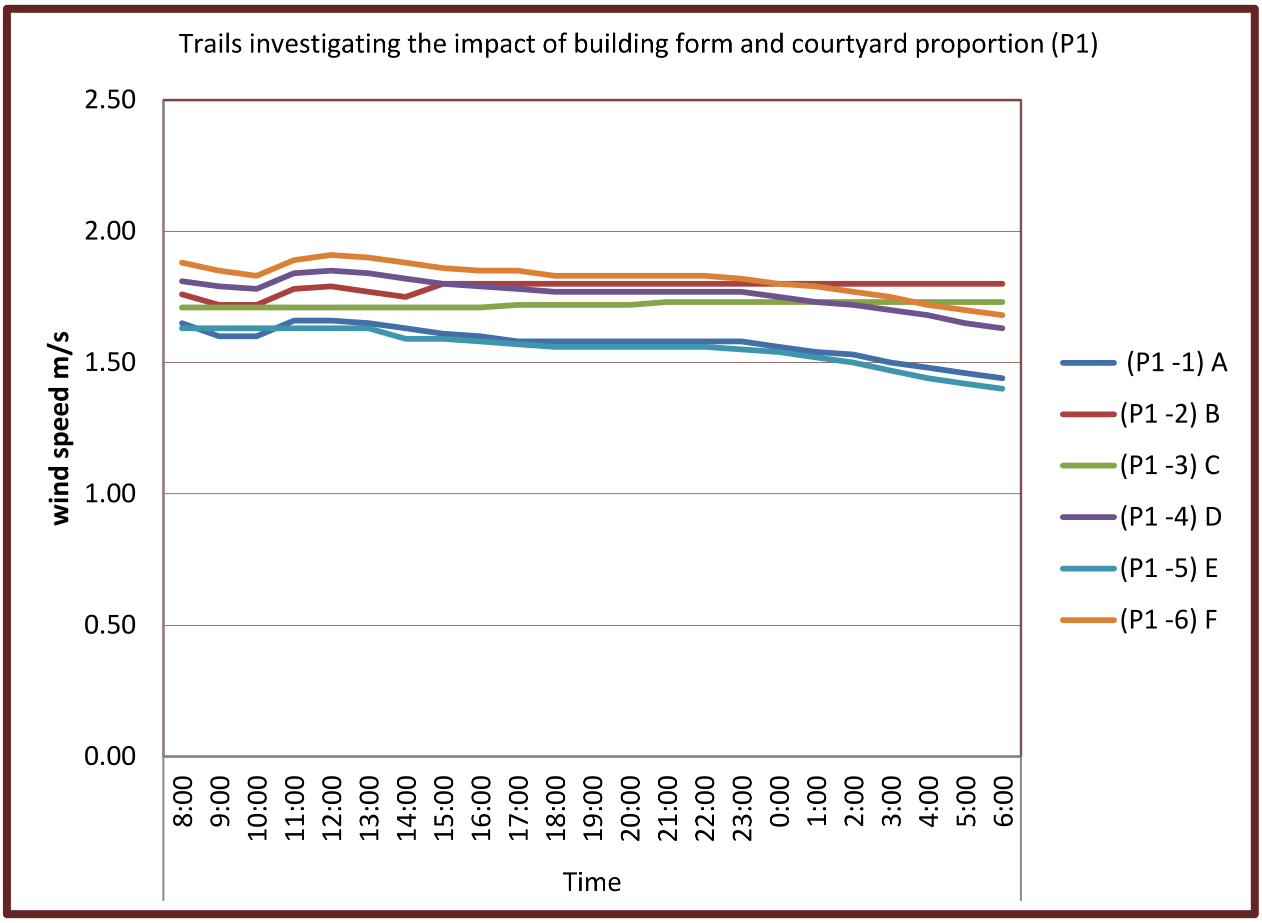


Figure 5.9: Hourly average wind speed for six urban configurations investigating the impact of building form and courtyard proportion (P1) – Initial wind speed 3.6 m/s

The extracted numerical data for average wind speed for each design proposal can be seen in Table 5.3, which shows that the proposed urban configurations of B, C, and D list near-identical average wind speeds of 1.79, 1.72, and 1.76 m/s respectively, while the existing base case A and configuration E have the lowest average wind speed of 1.58 and 1.55 m/s respectively. The highest average wind speed of 1.82 m/s of the trials was for configuration P1–6. This also shows how much temperature reduction was made by altering the building form from a closed shape (fortress) to the developed linear form, which allows for air movement. Figure 5.9 demonstrates various wind conditions for each proposed urban layout and the relationship between wind speed and air temperature. Overall, the table suggests good wind conditions reduce air temperature, especially when comparing base case in column A with the developed linear form in column F. It can be confirmed that wind speed increased from 1.58 m/s to 1.82 m/s, which means an increment of 0.24 m/s which could reduce outdoor temperature by approximately 2 ◦C. However, upon review of wind conditions for the proposed designs B, C, and D as per snapshot enlargement in Figure 5.10, it can be seen that different urban configurations of fortress and U-shape have no influence on the average wind speed and air movement around these buildings, which indicate only a small variation in air temperature, which is approximately 32.5 ◦C. Figure 5.9 shows a straight line of hourly average of wind speed, particularly for B and C. This is mainly because the closed building shape of a fortress resists wind penetration and air movement. It can also be noticed that the air temperature graph shown in Figure 5.6 registered similar trends across these two configurations.

Table 5.4: Comparison of numerical data extracted in Phase 1, average of wind speed and air temperature for proposed urban configurations A to F.

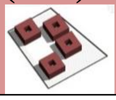
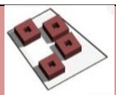
Time	Average of wind speed					
	(P1-1) A 	(P1-2) B 	(P1-3) C 	(P1-4) D 	(P1-5) E 	(P1-6) F 
8:00	1.65	1.76	1.71	1.81	1.63	1.88
9:00	1.60	1.72	1.71	1.79	1.63	1.85
10:00	1.60	1.72	1.71	1.78	1.63	1.83
11:00	1.66	1.78	1.71	1.84	1.63	1.89
12:00	1.66	1.79	1.71	1.85	1.63	1.91
13:00	1.65	1.77	1.71	1.84	1.63	1.90
14:00	1.63	1.75	1.71	1.82	1.59	1.88
15:00	1.61	1.80	1.71	1.80	1.59	1.86
16:00	1.60	1.80	1.71	1.79	1.58	1.85
17:00	1.58	1.80	1.72	1.78	1.57	1.85
18:00	1.58	1.80	1.72	1.77	1.56	1.83
19:00	1.58	1.80	1.72	1.77	1.56	1.83
20:00	1.58	1.80	1.72	1.77	1.56	1.83
21:00	1.58	1.80	1.73	1.77	1.56	1.83
22:00	1.58	1.80	1.73	1.77	1.56	1.83
23:00	1.58	1.80	1.73	1.77	1.55	1.82
0:00	1.56	1.80	1.73	1.75	1.54	1.80
1:00	1.54	1.80	1.73	1.73	1.52	1.79
2:00	1.53	1.80	1.73	1.72	1.50	1.77
3:00	1.50	1.80	1.73	1.70	1.47	1.75
4:00	1.48	1.80	1.73	1.68	1.44	1.72
5:00	1.46	1.80	1.73	1.65	1.42	1.70
6:00	1.44	1.80	1.73	1.63	1.40	1.68
Average	1.58	1.79	1.72	1.76	1.55	1.82

Figure 5.10: Visualisation of similar wind conditions for proposed urban configurations B (left), C (middle), and D (right) at 16:00 h on July 2, 2016.

5.2.2 Selection of Optimal Building Form and Courtyard Proportion

From the outcomes presented in previous section which were summarised and tabulated in Table 5.5 below to show the summary which includes average temperature and wind speed for the five proposed urban configurations and existing design of base case, it can be seen that the thermal behaviour for urban configuration F is the most favourable urban design with registered values of 31.59 C and 1.82 for air temperature and wind speed respectively.

Table 5.5: Comparison of numerical data extracted in Phase 1, average of wind speed and air temperature for proposed urban configurations A to F.

Outdoor thermal indicator	 **A**	 **B**	 **C**	 **D**	 **E**	 **F**
Average wind speed	1.58	1.79	1.72	1.76	1.55	1.82
Average air temperature	33.60	32.59	32.47	32.30	32.18	31.59

Considering the wind conditions in these urban configurations, Figure 5.7 and 5.8 displays the wind speed at the hottest time of the reference year for these six configurations.

A series of five hypothetical urban configurations were tested and compared against the base case A, where each urban configuration goes through a series of analyses of outdoor thermal comfort indicators such as air temperature and wind speed. The results allows a comparison between different urban configurations to narrow down design alternative proposals which have more comfortable outdoor thermal comfort and better thermal behaviour. The air temperature analysis shown in the graphs in Figure 5.6 revealed that the temperature trends are approximately similar across the four configurations B, C, D, and E. Particularly, average temperature readings showed almost negligible differences, in the order of 0.1 ◦C. Looking at no wind trials in the graphs in Figure 5.3 reveal that values for all three configurations B, C, and D have the same trend. Unlike for air temperature, configuration E has a different wind curve to configurations B, C, and D.

Comparing wind speed and air temperature in these six proposed urban configurations, the developed linear urban form F has the highest wind speed and lowest air temperature among all six urban configurations. Conversely, the existing base case has the lowest wind speed and highest air temperature. In Phase 1, the extracted numerical data was summarised in six trials, one for each design proposal, investigating the impact of building form and courtyard proportion on outdoor thermal comfort. In this section, the results of air temperature and wind speed are discussed independently to identify F as the most favourable urban configuration, to be tested in Phase 2.

The thermal behaviour of different urban forms is also confirmed by work of Taleghani et al. (2015), who analysed five different forms for the hottest day in the temperate climate of the Netherlands, concluding that models with different compactness provided different thermal environments. However, their results disagreed with the current research in terms of the optimal urban form, where simulation results of this research demonstrated that the developed linear form F behaved better than fortress forms B and C. This differed from research conducted by Taleghani et al. (2015) who validated their results through field measurement and reported that the fortress style provided the most comfortable microclimate in the Netherlands in June compared to other studied urban forms (Ignatius, Wong & Jusuf 2015).

The comparison undertaken by Rashdi and Embi (2016) for the courtyard shape and other essential shapes—such as rectangles and squares—revealed that the courtyard shape has a higher cooling load due to the fact most surfaces are prone to sun exposure from all sides. On the other hand, the deeper, rectangular and shallower courtyards are better in terms of thermal behaviour in hot arid climates and, moreover, provide better shade which improves outdoor thermal comfort.

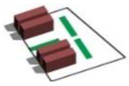
5.3 Phase 2: Results and Discussion

Phase 2 consists of six different urban configurations, as listed in Table 5.6, concentrating on the influence of building height parameter. Three different heights will be investigated: three storeys (12 m), four storeys (16 m), and six storeys (24 m) for the existing base case (A) and the optimal urban configuration (F), recommended from Phase 1 of this chapter. The base case is a four-storey building, and two other hypothetical building heights will be considered for better comparison with the optimal urban configurations.

5.3.1 Results Investigating the Impact of Building Height—P2

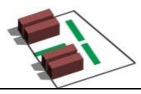
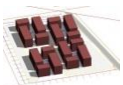
In this section, first the results of simulation runs focusing on the impact of different heights on air temperature are discussed independently to identify the best building height offering better thermal comfort. Second, the outcomes of simulation runs investigating the influence on wind speed will be analysed and compared to identify the optimal building height. This optimal urban configuration will be examined in the Phase 3 of the research, which is discussed in later sections.

Table 5.6: Bundle of simulation runs and their corresponding variables, investigating parameter 2 (P2)

Simulation runs	Configuration code	Building form	H/W ratio
P2–1		(A) Three storeys	12:7.5 = 1.5
P2–2		(A) Four storeys	16:12 = 1.5
P2–3		(A) Six storeys	24:48 = 0.5
P2–4		(F) Three storeys	12:12 = 1
P2–5		(F) Four storeys	16:8 = 2.0
P2–6		(F) Six storeys	24:18 = 1.5

The average of hourly surface temperatures on July 2, 2016 is illustrated in Figure 5.11, and numerical data extracted in Table 5.7 for all simulation runs mentioned in Table 5.6. At first glance, all five proposed urban configurations have an average air temperature lower than the existing base case. It seems that the three different building heights of urban configuration F have minor differences in average air temperature. Similarly, the impact of different heights is negligible in urban configuration A, including the existing case.

Table 5.7: Summary of numerical data extracted in Phase 2, average air temperature for proposed urban configurations (A) and (F)

Time	Average of air temperature: P2–1 to P2–6					
	(P2–1) Three storeys (A)	(P2–2) Four storeys (A)	(P2–3) Six storeys (A)	(P2–4) Three storeys (F)	(P2–5) Four storeys (F)	(P2–6) Six storeys (F)
						
8:00	25.83	26.80	26.56	25.95	26.22	27.15
9:00	27.52	28.80	28.13	27.30	28.02	28.86
10:00	28.83	31.25	29.88	28.77	30.49	31.00
11:00	31.32	32.40	31.37	30.53	31.46	31.77
12:00	32.38	33.80	32.17	31.36	31.95	32.49
13:00	34.21	36.10	33.43	32.35	33.88	33.90
14:00	36.70	38.96	35.24	33.92	36.32	35.76
15:00	38.54	40.59	37.10	35.63	37.96	37.31
16:00	38.63	40.37	38.00	36.64	37.88	37.63
17:00	37.58	39.16	37.75	36.70	36.50	36.78
18:00	35.67	37.15	36.68	35.94	34.95	35.24
19:00	33.66	35.09	35.03	34.62	33.09	33.33
20:00	32.90	34.35	33.15	33.06	32.37	32.06
21:00	32.34	33.80	32.24	32.30	31.81	31.45
22:00	31.84	33.25	31.69	31.77	30.92	30.94
23:00	31.35	32.77	31.23	31.30	30.45	30.44
0:00	30.89	32.29	30.80	30.83	30.20	29.93
1:00	30.44	31.90	30.39	30.35	29.57	29.44
2:00	30.02	31.36	29.99	29.89	29.30	28.98
3:00	29.62	30.95	29.60	29.47	28.63	28.56
4:00	29.25	30.55	29.25	29.08	28.63	28.16
5:00	28.90	31.15	29.90	29.05	27.72	27.86
6:00	28.58	29.88	29.34	28.58	27.63	27.40
Average	32.04	33.60	32.13	31.54	31.56	31.58

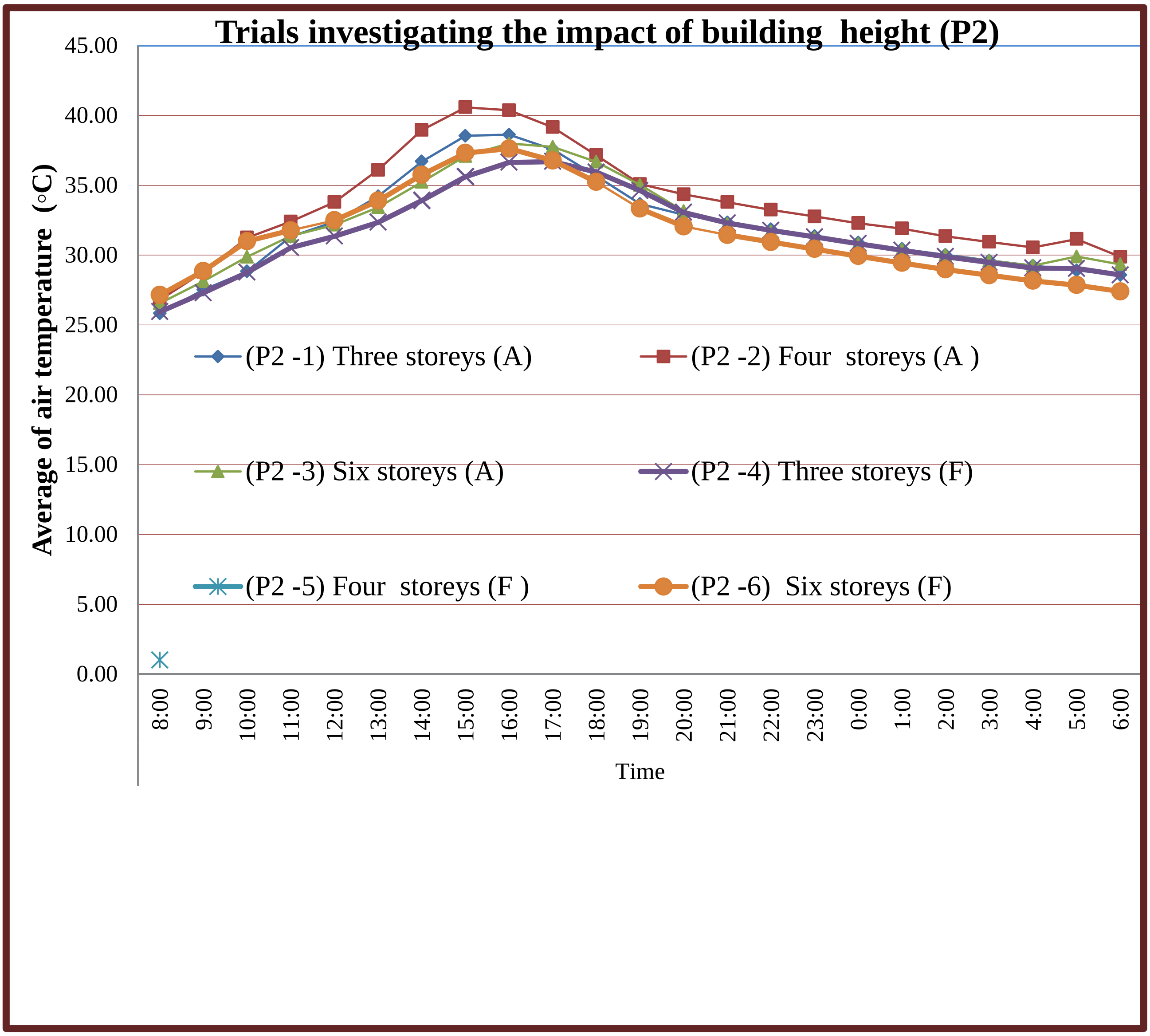


Figure 5.11: Average hourly air temperatures for six trials investigating the impact of building height on July 2, 2016.

However, the graph in Figure 5.11 reveals that different configurations depict diverse thermal behaviours, particularly from 12:00 to 16:00, and that occurs because this period is the peak time for the solar radiation. The average air temperature for urban configuration F was variable; the highest, six storey simulation trial showed lower average temperatures, especially during night-time, however the lowest building height had lower average air temperatures during the peak period of solar radiation. Table 5.7 shows that urban configuration F had an average approximately of 31.50 ◦C air temperature for the three different heights. Also, the table suggests that that the existing case A with four storeys resulted in the highest air temperatures during the day. It can be noticed from Figure 10 that the same urban configuration with different heights behaves differently during daytime and night-time; for example, the results of simulation trial P2-6 show the lowest average during night-time, while P2-4 and P2-5 results show the same higher averages. The graph also demonstrates that a lower height offered the better air temperature during daytime compared to night-time.

Table 5.8: Summary of numerical data extracted in Phase 2, of average wind speed for proposed urban configurations A and F with three different heights on July 2, 2016.

Time	Average of wind speed					
	P2–1 Three storeys (A)	**P2–2 Four storeys (A)**	**P2–3 Six storeys (A)**	**P2–4 Three storeys (F)**	**P2–5 Four storeys (F)**	**P2–6 Six storeys (F)**
8:00	1.69	1.65	1.84	1.55	1.88	1.69
9:00	1.65	1.60	1.80	1.52	1.85	1.65
10:00	1.62	1.60	1.77	1.49	1.83	1.64
11:00	1.64	1.66	1.78	1.49	1.89	1.67
12:00	1.66	1.66	1.80	1.50	1.91	1.69
13:00	1.66	1.65	1.80	1.51	1.90	1.69
14:00	1.65	1.63	1.79	1.51	1.88	1.67
15:00	1.63	1.61	1.78	1.50	1.86	1.65
16:00	1.61	1.60	1.76	1.48	1.85	1.64
17:00	1.61	1.58	1.75	1.47	1.85	1.62
18:00	1.60	1.58	1.73	1.46	1.83	1.61
19:00	1.58	1.58	1.72	1.45	1.83	1.59
20:00	1.58	1.58	1.71	1.43	1.83	1.58
21:00	1.57	1.58	1.70	1.41	1.83	1.57

22:00	1.57	1.58	1.70	1.41	1.83	1.57
23:00	1.56	1.58	1.69	1.40	1.82	1.55
0:00	1.54	1.56	1.69	1.38	1.80	1.53
1:00	1.53	1.54	1.67	1.36	1.79	1.50
2:00	1.51	1.53	1.66	1.34	1.77	1.48
3:00	1.50	1.50	1.64	1.32	1.75	1.46
4:00	1.48	1.48	1.62	1.30	1.72	1.44
5:00	1.46	1.46	1.60	1.28	1.70	1.42
6:00	1.44	1.44	1.58	1.27	1.68	1.40
Average	**1.58**	**1.58**	**1.72**	**1.43**	1.82	**1.58**

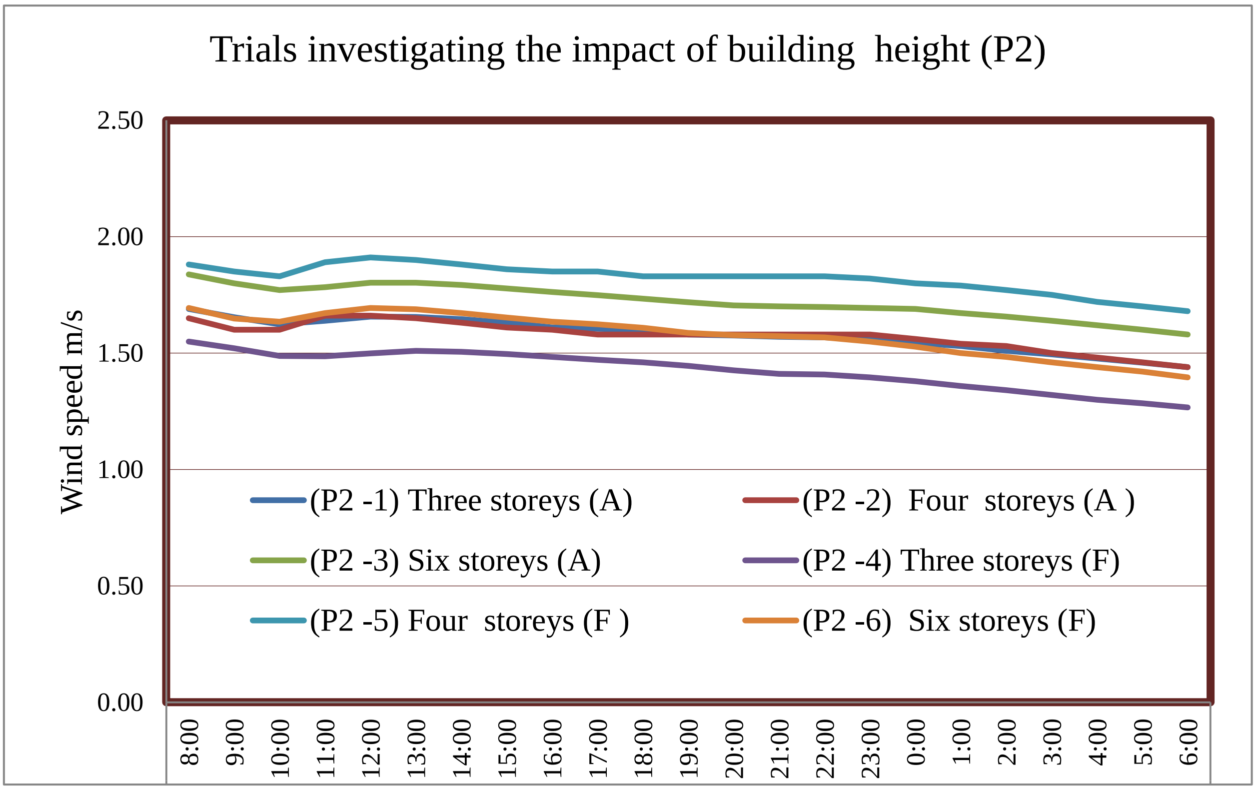


Figure 5.12: Hourly average wind speed for six urban configurations investigating the impact of building height (P2) – initial wind speed 3.6 m/s, on July 2, 2016.

Table 5.8 and Figures 5.12 show a comparison of the average hourly wind speed in July for three different heights of two urban configurations: the existing base case and the most favourable urban configuration design (F) as recommended from Phase 1. Like the previous parameter, different configurations having different heights depict individual behaviours, however three trials show identical wind speed averages and trends; P2-6, P2-2, and P2-1 have the same average of wind speed with registered value of 1.58 considering the initial wind speed 3.6 m/s as listed in Table 6. Unlike the air temperature average illustrated in Figure 8, the trial (P2–4) three-storey configuration (F) has the lowest wind speed of 1.43 m/s and air temperature was 31.59 ◦C.

P2–4 and P2–5 show the lowest and highest wind speed averages respectively, however these results did not influence air temperature for these urban configurations, which was 31.50 ◦C for both, despite different averages of wind speeds relative to other configurations. In some instances, wind speed was lower than in other configurations, and in other instances (such as P2–1, P2–2, and P2–6, it was intermediate. The highest average of wind speed was registered by urban configuration (F), the developed linear form at four-storeys height. Nevertheless, this did not contribute to a reduction in temperature relative to the other configurations. This was due to the effect the configuration had on the behaviour of the wind.

5.3.2 Selection of Optimal Building Height

In Phase 2, first the results of simulation runs focusing on the impact of different heights on air temperature are discussed, followed by the influence on wind speed. Secondly, a comparison between these outcomes is carried out in order to identify the most favourable building height. These outcomes show that the H/W ratio mostly affects air temperature during the morning and peak periods of 8:00 h to 16:00 h, when shading is crucial because sun penetration is higher than at night. For example, P2–4, P2–5, and P2–6, with H/W ratios of 1, 2, and 1.5 respectively, reported the same average air temperature. This differs from the graph in Figure 5.11 showing better air temperature trends during peak time for P2–4, and P2–6 with lower air temperature during night-time. However developed linear F with three story have the best thermal behaviour and will be considered as the most favourable urban configuration .

For each configuration, the greater the height to width ratio, the more compact the urban configuration, and therefore wind speed conditions were better; however different H/W ratios have little effect on air temperature, particularly in the developed linear urban configuration.

Table 5.9: Summary of numerical data extracted in Phase 2, average of wind speed and air temperature compared to H/W ratio, on July 2, 2016.

	(P2 -1) Three storeys (A)	(P2 -2) Four storeys (A)	(P2 -3) Six storeys (A)	(P2 -4) Three storeys (F)	(P2 -5) Four storeys (F)	(P2 -6) Six storeys (F)
H/W ratio	1.50	1.50	0.50	1	2	1.5
Average air temperature	32.04	33.60	32.13	31.59	31.56	31.58
Average wind speed	**1.58**	**1.58**	**1.72**	**1.43**	1.82	**1.58**

Outcomes summarized in Table 5.9 and 5.10 confirm that the lower the height, the lower air temperature. In this regard, from six-storey buildings to three-storey building, the number of buildings is increased to maintain the same buildable area, as mentioned in Chapter 4. In parallel, compactness is increased and this indicates that air temperature is relevant to number of buildings in a certain urban area. In other words, the greater the compactness, the lower the air temperature, as less area is exposed to the sun. Eventually, more compactness leads to better outdoor thermal comfort. Consequently, in a hot arid climate, H/W ratio and orientation together play an important role in outdoor thermal comfort The role of urban compactness and appropriate building height in microclimate design in hot and arid climates are also extensively studied by Ignatius, Wong & Jusuf (2015) who confirmed that Site coverage of 60% had the least heat gain compared to 20% site coverage, that means the more compactness with lower height is the better thermal behavior.

Table 5.10: Comparison of numerical data extracted in Phase 2, average of wind speed and air temperature for proposed urban configurations A and F.

Outdoor thermal indicator	(P2–1) Three storeys (A)	(P2–2) Four storeys (A)	(P2–3) Six storeys (A)	(P2–4) Three storeys (F)	(P2–5) Four storeys (F)	(P2–6) Six storeys (F)
Average wind speed	32.04	33.60	32.13	31.59	31.56	31.58
Average air temperature	1.58	1.58	1.72	1.43	1.82	1.58

5.4 Phase 3: Results and Discussion

Phase 3 comprises three simulation trials for two different configurations as shown in Table 5.11 and numerical data extracted in Table 5.12. Axis 1 (north west–south east) and Axis 2 (north–south) were selected as the most favourable urban configuration as concluded by the end of Phase 2. The base case is also tested for comparison purposes. In order to test this orientation parameter, the most important thermal comfort indicators–air temperature and wind speed–will be tested focusing on orientation, which some literature determines to be crucial. The selection of these particular orientations is based on recommendations from the literature review (Chapter 2).

Table 5.11: Bundle of simulation runs and their corresponding variables, investigating parameter 3 (P3)

Trial	P3 -Variable parameter – orientation	P1–Fixed parameter – building form	P2–H/W ratio
P3–1	Axis 1: north west–south east	Four storeys (A) base case	16:8=2
P3–2	Axis 1: north west–south east	Developed linear form (F)	12:12=1
P3–3	Axis 2: north–south	Developed linear form (F)	12:12=1

Table 5.12: Summary of numerical data extracted in Phase 3, average of air temperature to investigate Axis 1 and Axis 2.

Time	P3–1 Four storeys (A) Axis 1: north west–south east	P3–2 Three storeys (F) Axis 1: north west–south east	P3–3 Three storeys (F) Axis 2: north–south
8:00	26.80	25.95	25.29
9:00	28.80	27.30	26.91
10:00	31.25	28.77	29.28
11:00	32.40	30.53	30.70
12:00	33.80	31.36	31.72
13:00	36.10	32.35	33.54
14:00	38.96	33.92	35.95
15:00	40.59	35.63	37.95
16:00	40.37	36.64	38.25
17:00	39.16	36.70	37.42
18:00	37.15	35.94	35.78
19:00	35.09	34.62	34.00
20:00	34.35	33.06	33.28
21:00	33.80	32.30	32.70
22:00	33.25	31.77	32.16
23:00	32.77	31.30	31.63
0:00	32.29	30.83	31.11
1:00	31.90	30.35	30.58
2:00	31.36	29.89	30.09
3:00	30.95	29.47	29.60
4:00	30.55	29.08	29.15
5:00	31.15	29.05	28.74
6:00	29.88	28.58	28.35
Average	**33.60**	**31.54**	**31.92**

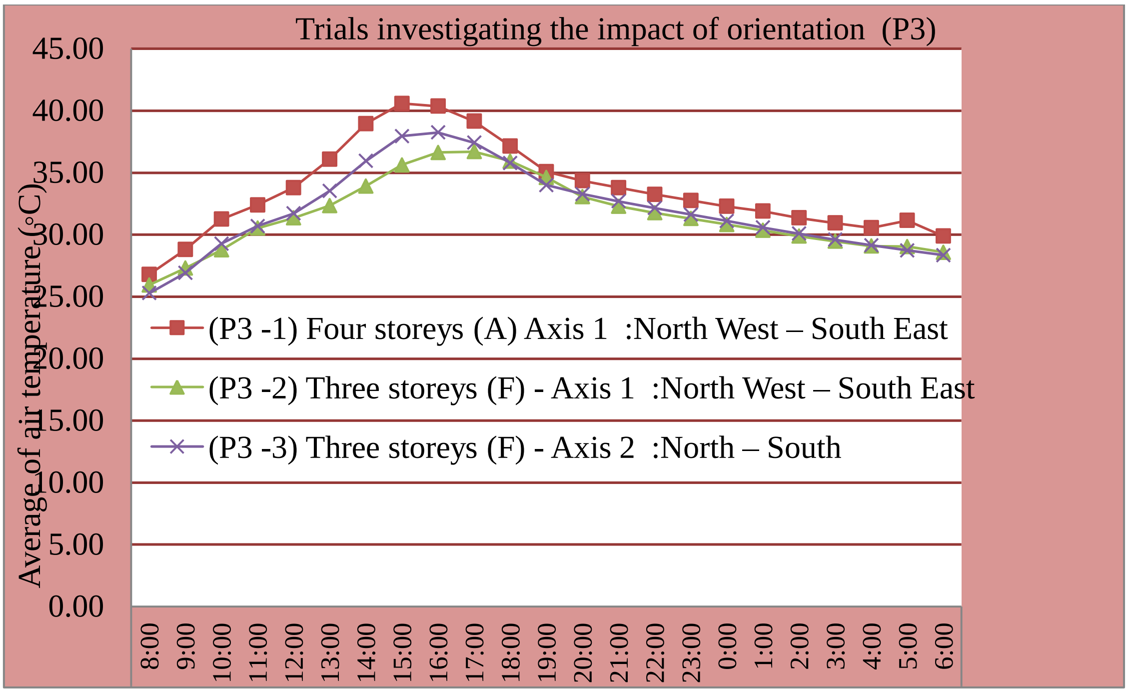


Figure 5.13: Average hourly air temperatures for six trials investigating the impact of building height and (P3), on the July 2, 2016.

5.4.1 Results Investigating the Impact of Orientation—P3

. The developed linear design F model with Axis 2 model had a long duration of direct sun as shown in Figure 5.13. The difference between this model and Axis 1 concerning solar radiation occurred between 12:00 h and 16:00 h. During this peak period, the air temperature of the developed linear design F with Axis 1 decreased due to the shading effect of this configuration. Furthermore, when direct sunlight appeared again from behind the obstacle, the air temperature rose to the same temperature as at 12:00 h. In contrast, the urban configuration F with Axis 2 showed different behavior.

Before 11:00 h, the central point was protected by surrounding buildings, and air temperature increased on at a slow gradient, yet between 12:00 h and 16:00 h, the point received direct sun and air temperature increased very quickly. Similarly, the urban configuration A (base case) on Axis 1 had the same increase in air temperature; however, its peak was lower than that of Axis 2. This is due to the blockage of the sun by the south façade of the linear building forms working together to create a courtyard. The average air temperature and wind speed of the two orientations of urban configurations are described in Figure 5.13 and 5.14, respectively. Axis 1 north west–south east provided average air temperature values at satisfactory levels of thermal comfort conditions for most of the day. On the contrary, the urban configuration F on Axis 2,north–south axis, all air temperature values were higher than those for Axis 1.

Table 5.13: Summary of numerical data extracted in Phase 3, average of wind speed to investigate Axis 1 and Axis 2.

Time	P3–1	P3–2	P3–3
8:00	1.65	1.55	1.26
9:00	1.60	1.52	1.23
10:00	1.60	1.49	1.21
11:00	1.66	1.49	1.24
12:00	1.66	1.50	1.25
13:00	1.65	1.51	1.25
14:00	1.63	1.51	1.25
15:00	1.61	1.50	1.24
16:00	1.60	1.48	1.23
17:00	1.58	1.47	1.22
18:00	1.58	1.46	1.21
19:00	1.58	1.45	1.20
20:00	1.58	1.43	1.19
21:00	1.58	1.41	1.19
22:00	1.58	1.41	1.18
23:00	1.58	1.40	1.17
0:00	1.56	1.38	1.16
1:00	1.54	1.36	1.15
2:00	1.53	1.34	1.14
3:00	1.50	1.32	1.12
4:00	1.48	1.30	1.10
5:00	1.46	1.28	1.09
6:00	1.44	1.27	1.07
Average	**1.58**	**1.43**	**1.19**

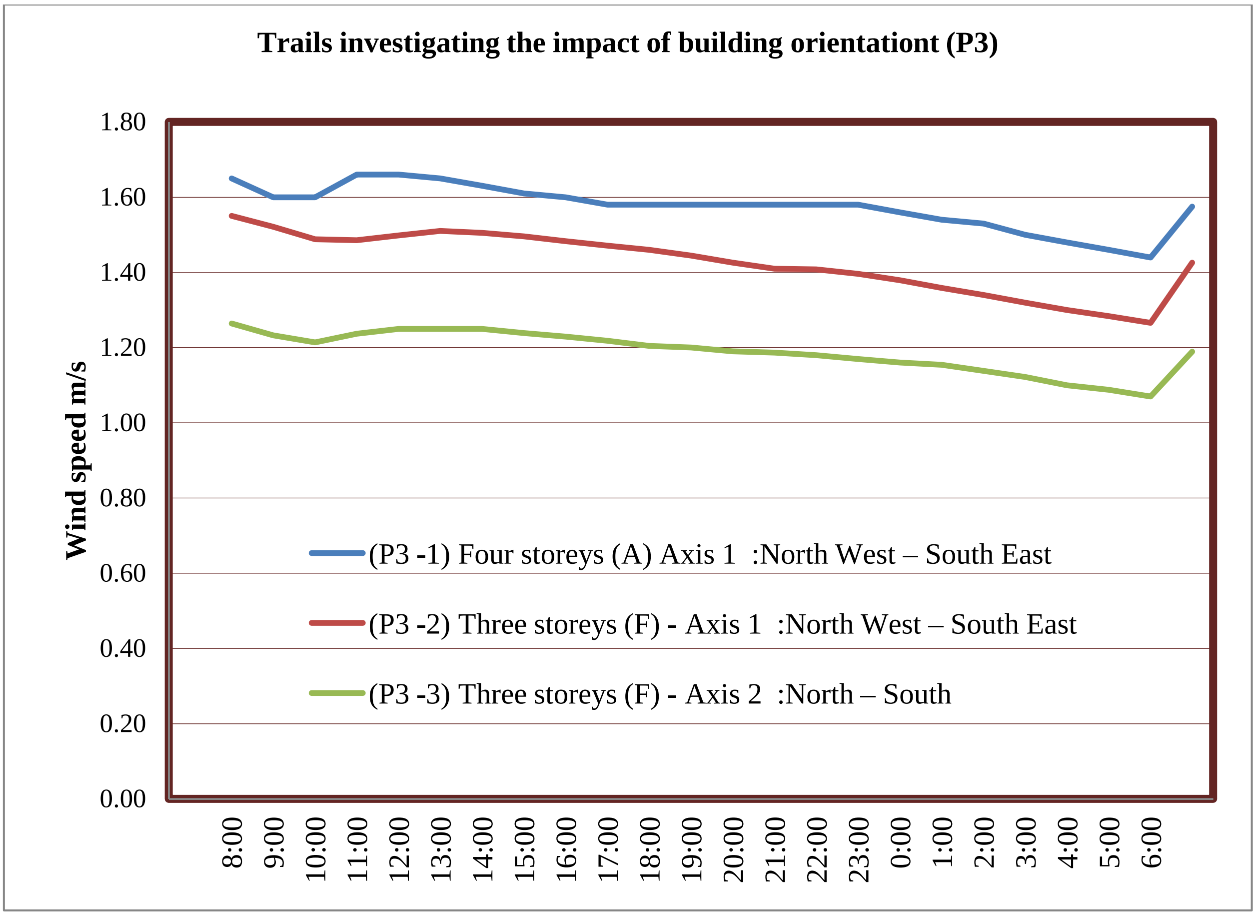


Figure 5.14: Average hourly wind speed for three trials investigating the impact of building orientation (P3), on the July 2, 2016.

5.4.2 Selection of Optimal Orientation

Two different orientations were investigated taking into consideration that the duration exposures to direct sunlight were influenced by urban form and its orientation. Thus, urban configurations play the most important role in thermal comfort. The selected two orientations of the configuration are not seen to be significant in terms of their alignment to the sun; however, orientation is relevant in terms of the wind direction as illustrated in Figure 5.14. The orientation of most of the most beneficial urban configuration towards the wind contributed to reducing temperatures. A comparison of average air temperature for all the three trials is shown in Figure 5.13

above. This overall comparison also proves the diverse behaviour of individual configurations during the morning, peak hours, and at night.

Reviewing the results of three urban configurations and graphs in Figures 5.13 and Table 5.12, all simulation trials indicate the maximum difference in value in the hour from 14:00 h and 15:00 with 5 C approximately difference between the base case A and F. The graph indicates that all urban configuration F for axis 1 and 2 behaved similarly during the morning and night time.

Table 5.14: Comparison of numerical data extracted in Phase 3, average of wind speed and air temperature for proposed urban configurations A and F , Axis 1 and 2.

Outdoor thermal indicator	P3–1 Four storeys (A) Axis 1: north west–south east	P3–2 Three storeys (F) Axis 1: north west–south east	P3–3 Three storeys (F) Axis 2: north– south
Average wind speed	33.60	31.54	31.92
Average air temperature	1.58	1.43	1.19

Orientation Axis 1: north west–south east for urban configuration F showed lower air temperature and better wind speed while the simulation runs which represented the worst degree of comfort was Axis 1 oriented for base case A. Moreover Axis 2 for urban configuration F showed discomfort; this is due to sun exposure and solar radiation penetrations during long period of summer day, unlike the north west–south east orientation, prevailing wind direction enhances the wind to infiltrate and overheating is dispelled accordingly.

From the results presented in the previous sections, the following will provide observations regarding the six configurations in comparison to each other with discussion of the possible causes for these findings. The results analysis focused on the month of July as it is important to understand temperature behaviour in summer when temperature reductions are most critical. In this study, results confirmed that building forms and courtyard proportion were more crucial than building height and orientation. For example, the most favourable urban configuration (F) was 2 ◦C cooler than the most unfavourable case base case (A), when investigating P1. Conversely, the impact of building height was responsible for only a 0.5 ◦C difference, demonstrated in trials P2–1 and P2–4.

In the end, two important results can be concluded as follows: selection of appropriate urban configuration helps improve thermal comfort through improving wind speed; consequently, air temperature is influenced by building form and courtyard proportion. That means the urban morphological condition is important for determining the wind condition of a certain area. The height of a building determines the number of buildings in certain urban areas, and influences the availability of green spaces, which has been proven to reduce outdoor temperatures and concurrently improve outdoor thermal comfort. The existing base case urban configuration was the *warmest* configuration. It recorded the highest average temperature of all configurations in July with registered valued of 33.6 C, with a lower wind speed. This is mainly because the configuration did not allow the wind to behave in a way conducive to lowering the temperature. On The other hand, urban configuration of developed linear form F having three storey buildings and oriented toward north west–south east orientation was the most optimal configuration, it reduces the air temperature by 2 ◦C average and 5 ◦C during peak time at 14:00 H.

6 CONCLUSION

6.1 Conclusion

The main focus of this research was on the effect of different urban configurations on outdoor thermal comfort in military camps in Abu Dhabi. This study answered the research question that different urban configurations within a definite military camp behave differently in terms outdoor thermal comfort taking into consideration the most important microclimatic variables influence outdoor thermal comfort in hot arid climate which are temperature and wind. After previous research has substantiated that the four different parameters of urban configuration; building forms, open space proportion, building height and orientation influence the outdoor thermal comfort independently and separately, this study concentrated on the impact of these four parameters simultaneously. Beyond the one-to one relationship between single parameter of urban configuration and its influence on outdoor temperature and wind, the overall interaction of all these parameters performs a character in the simulation results and readings. The six main configurations investigated were, existing linear blocks with rectangular courtyard, proposed fortress blocks with square and rectangular courtyard, proposed U-shape blocks with square courtyard, and proposed L-shape blocks with square courtyard and Proposed developed linear blocks with rectangular courtyard.

The analysis of urban configuration involves four factors: building form, courtyard proportion (particularly L/W ratio), H/W ratio, and building height and orientation. For each urban configuration, a bundle of simulation runs have been performed in climate parameters on a typical day of summer, during the month of July. The microclimatic three-dimensional ENVI-met model was used to simulate air temperature and wind speed, identified in the literature review as the greatest influences on microclimatic interactions for outdoor thermal comfort. Firstly, outcomes of five different urban configurations were compared against the base case, with two reference points for each configuration that represent points of comparison. Outcomes revealed that urban configuration (F) resulted in the lowest air temperatures, based on best wind speed and air movement results. Secondly, simulation readings confirmed that developed linear F with three story have the best thermal behaviour and was considered as the most favourable building height. Finally the orientation was examined through trials of two different axes, north west–south east, and north–south compared to the existing base case.

From the results presented in the previous section, the following will provide observations regarding the six urban configurations in comparison to each other, with discussion of the possible causes for these findings. The average temperatures and wind speed reported in the previous section will be used to select the corresponding visual snapshots to discuss the findings. The analysis focused on the month of July, as it is important to understand temperature behavior in summer when temperature reductions are most critical.

This study revealed that outdoor thermal comfort indicators are influenced by urban configuration including building forms, courtyard proportion, building height, and orientation. Previous research has substantiated the impact of building form and open spaces separately, while this research investigates both factors them simultaneously and the most important microclimatic variables influence outdoor thermal comfort in hot arid climate are identified. Beyond the single relationship between urban elements, the holistic approach of this paper tested the impact of different urban configurations on air temperature and wind conditions, as they are the most prominent micro-climate parameters influencing outdoor thermal comfort.

The lowest average air temperature was recorded by the developed linear form F having a courtyard proportion of L/W 2:1. Similarly, the best wind conditions were recorded for this urban configuration, with a registered value of 1.82 m/s considering the initial wind speed of 3.6 m/s. When urban planners design a military camp in the UAE, it is recommended a fortress shape of building form be avoided. Designers should always consider the importance of wind conditions and its effect on reducing excess heat in urban areas by dispelling heat away from buildings, thus improving outdoor thermal comfort.

Urban planners should study the relationship between urban forms, open space proportion, building height, and orientation, and the influence of these factors on microclimate conditions. Low height and compacted urban configuration is recommended particularly for hot, arid climates. The minimum impact on air temperature reduction in employing L-shape and U-shape building forms is also important to highlight.

Courtyard proportions for a fortress building form have a negligible impact not only on the air temperature but also on wind conditions; for example, rectangular and square courtyards behaved in a similar manner in Phase 1 of this research. In principle, it is recommended to aim to reduce air temperature and improve wind conditions when applying urban design guidelines to select the most favorable urban configuration.

From this research it can be concluded that wind conditions and air temperature—which have the most important impact on outdoor thermal comfort—are not only influenced by building form, but also by building height and urban area compactness, which both play a significant role in temperature variations.

As such, input wind speed did not impact temperature variations. This study showed that the building configuration shape was the key factor in manipulating wind within building forms, which became independent of input wind speed. Thus, wind behavior is seen as *resultant* of configuration shape. By comparing results between the presence and absence of wind, it was confirmed that wind had the effect of eliminating major temperature fluctuations and therefore reducing the occurrence of hotspots. It contributed to a smoother distribution of temperature throughout the entire site.

The impact of wind speed amplification in the area of the three different building heights is obvious, however, it should be noted that all these findings are limited to the specific configurations investigated. Finally, it should be noted that the urban design for the existing base case emphasizes the impact of building form and courtyard proportion, where only three heights of 3, 4 and 6-storey buildings were used respectively for the base case and the most favorable urban design (Liu, Niu & Xia 2016).

In this research, it is safe to conclude that it is not the building height and orientation are the influencing parameters on the outdoor thermal comfort, but it is the building form and open space proportion that played a more significant role in outdoor temperature and wind variations. The outcomes from analysis' and simulation trails for Phase 1, Phase 2, and Phase 3 demonstrate that outdoor thermal comfort is mainly influenced by building form and courtyard proportion. These two morphological factors have the most significant impact on exposure to solar radiation, wind speed, and air temperature, accordingly. The impact of these study achievements on microclimate and outdoor thermal comfort can be considered as design guidelines, which help urban designers. It is true that this research does not allow for the most favourable sustainable urban configuration as the best design proposal that suits all military camps, however, it already allows raising the levers of action to improve the conditions of outdoor thermal comfort and to reduce, on the longer run, problems arising from urban heat islands.

6.2 Recommendations for Further Research

This study has been specifically carried out in the city of Abu Dhabi. The results showed that building height and orientation have the minimum impact on outdoor thermal comfort compared to the building form and open space proportion.

The fact that the variations are minor between the one configuration with different height and orientation does not mean they may be interchangeable in terms of their performance. It is recommended that designers capitalize on those minor differences. Some future work that could be carried out would involve. Repeating the simulations for configurations that have big range of different heights and orientations and specifically in various locations in hot arid climate may be explored in order to further understand the behavior of these configurations in different climatic conditions.

The outcomes lead to further possible areas of research in this field. Some of these possibilities are:

1. Exploring the effects of different building heights and open space proportions for one urban configuration, with a larger urban area selected to address the impact of urban density and optimum building height.
2. Investigating the effects of these six different urban configurations on variables influence the outdoor thermal comfort such as humidity.
3. Investigating the effects of these six different urban configurations on cooling load and energy consumption.
4. Testing the optimal design strategies in hot, arid climates to determine the most favorable building prototype to be used for residential, office, and mixed uses in military camps in the UAE.
5. Moreover, more demanding research in the field of urban design must be encouraged and carried out by regulating authorities in order to establish the

best suiting urban configurations to the city with the least negative impact to the environment and climatic variations.

6. Extending the season of the simulation to incorporate winter temperature variations, to understand the behavior of the different urban configurations during summer and winter seasons.
7. Investigating the effect of different building envelope and façade treatments, as well as the impact of thermal mass of the most favourable configuration (F).

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Appendices

Appendix A

Samples of extracted data manipulation showing the daily average of temperature and wind speed– remaining files available in soft copy

Table A.1: Summary of numerical data extracted in Phase 1, average of wind speed for proposed urban configurations A to F on July 2, 2016

Time	(P1 -1) A	(P1 -2) B	(P1 -3) C	(P1 -4) D	(P1 -5) E	(P1 -6) F
8:00	1.65	1.76	1.71	1.81	1.63	1.88
9:00	1.60	1.72	1.71	1.79	1.63	1.85
10:00	1.60	1.72	1.71	1.78	1.63	1.83
11:00	1.66	1.78	1.71	1.84	1.63	1.89
12:00	1.66	1.79	1.71	1.85	1.63	1.91
13:00	1.65	1.77	1.71	1.84	1.63	1.90
14:00	1.63	1.75	1.71	1.82	1.59	1.88
15:00	1.61	1.80	1.71	1.80	1.59	1.86
16:00	1.60	1.80	1.71	1.79	1.58	1.85
17:00	1.58	1.80	1.72	1.78	1.57	1.85
18:00	1.58	1.80	1.72	1.77	1.56	1.83
19:00	1.58	1.80	1.72	1.77	1.56	1.83
20:00	1.58	1.80	1.72	1.77	1.56	1.83
21:00	1.58	1.80	1.73	1.77	1.56	1.83
22:00	1.58	1.80	1.73	1.77	1.56	1.83
23:00	1.58	1.80	1.73	1.77	1.55	1.82
0:00	1.56	1.80	1.73	1.75	1.54	1.80
1:00	1.54	1.80	1.73	1.73	1.52	1.79
2:00	1.53	1.80	1.73	1.72	1.50	1.77
3:00	1.50	1.80	1.73	1.70	1.47	1.75
4:00	1.48	1.80	1.73	1.68	1.44	1.72
5:00	1.46	1.80	1.73	1.65	1.42	1.70
6:00	1.44	1.80	1.73	1.63	1.40	1.68
Average	1.58	1.79	1.72	1.76	1.55	1.82

Table A.2: Summary of numerical data extracted in Phase 1, average of air temperature for proposed urban configurations A to F on July 2, 2016

Time	(P1 -1) A	(P1 -2) B	(P1 -3) C	(P1 -4) D	(P1 -5) E	(P1 -6) F
8:00	26.80	26.17	26.55	26.23	26.23	26.22
9:00	28.80	28.11	28.65	28.13	28.13	28.02
10:00	31.25	30.58	30.67	30.61	30.55	30.49
11:00	32.40	31.50	31.63	31.52	31.54	31.46
12:00	33.80	32.86	32.88	32.71	32.71	31.95
13:00	36.10	34.98	34.95	34.66	34.69	33.88
14:00	38.96	37.62	37.55	37.16	37.21	36.32
15:00	40.59	39.27	39.19	38.83	38.88	37.96
16:00	40.37	39.17	39.05	38.78	38.77	37.88
17:00	39.16	38.06	37.88	37.73	37.62	36.50
18:00	37.15	36.12	35.88	35.84	35.65	34.95
19:00	35.09	34.19	33.91	33.69	33.69	33.09
20:00	34.35	33.46	33.16	33.20	32.94	32.37
21:00	33.80	32.88	32.59	32.62	32.37	31.81
22:00	33.25	32.35	32.07	32.09	31.85	30.92
23:00	32.77	31.85	31.58	31.58	31.35	30.45
0:00	32.29	31.35	31.10	31.07	30.86	30.20
1:00	31.90	31.10	30.63	30.58	30.35	29.57
2:00	31.36	30.40	30.18	30.11	29.84	29.30
3:00	30.95	29.97	29.76	29.66	29.35	28.63
4:00	30.55	29.55	29.36	29.24	28.90	28.63
5:00	31.15	29.16	28.98	28.48	28.50	27.72
6:00	29.88	28.81	28.64	28.48	28.17	27.63
Average	33.60	32.59	32.47	32.30	32.18	31.56

Table A.3: Summary of numerical data extracted in Phase 2, average of wind speed on July 2, 2016

Time	(P2 -1) Three storeys (A)	(P2 -2) Four storeys (A)	(P2 -3) Six storeys (A)	(P2 -4) Three storeys (F)	(P2 -5) Four storeys (F)	(P2 -6) Six storeys (F)
8:00	1.69	1.65	1.84	1.55	1.88	1.69
9:00	1.65	1.60	1.80	1.52	1.85	1.65
10:00	1.62	1.60	1.77	1.49	1.83	1.64
11:00	1.64	1.66	1.78	1.49	1.89	1.67
12:00	1.66	1.66	1.80	1.50	1.91	1.69
13:00	1.66	1.65	1.80	1.51	1.90	1.69
14:00	1.65	1.63	1.79	1.51	1.88	1.67
15:00	1.63	1.61	1.78	1.50	1.86	1.65
16:00	1.61	1.60	1.76	1.48	1.85	1.64
17:00	1.61	1.58	1.75	1.47	1.85	1.62
18:00	1.60	1.58	1.73	1.46	1.83	1.61
19:00	1.58	1.58	1.72	1.45	1.83	1.59
20:00	1.58	1.58	1.71	1.43	1.83	1.58
21:00	1.57	1.58	1.70	1.41	1.83	1.57
22:00	1.57	1.58	1.70	1.41	1.83	1.57
23:00	1.56	1.58	1.69	1.40	1.82	1.55
0:00	1.54	1.56	1.69	1.38	1.80	1.53
1:00	1.53	1.54	1.67	1.36	1.79	1.50
2:00	1.51	1.53	1.66	1.34	1.77	1.48
3:00	1.50	1.50	1.64	1.32	1.75	1.46
4:00	1.48	1.48	1.62	1.30	1.72	1.44
5:00	1.46	1.46	1.60	1.28	1.70	1.42
6:00	1.44	1.44	1.58	1.27	1.68	1.40

Table A.4: Summary of numerical data extracted in Phase 2, average of air temperature on July 2, 2016

Time	(P2 -1) Three storeys (A)	(P2 -2) Four storeys (A)	(P2 -3) Six storeys (A)	(P2 -4) Three storeys (F)	(P2 -5) Four storeys (F)	(P2 -6) Six storeys (F)
8:00	25.83	26.80	26.56	25.95	26.22	27.15
9:00	27.52	28.80	28.13	27.30	28.02	28.86
10:00	28.83	31.25	29.88	28.77	30.49	31.00
11:00	31.32	32.40	31.37	30.53	31.46	31.77
12:00	32.38	33.80	32.17	31.36	31.95	32.49
13:00	34.21	36.10	33.43	32.35	33.88	33.90
14:00	36.70	38.96	35.24	33.92	36.32	35.76
15:00	38.54	40.59	37.10	35.63	37.96	37.31
16:00	38.63	40.37	38.00	36.64	37.88	37.63
17:00	37.58	39.16	37.75	36.70	36.50	36.78
18:00	35.67	37.15	36.68	35.94	34.95	35.24
19:00	33.66	35.09	35.03	34.62	33.09	33.33
20:00	32.90	34.35	33.15	33.06	32.37	32.06
21:00	32.34	33.80	32.24	32.30	31.81	31.45
22:00	31.84	33.25	31.69	31.77	30.92	30.94
23:00	31.35	32.77	31.23	31.30	30.45	30.44
0:00	30.89	32.29	30.80	30.83	30.20	29.93
1:00	30.44	31.90	30.39	30.35	29.57	29.44
2:00	30.02	31.36	29.99	29.89	29.30	28.98
3:00	29.62	30.95	29.60	29.47	28.63	28.56
4:00	29.25	30.55	29.25	29.08	28.63	28.16
5:00	28.90	31.15	29.90	29.05	27.72	27.86
6:00	28.58	29.88	29.34	28.58	27.63	27.40
Average	**32.04**	**33.60**	**32.13**	**31.54**	**31.56**	**31.58**

Table A.5: Summary of numerical data extracted in Phase 3, average of wind speed on July 2, 2016

Time	(P3 -1) Four storeys (A) Axis 1 :North West – South East	(P3 -2) Three storeys (F) - Axis 1 :North West – South East	(P3 -3) Three storeys (F) - Axis 2 :North – South
8:00	1.65	1.55	1.26
9:00	1.60	1.52	1.23
10:00	1.60	1.49	1.21
11:00	1.66	1.49	1.24
12:00	1.66	1.50	1.25
13:00	1.65	1.51	1.25
14:00	1.63	1.51	1.25
15:00	1.61	1.50	1.24
16:00	1.60	1.48	1.23
17:00	1.58	1.47	1.22
18:00	1.58	1.46	1.21
19:00	1.58	1.45	1.20
20:00	1.58	1.43	1.19
21:00	1.58	1.41	1.19
22:00	1.58	1.41	1.18
23:00	1.58	1.40	1.17
0:00	1.56	1.38	1.16
1:00	1.54	1.36	1.15
2:00	1.53	1.34	1.14
3:00	1.50	1.32	1.12
4:00	1.48	1.30	1.10
5:00	1.46	1.28	1.09
6:00	1.44	1.27	1.07
Average	1.58	1.43	1.19

Table A.6: Summary of numerical data extracted in Phase 3, average of air temperature on July 2, 2016

Time	(P3 -1) Four storeys (A) Axis 1 :North West – South East	(P3 -2) Three storeys (F) - Axis 1 :North West – South East	(P3 -3) Three storeys (F) - Axis 2 :North – South
8:00	26.80	25.95	25.29
9:00	28.80	27.30	26.91
10:00	31.25	28.77	29.28
11:00	32.40	30.53	30.70
12:00	33.80	31.36	31.72
13:00	36.10	32.35	33.54
14:00	38.96	33.92	35.95
15:00	40.59	35.63	37.95
16:00	40.37	36.64	38.25
17:00	39.16	36.70	37.42
18:00	37.15	35.94	35.78
19:00	35.09	34.62	34.00
20:00	34.35	33.06	33.28
21:00	33.80	32.30	32.70
22:00	33.25	31.77	32.16
23:00	32.77	31.30	31.63
0:00	32.29	30.83	31.11
1:00	31.90	30.35	30.58
2:00	31.36	29.89	30.09
3:00	30.95	29.47	29.60
4:00	30.55	29.08	29.15
5:00	31.15	29.05	28.74
6:00	29.88	28.58	28.35
Average	**33.60**	**31.54**	**31.92**

Appendix B

Tabulated simulation results for all tests performed P1,P2 and P3 of the research showing average surface temperatures and wind Speed

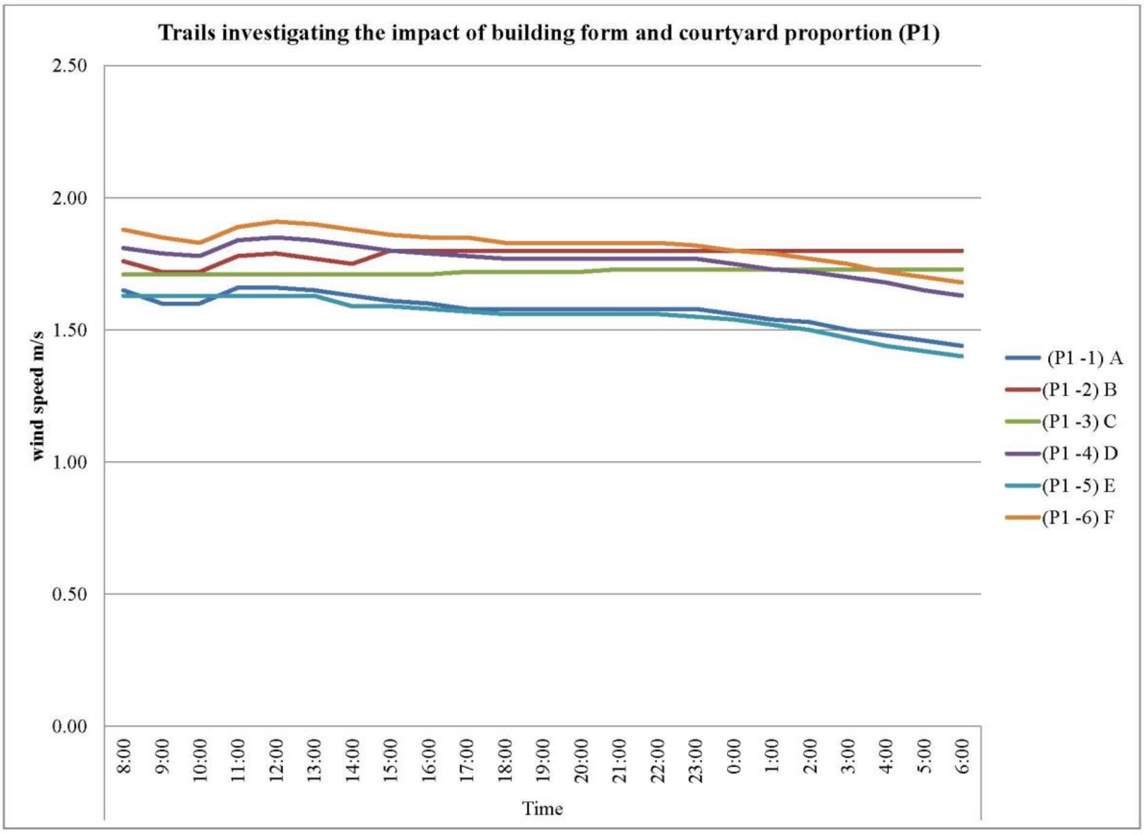

Figure B.1: Average hourly wind speed for six trials investigating the impact of building form and courtyard proportion **(P1)**

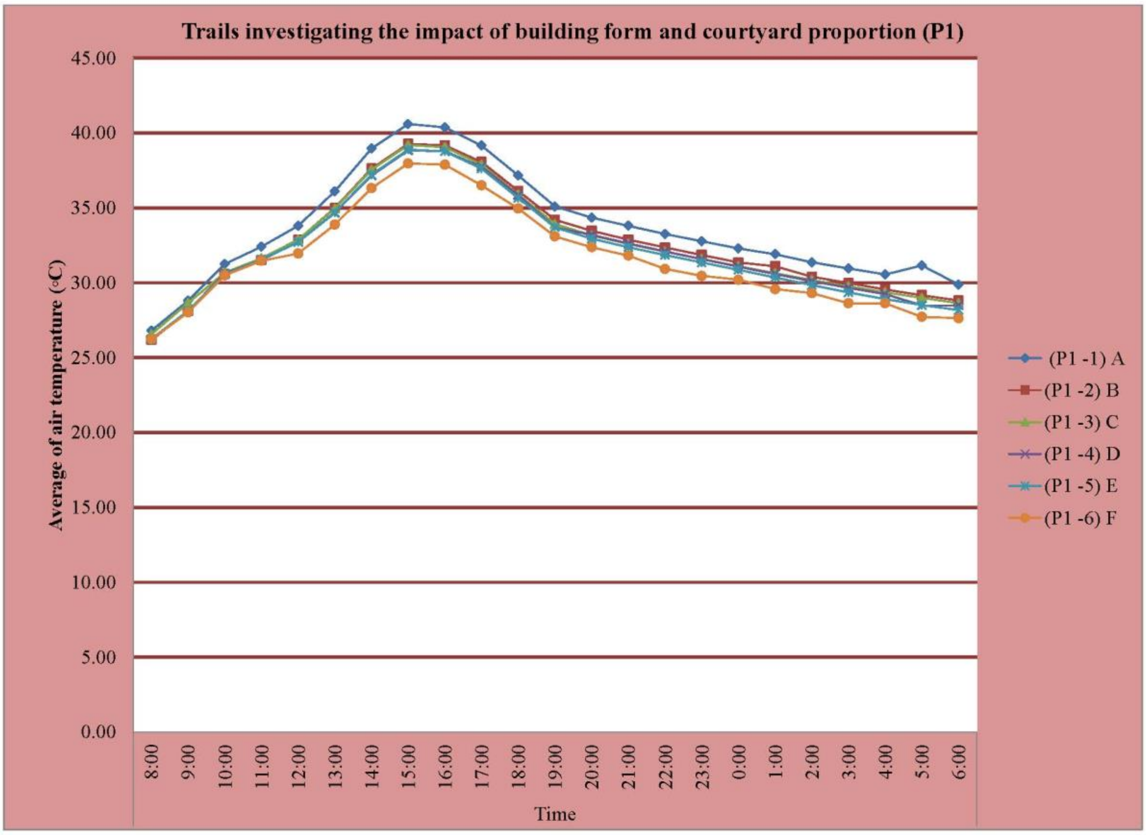

Figure B.2: Average hourly air temperatures for six trials investigating the impact of building form and courtyard proportion **(P1)**

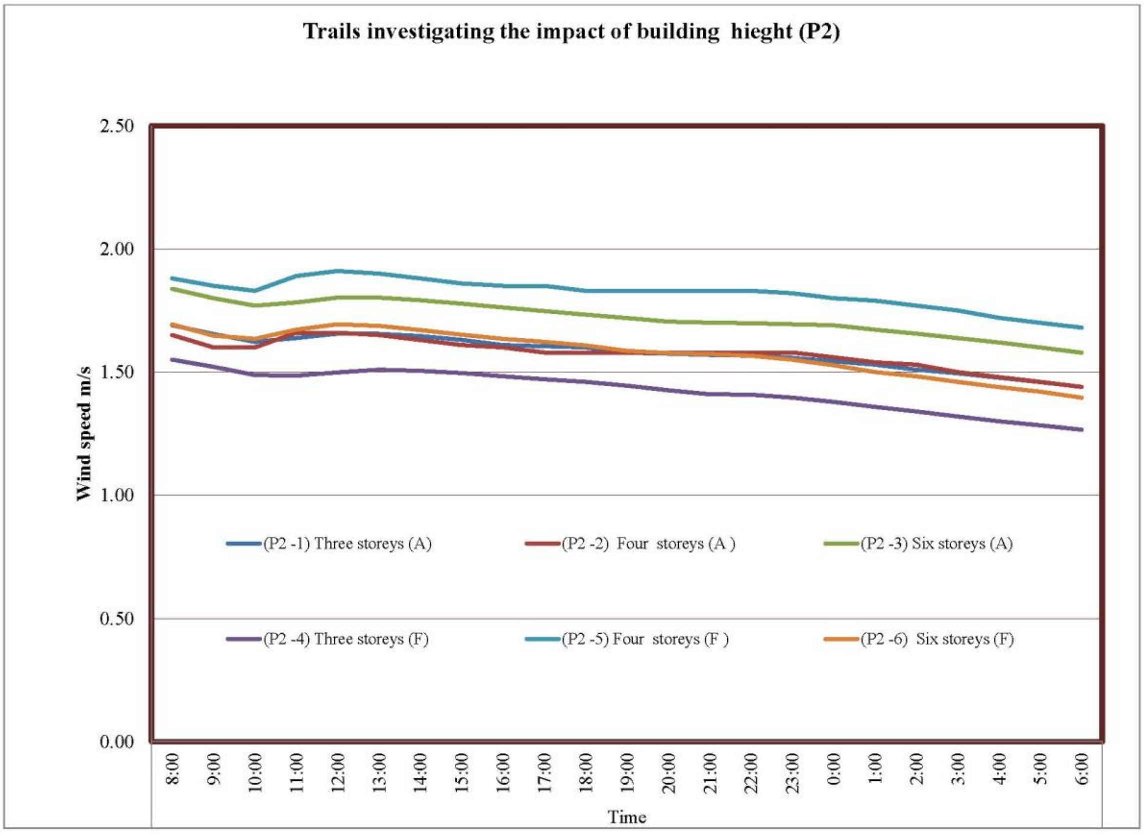

Figure B.3: Average hourly wind speed investigating the impact of building height **(P2)**

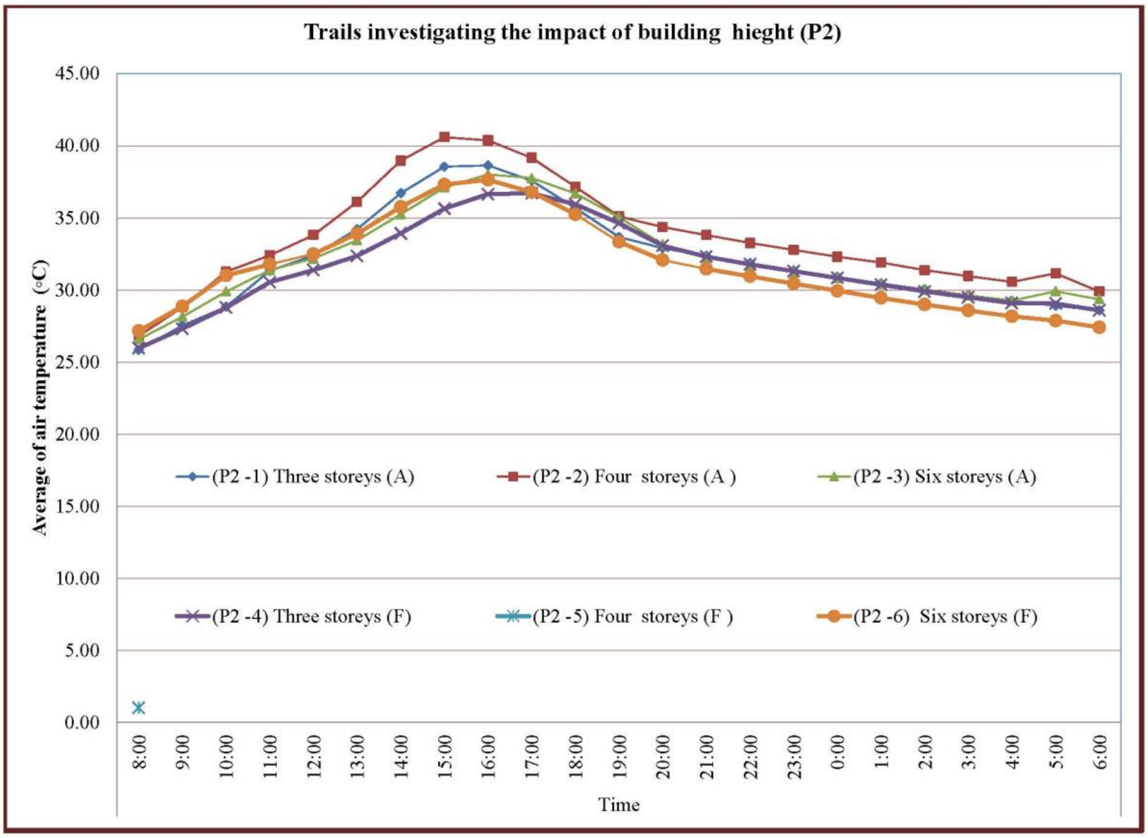

Figure B.4: Average hourly air temperatures for six trials investigating the impact of building height **(P2)**

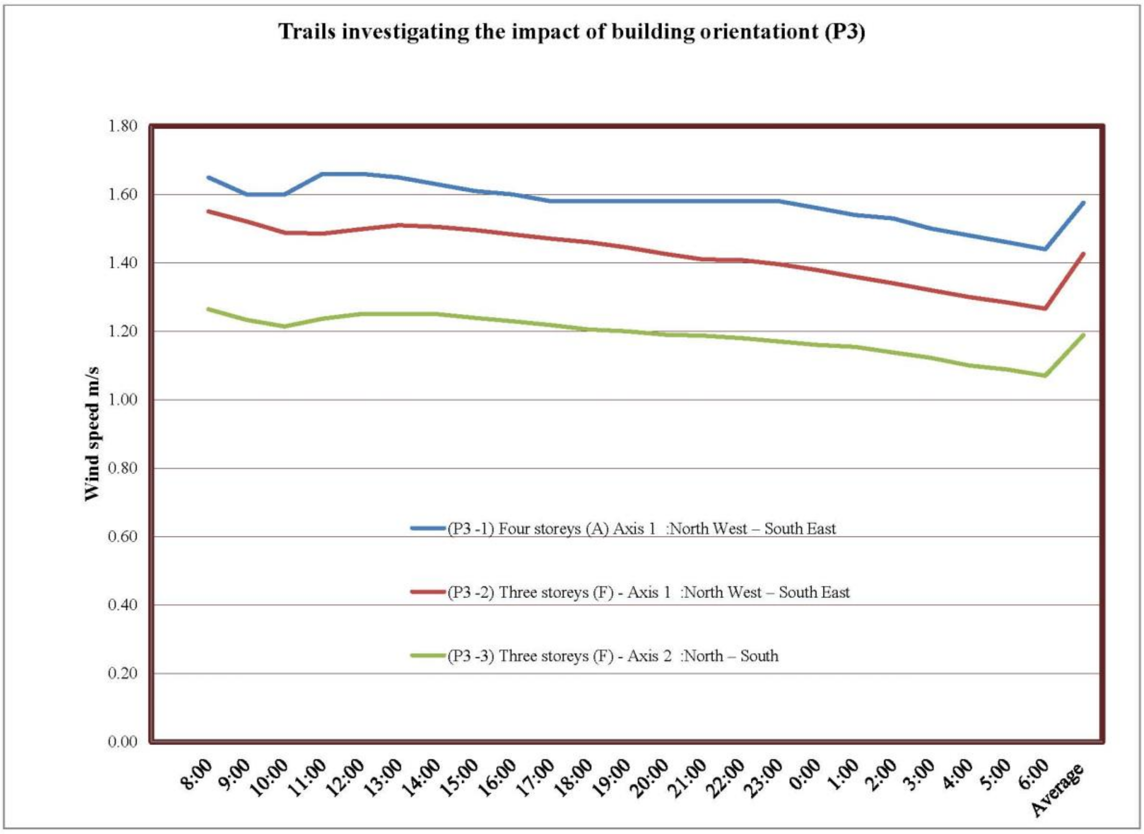

Figure B.5: Average hourly wind speed investigating the impact of building orientation **(P3)**

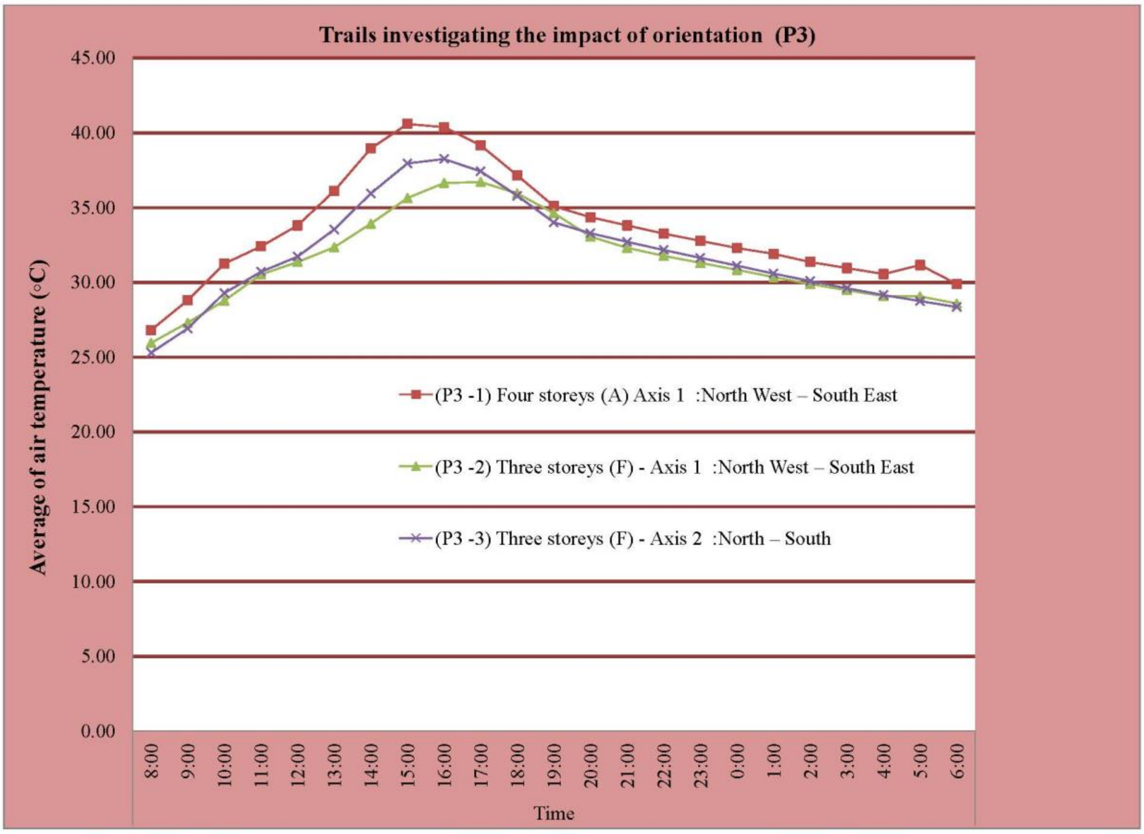

Figure B.6: Average hourly air temperatures for six trials investigating the impact of building orientation **(P3)**

Appendix C Tabulated simulation results showing average air temperatures of urban configuration A and F .

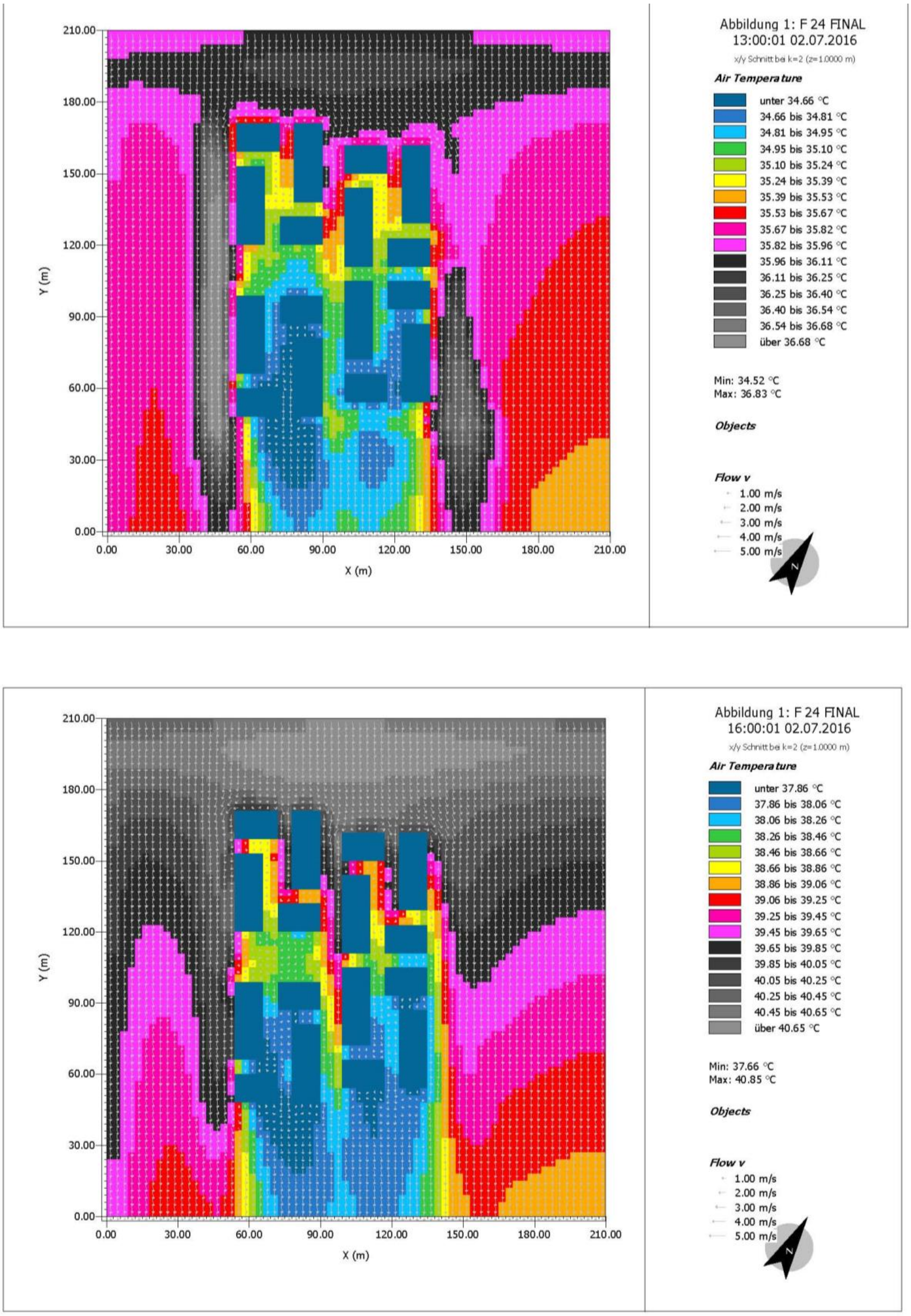

Figure C.1: Air temperature for proposed urban configurations F at 13:00 h and 16:00 h on July 2, 2016 (P1).

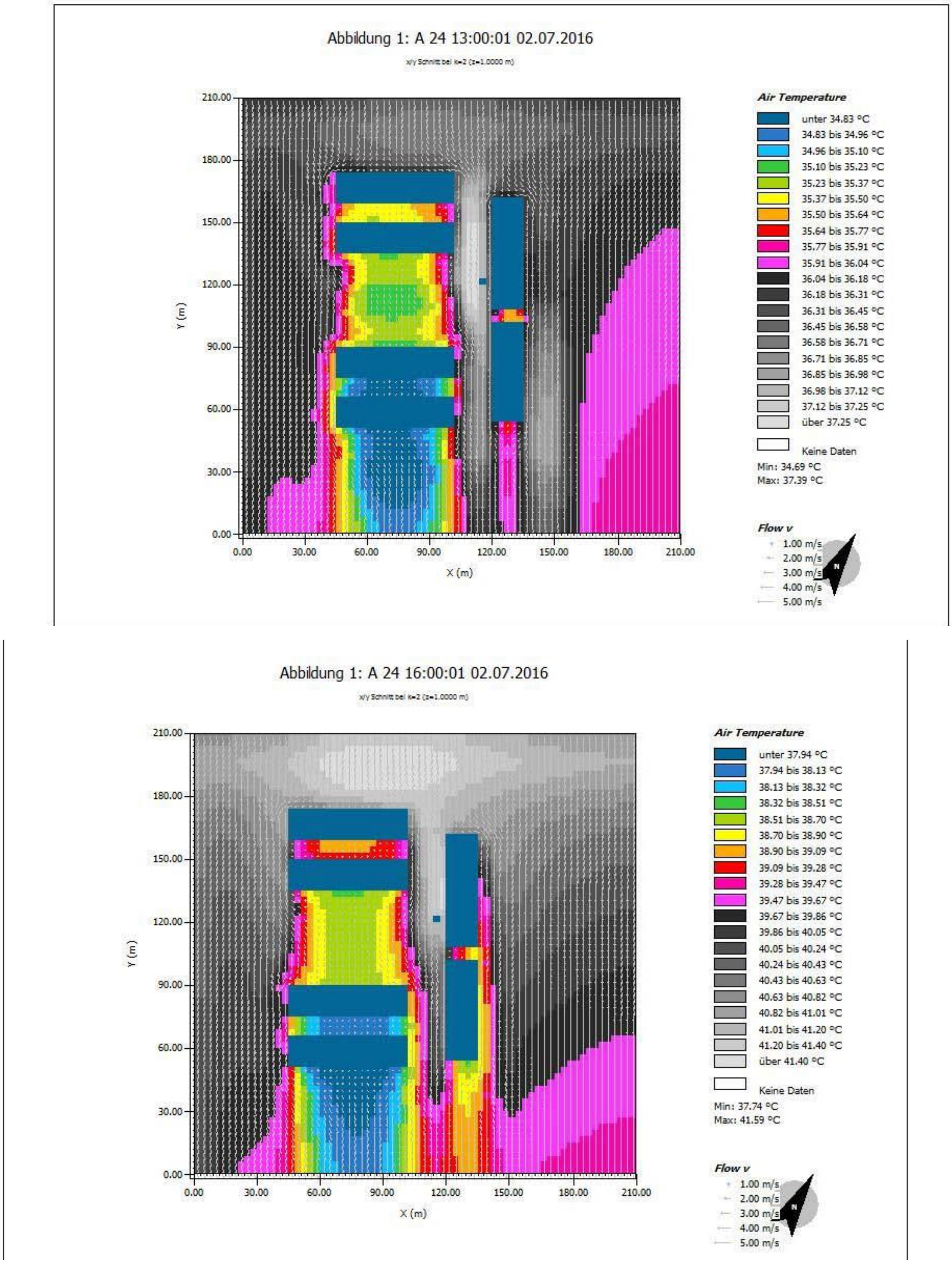

Figure C.1: Air temperature for proposed existing base case A at 13:00 h and 16:00 h on July 2, 2016 (P1).