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Institute of the Built Environment
Master of Environmental Design of Buildings

INCREASING THE AIR FLOW BETWEEN BUILDINGS IN HIGH DENSITY URBAN AREAS IN RAS AL-KHAIMAH, UNITED ARAB EMIRATES

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I dedicate this research to my wife

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Abstract

This research is a study of how to increase the flow of natural ventilation in a high density urban area. It was carried out in Ras Al Khaimah (RAK) city in the United Arab Emirates (UAE). Distance between the buildings is an important variable in promoting ventilation in urban design. High density zones in RAK cause poor ventilation and the small distance between buildings prevent deeper penetration by the wind. Thus, the scope of the study is to raise the amount of natural ventilation in high density urban areas in RAK. A review of literature on the research topic is provided in this study while both quantitative and qualitative data were collected through numerical simulation, experimental approach and case study in order to maintain both reliability and validity. The results of this research revealed that there is a considerable improvement in the airflow movements around the buildings after the urban parameters of the study area have been modified.

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1.0 INTRODUCTION

Most architects design buildings without taking into account that the distance between the buildings is an important variable in promoting ventilation in urban design. High density zones in RAK cause poor outdoor ventilation and high rise buildings prevent deeper penetration by the wind. Furthermore, building design today depends more on using mechanical techniques in order to provide indoor climatic comfort and simultaneously ignore and forget the outdoor climatic comfort. There is no doubt that outdoor air quality has direct effects on different areas of daily social and economic life. One clear example is that improving air quality can reduce health risks by decreasing outdoor air pollution. Furthermore, using passive energy resources instead of using active methods can save energy and improve air quality (Bruse, 1999). For that reason focusing on improving the outdoor air quality in high density urban areas, through promoting airflow between buildings in Ras Al Khaimah is very necessary.

This dissertation is therefore an attempt to promote airflow around the buildings examining some parameters for urban design such as building proportions (length and width), urban pattern types, the height of buildings as well as their shape and the width of street canyons.

In this investigation, the advanced three-dimensional computer tool, Envi-met, version 3.0 was used in order to simulate the study area. Envi-met is a 'non-hydrostatic' model that predicts all exchange processes including wind flow, turbulence, radiation fluxes, temperature and humidity' (Toudert, 2005).

1.1 Justification

This investigation tries to maximize outdoor air quality in RAK in order to improve the quality of life by creating comfortable bioclimatic conditions. The reasons for choosing R.A.K as a case study are that R.A.K has suffered from a lack of planning laws and regulations and equally important, that R.A.K is being under the development stage and it can be noticed that there is a high density zone with narrow spaces between buildings. Land use planning in Ras Al Khaimah needs to be integrative and holistic in order to control urban development including urban growth, industrial, commercial and residential location and infrastructure growth. Control of urban planning can be done through the use of master plan for urban construction and progress which define a city's character and its future direction and scale of development.

The population in RAK grew from 159,000 in 1998 to 197,000 in 2005. Furthermore, it demonstrates the gross domestic production (GDP) growth from AED 5,218,000 in 1998 to AED 9,253,000 in 2005 (Government of Ras Al Khaimah, 2007). In Ras Al Khaimah the private sector plays a leading role in the local economy and is characterized by its specialization and success in specific business activities, particularly the industrial field. Thus the economy grew by 3.8% to 5% in 2005. The main exports of Ras Al Khaimah include ceramic tiles, medicines, cement, crushed rocks and fish while the main imports include clinker, live sheep, cars and gold. The imports and exports are developing dramatically as shown in appendix 1.1. Table 1 illustrates the numbers of buildings that were constructed in 2004. It can be noticed that the number of multi-story buildings is 11 while the number of villas is 651 (Economic department, 2005). This research is therefore an attempt to minimize the drawback effect of urban development on the environmental aspects in RAK. For that reason, the densest area in RAK will be analyzed as a case study in order to improve the most important environmental aspect which is the natural ventilation.

Table1: Numbers of buildings and types in RAK (Economic department, 2005)

Construction and Building:	2004
Building permits	2219
Multi-floor Buildings	11
Villas	651
Arabic houses	166
Commercial & industrial buildings	60
Additions	438
Mosques	13
Others	880

Ras Al Kamiah is situated in the north of the UAE's seven emirates. It is located in Latitude 25.37, Longitude 55.56 and Altitude 26m. The time zone of Ras Al Khaimah is Greenwich Mean Time (GMT) + 4 hours (About Ras Al Khamiah, n.d). According to the weather tool software, the climate in RAK is hot and humid. The mean temperature is 26.55 C^{o} and the lowest temperature (winter) is 11.4 C^{o} while the highest temperature (summer) is 41.7 C^o. The solar radiation is highest in the North-West and the clearest sky can be seen in November, while April is the cloudiest month of the year. The maximum prevailing wind average is 4.3 m/s coming from the North-West. The max relative humidity in January is 70%, while in June it is 45%. Air temperatures show that buildings can be naturally ventilated from November to April. See appendix 1.2

1.2 Objectives

This investigation aims to answer the above question by:

- Testing and evaluating the airflow movement in the urban area by using a simulation method.
- Changing the urban parameters in order to improve the outdoor air quality in the urban area, decrease air pollution and offer comfort pedestrian level wind flow.

1.3 Study area

Ras Al-Khaimah began its urban development recently, but this has not been based on a well-planned urban design. The absence of planning has an affect on some aspects of the environment in certain areas in Ras Al Khaimah. For example, there are some observed problems in these areas such as lack of daylight and natural ventilation, air pollution, noise and heat islands. The inquiry focuses on the outdoor air quality in a specific area of Ras Al Khaimah.

Al-Quasim corniche is the densest area in Ras Al Khaimah and a huge area has been chosen in order to make a study of it in terms of the air flow. This area has been designed in accordance with regulations issued by the Department of Planning and Surveying. These regulations are:

- First two rows near the creek with height G+6
- The next rows with height G+4
- Keep 1.5 m from the neighbor site
- Use only 50% of the land

The study area is located in Ras Al Khaimah city, the capital of the emirate, in the area called Old Ras Al Khaimah. Ras Al Khaimah city itself is divided into two parts by a creek called *Khour* Ras Al Khaimah. Old Ras Al Khaimah is in the western part of the city while the eastern part is known as Al Nakheel. The two parts are connected by a large bridge built across Al Khour as shown in figure 1.

Figure 1: Map of study area in RAK (Google earth software, 2007)

The site chosen has an area of 376025 m^2 and overlooks Al-Quasim Corniche. The reason behind choosing this site is that it is located in the center of RAK city which is considered as the main developing area in the Emirate of RAK. Many high-rise buildings were constructed in this area according to the authority of RAK government. In addition, the area contains many buildings with different heights in the first two rows starting from 25 m up to 90 m. However, the second rows of buildings have heights around 15 m in tall as shown in figure 2. See also Appendix 1.3. Furthermore, figure 1 shows that there is a significant built up area between the site and the sea, the direction from which the main wind is coming.

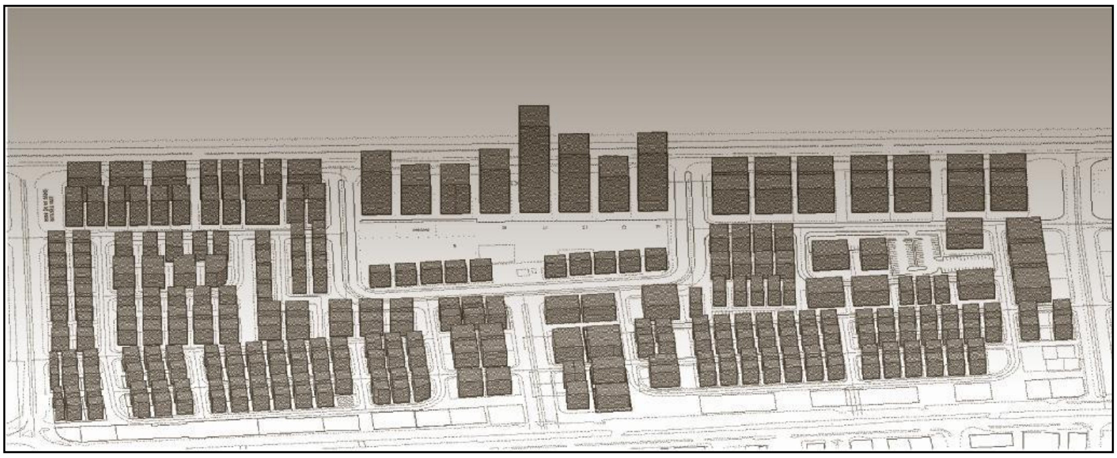


Figure 2: the study area map

The design of the study area is a large grid pattern, containing many small grids so there are many types of access. The size of the buildings is depending on the plot area. The distance between buildings is, generally, small. Also, the buildings are extremely close to each other as shown in figure 3. See also appendix 2.1

Figure 3: The study area

Additionally, the shapes of the buildings vary from square to rectangle and the general form of the study area is rectangular. The buildings proportion in the study area is divided into two types. The first one is length equals width while the second one is length equals double width so there are different types of building proportions. In addition, the height of the buildings varies in the first two rows while it is equal in the next rows. There are some buildings in the first two lines with a height of G+20. The study area consists of a large number of buildings with a height of G+4 and two lines of buildings with different heights from 25 m to 90 m see figure 4.

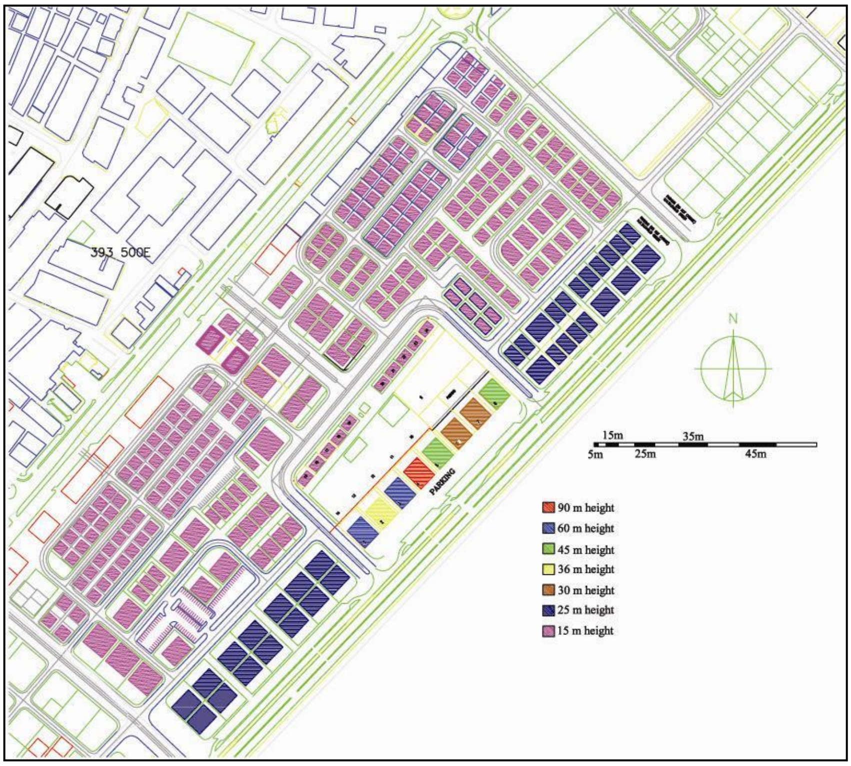


Figure 4: The study area location (Google earth software, 2007)

1.4 Identifying gaps in the source material

Some studies about natural ventilation by Muller et al. (2007) recommend solutions that suit cold area. This is not the case in the Arabian Gulf countries where the weather is extremely hot and humid. Furthermore, high buildings with high density reflect the contemporary life-style that contributes to the poor ventilation as they prevent deeper air penetration. The achievable density is largely dependent on the necessary distance between buildings and this is realized as an important variable in improving ventilation in urban design. Hence, this investigation aims to answer the following question:

"Which urban parameters can increase the flow of natural ventilation with the high density of buildings in the urban area in RAK?

1.5 Limitations

The analysis focuses on outdoor air quality. The heat islands effect is considered but it not the main concept from which to arrive to conclusions due to the complexity of measuring heat islands in the study area. The urban parameters are taken into account because of the effective role they play in improving natural ventilation.

Another important limitation is that there are not many studies that recommend solutions for improving natural ventilation in the Arabian Gulf. In addition, there is a lack of references related to the research topic in the UAE.

The simulation grid size is too large which results in having continuous errors, therefore the simulation is considered as time-consuming.

1.6 Structures of the thesis

Chapter II Gives general information about the study area and mentions the problems that are expected to occur in the study area.

Chapter III Contains a review of the literature and what researchers have said about natural ventilation and air quality. General characteristics of air flow, street canyon and heat island are also described.

Chapter IV Discusses the research methods which are experimental approach, Computational Fluid Dynamic and the case study with a focus on a model ENVI-met, of particular relevance in the framework of this study. Research instruments in accordance to the validity and reliability will also be mentioned in this chapter.

Chapter V Discusses the implementation of action and the process of using numerical simulation.

Chapter VI The results of the simulations by Envi-met software are discussed in this chapter, which summarizes the most significant findings related to airflow around buildings.

Chapter VII Discusses the research outcomes after modification some urban parameters.

Chapter 2

2.0 BACKGROUND

This literature discusses some points about air quality and natural ventilation. It provides a theoretical framework in understanding factors influencing air quality and natural ventilation of the study area. In this literature review, natural ventilation will be discussed in terms of the shape of buildings to find out which is more suitable for natural ventilation. The arrangement of buildings will also be pointed out in order to discover what type of buildings' arrangement can provide the maximum air flow to the downstream buildings. In addition, air pollution will be mentioned which is another factor that obstructs air quality. As a result of the important role that wind plays in improving natural ventilation, wind flow will be analyzed. Then wind flow will be examined in a street canyon and an urban environment as well as the effect of wind on pedestrians. Lastly, heat island will be identified and the cause and the treatment of urban heat island will be referred to.

Many researchers have pointed out to some themes that have been mentioned in this inquiry. However, there is no similar inquiry to this investigation that follows, more or less, the same simulation method. Most studies on natural ventilation have been done in western countries where the weather is cold; but there are few research document have been found that study natural ventilation in hot and humid climate such as (Chen, 2007). Thus, some adaptation has been made to the themes that refer to the current research subject, taking into account the study area. Furthermore, in this research some strategies will be evaluated in order to find out the suitable solution and put it into practice by using a simulation method.

2.1 Natural ventilation

Outdoor ventilation in urban areas is a sophisticated concept that concerns architects. Natural ventilation refers to the process of taking in and expelling fresh air by using natural means rather than by mechanical ventilation. There are two variables that control natural ventilation in buildings which are wind driven ventilation and stack ventilation. The pressures of the stack effect resulting from the air movement out of the building are considerably lower than wind pressure. Tablada (2006) states that these pressure differences are related to the two forces temperature difference between inside a building and outside, as well as thermal force and wind pressure as shown in figure 5.

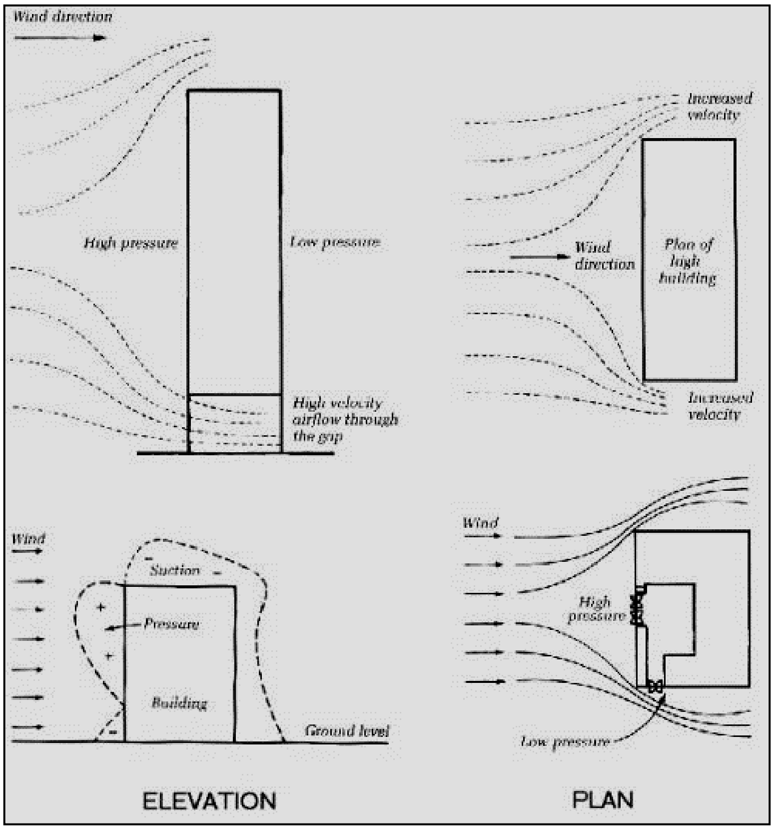
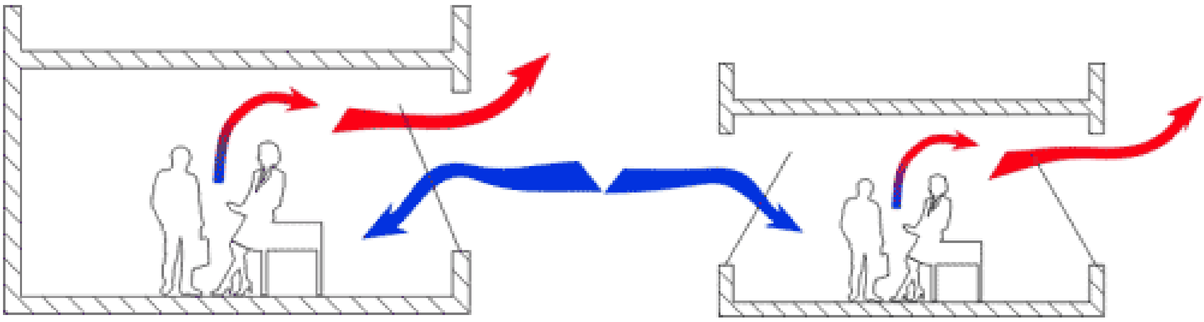


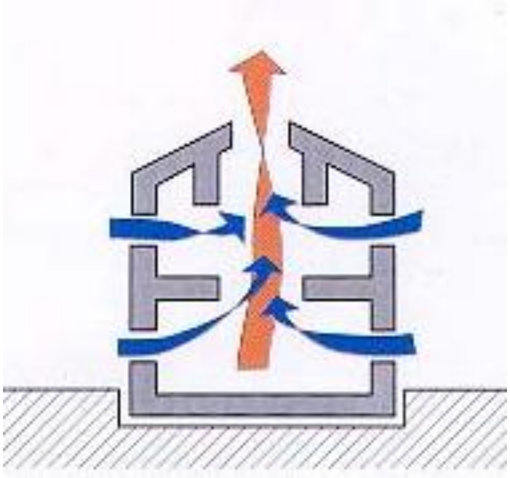
Figure 5: Wind pressure on the buildings (Cheung, 2001)

Modern buildings in the Arabian Gulf countries rely mostly on wind-driven ventilation as the main source of ventilation. Although, stack ventilation can improve the air temperature of the space and rise up the warmer and pollutant air to flow out of the buildings. See figure 6.



Single-sided ventilation

Cross ventilation



Stack ventilation

Figure 6: Natural ventilation types (University of Florida, 2008)

Researchers like Allard (1998) suggest that effective design for natural ventilation necessitates implementing both types of ventilation. This suggestion would be more appropriate in cold regions of the world since the weather is appropriate most time of the year. Furthermore, some authors discuss natural ventilation in office buildings for different environments and wind influences like Muller et al. (2007). However the wind pressure is neglected because Muller et al. (2007) does not consider the buildings envelope shape and the surroundings.

Emmanuel (2005) points out to the important variables in controlling ventilation in the urban areas which are built densities and heights. Usually poor ventilation system occurs on the account of high-density zones, and long walls of building fabric which prevent deeper penetration wind. For that reason wind turbulence characterizes the urban area clearly as compared to that in a rural area. Figure 7 illustrates clearly that high density zone and different height buildings characterize the study area in the current investigation.

Figure 7: High density and high-rise buildings in the study area

Givoni (1994) states that 'an urban profile of variable building height, where buildings of different heights are placed next to each other, and when the long facades of the buildings are oblique to the wind enhance urban ventilation'(Givoni, 1994 cited in Emmanuel, 2005, p.118).

2.2 Height of buildings

Allard (1998) points to logical consequences which are changing the height of a building while remaining the length and width the same will increase the depth of the downwind wake and leave the shape unchanged as shown in figure 8.

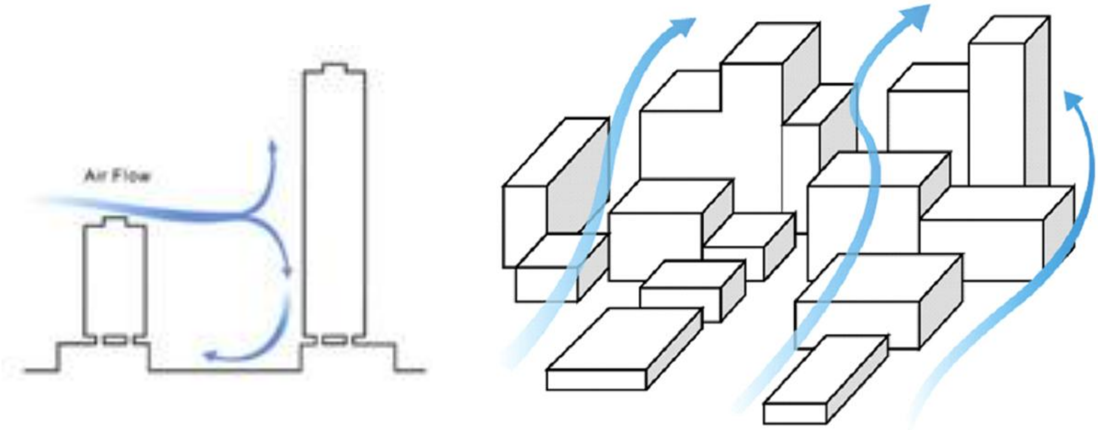


Figure 8: Air flow and buildings heights (Planning Department, 2006)

Changing the high of a building also resulted in unequally distribution of the airflow paths around and within the building. There is a direct proportion between the amount of air passing around the sides of the building and the amount of air traveling over it. According to Allard (1998), this causes less upward air movement through the openings placed on the lower two-thirds of the building windward façade; however, the top one-third of the building windward façade will face more upward airflow, regardless of the height of the building.

The wind velocity increases in proportion to the high of the building so wind velocity close to the earth's surface equals approximately zero and it increases with an increase in height. Allard (1998) maintains that the wind velocity increases at higher levels as well as the airflow rate through the windward openings of the top floors and higher suction at the side walls. As a consequence, 'the presence of one or a few tall buildings near a group of low-rise buildings results in high speed wind in the passages and streets around tall buildings' (Ahuja et al., 2006). In other words, the construction of tall buildings in a region of low-rise buildings changes the street level wind environment. The reasons behind this is that the air which hits tall building surface turns aside the ground sourcing high-wind velocity on the down-wind and near the corners of the buildings at street / pedestrian level as shown in figure 9.

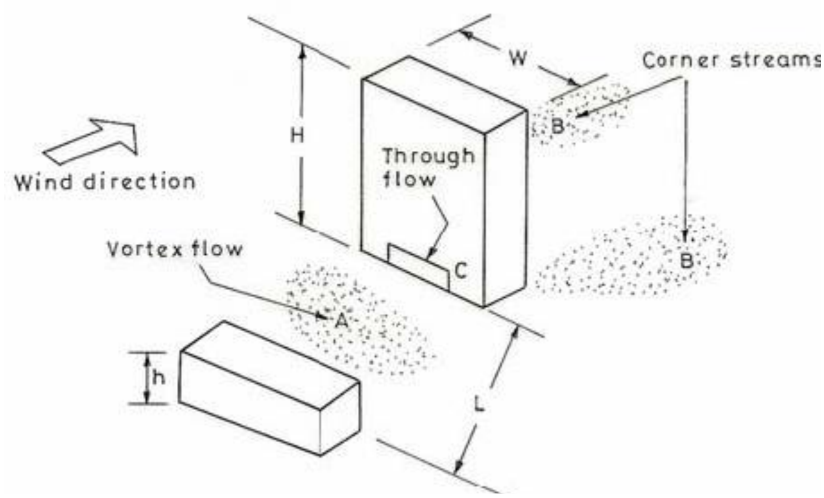


Figure 9:.high surface wind speeds around a tall building (Ahuja et al., 2006).

2.3 Shape of the buildings

The extent to which the shape of a building affects the performance of natural ventilation is a complex question that attracts the attention of many researchers. Taking into account the shape of the buildings is essential in order to obtain thermal comfort and natural ventilation. Srebric et al. (2001) simulated several rows of houses with two types of shapes square and rectangular to determine airflow and they found that square-shaped buildings are more suitable than rectangular-shaped buildings for natural ventilation. The reason for this is that rectangular-shaped buildings make the distance between the two buildings very small, which blocks the passage of wind. Thus, buildings with square shapes will give a higher air velocity at the space than rectangular buildings as shown in figure 10. Furthermore, Srebric et al. (2001) point to a logical consequence that was indicated by the site plan CFD results which is that wind speed on the first floor is higher than that on the second floor.

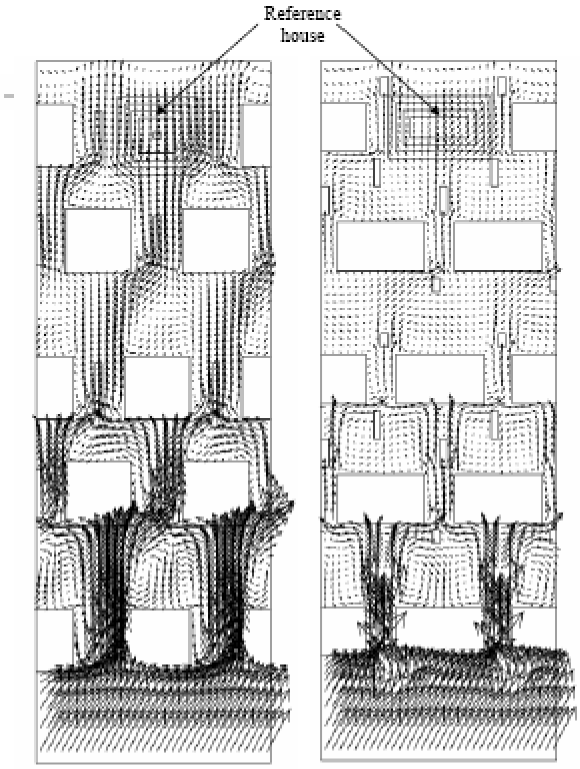


Figure 10: Plan view the airflow around the house (a) square shape and (b) rectangular shape Srebric et al., (2001)

The differences in the shape of buildings are essential to get a high performance of natural ventilation and. The shape of the building causes a positive pressure on the windward face of a building and negative pressure on the leeward and other faces of the building. Thus the building shape is vital in creating the wind pressures that will pass wind flow through its apertures. In other words, wind pressure will differ significantly, creating complex air flows and turbulence by their interaction with elements of the natural environment (trees, hills) and urban context (buildings, structures) See appendix 2.2.

2.4 Buildings pattern

Today's buildings and houses do not support the use of natural ventilation because most buildings with a typical area land have been designed to be aligned with the street grid. This makes the buildings upstream block wind from those downstream. In order to decrease the wind blockage by the buildings, they must be staggered to encourage natural ventilation. Linear alignments create a low-pressure area since a wind shadow is available at the back of each building. Srebric et al. (2001) believe that the effective arrangement is to 'stagger the buildings according to the prevailing wind direction'. This arrangement would decrease the wind shadow area at the back of each building and provide the maximum wind flow to the downstream buildings.

A stagger pattern layout is more suitable to an optimum use of air movement within the buildings than a grid pattern layout, because the configuration provides less sheltering from the wakes, and a similar effect can be also obtained with a grid pattern as shown in figure 11. (Allard, 1998, p.198) indicates that 'a building should be designed to be high enough to overcome the wind sheltering obstructions, subject to considerations related to other requirements and building regulations'. Allard's proposal will be appropriate when the density and configuration of the surrounding buildings do not allow for a proper wind exposure.

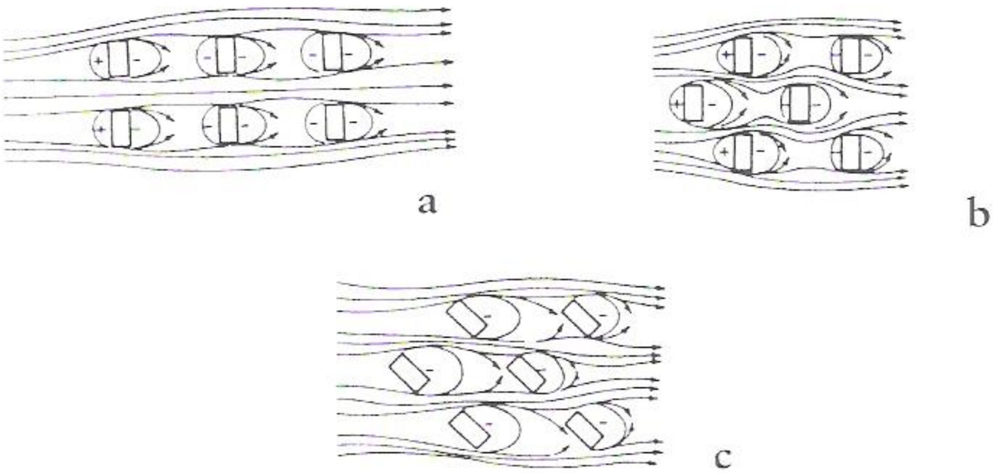


Figure 11: Airflow patterns through (a) a normal, (B) a scattered and (C) a diagonal layout of buildings (Allard, 1998, p.198)

2.5 Wind pressure

Wind has an obvious influence on natural ventilation. Wind produces air flows inside buildings as a result of high and low pressures on buildings of different sides. These movements are strongly dependent on the air flow around buildings. (Allard, 1998, p. 27) believe that 'wind causes surface pressures that vary around buildings, changing intake and exhaust system flow rates, natural ventilation, infiltration and exfiltration, and interior pressure'. The main flow patterns and wind turbulence moving over a building can even result in recirculation of exhaust gases to air intake (Moeseke et al., 2005).

2.6 Air Regimes

Moeseke et al. (2005) advocate that there are three types of air flows that may take place in the built environment when taking into account street canyons with perpendicular wind. 'Isolated roughness flow' and 'wake interference flow' transpire as the wake is entirely or partly developed in function of relative distance between buildings, while ' skimming' flow regime takes place where the bulk of flow does not go through the canyon and stable vortexes appear in the canyon (See figure 12). However, a passage between wake interference and isolated roughness flow happens when street width equals around 1.5 building heights (Moeseke et al., 2005).

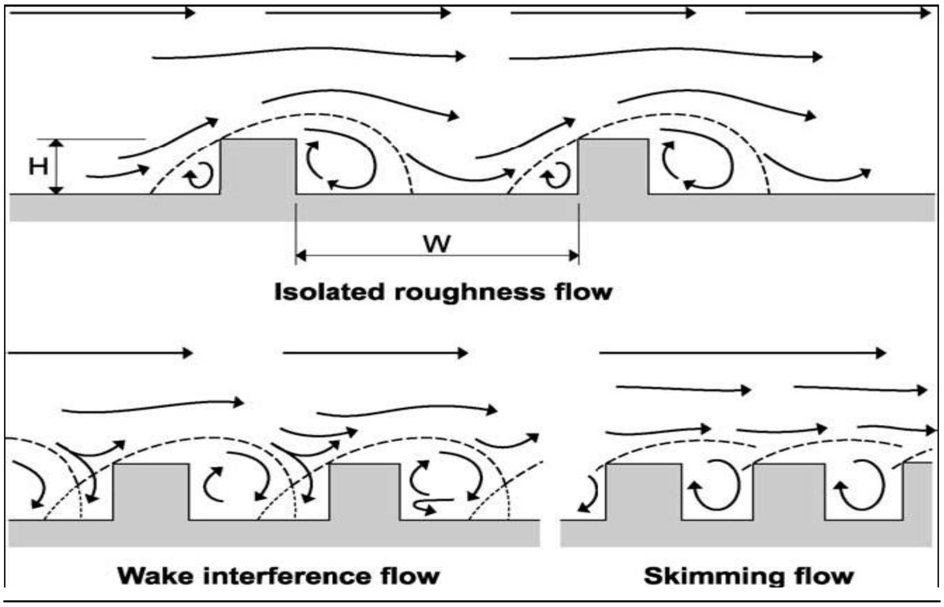


Figure 12: Wind flow regimes (Moeseke et al., 2005)

Sensitive urban planning measures could utilize these wind-flow patterns through promoting deep wind penetration into cities. In urban area, wind speed is reduced considerably while its turbulence (i-e. speed variation) rises even within a short distance. This is because of the occurrence of several barriers that increase the roughness of the ground as compared to a rural area and thereby raises the effect of friction on the airflow. This is clearly presented by Giridharan & Ganesan (2004) via numerical data. They find that for moderate to strong winds and for a height of 20 m above the ground, a drop of 20% to 30% in the average air speed results when moving from a rural area into an urban one. Buildings in urban area that are rigid sharp-angled bodies distributed along streets cause the wind speeds to slow down, but simultaneously the turbulence of the flow is greatly improved (Emmanuel, 2006, p.116). (Santamouris, 2001, p. 33) finds out that 'the flow in the urban areas is rarely centripetal, because the irregularity of the urban area and the differences with the surroundings prevent such a flow' as shown on figure 13.

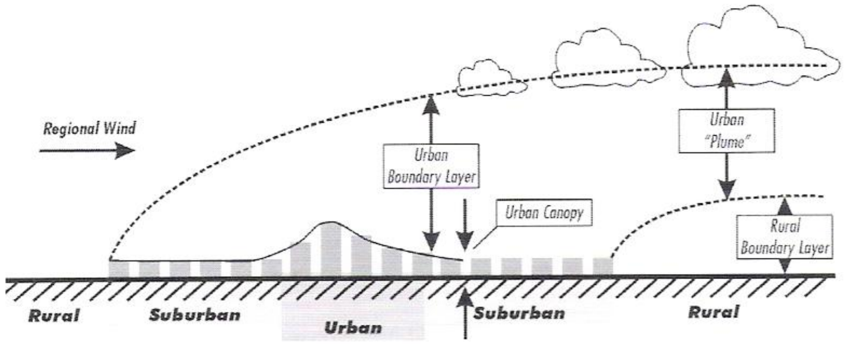


Figure 13: The urban canopy and boundary layer over cities (Santamouris, 2001, p.33)

The temperature in the urban environment is not stable which leads to short bursts of wind from the countryside to the urban area. The same findings have been reported by Giridharan & Ganesan (2004) that is the 'air converges at the center of the city under the impact of the pressure gradient induced by the horizontal temperature difference'. Thus, the continuity of the flow creates an upward movement of air which stops at a given height.

2.7 Street Canyon

Emmanuel (2005) defines urban canyon as an urban area that is characterized by the three-dimensional space bordered by a street, surrounding by buildings. In other words, the term street canyon can be identified as a relatively narrow street with buildings aligned continuously along both sides. Conversely, street canyon can also refer to larger streets which are known as avenue canyons. Furthermore, the term street canyon has been expanded to include urban streets which is not necessary has aligned by buildings on their sides (Vardoulakis et al., 2003).

Concern about attaining the maximum environmental benefits by optimizing the layout of the urban street canyon has become a contemporary concept for modern urban design and planning.

Urban canyons are characterized by the parameters shown in Figure 14:

1. The mean height of the buildings in the canyon (H)
2. The canyon width (W)
3. The canyon length (L).

The *aspect ratio* (H/W), i.e. the ratio of the average height (H) of buildings and the width of a street (W), is a significant geometrical feature that affects the flow structure between the buildings.

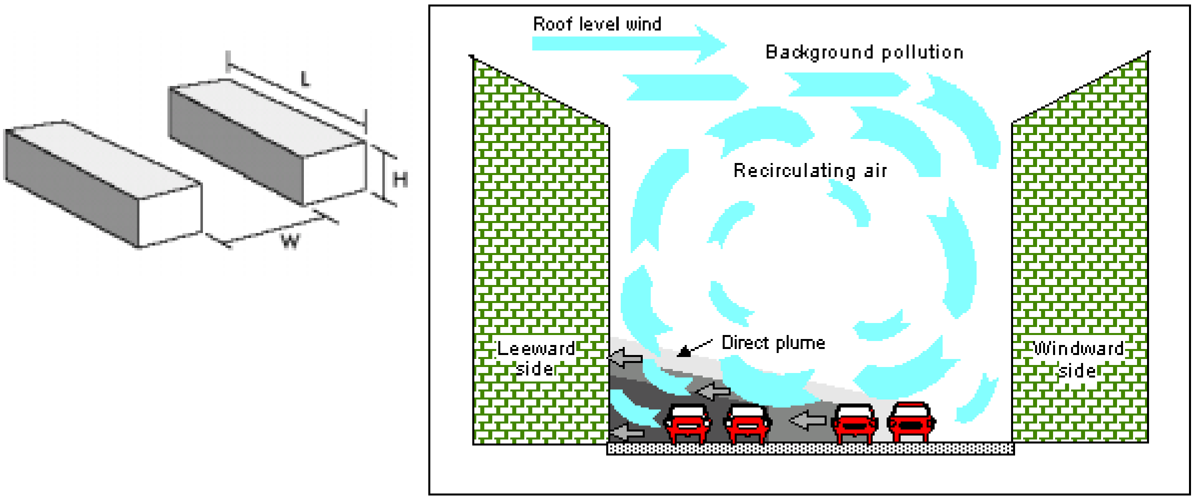


Figure 14: Street canyon (Friends of Environment, n.d.)

Street canyon characteristics are clarified by Vardoulakis et al., (2003):

> *The dimensions of a street canyon are usually expressed by its aspect ratio, which is the height (H) of the canyon divided by the width (W). A canyon might be called regular, if it has an aspect ratio of approximately equal to 1 and no major openings on the walls. An avenue canyon may have an aspect ratio below 0.5, while a value of 2 maybe representative of a deep canyon. Finally, the length (L) of the canyon usually expresses the road distance between two major intersections, subdividing street canyons into short (L/H=3) medium (L/H=5) and long canyons (L/H=7). Urban streets might be also classified in symmetric (or even) canyons, if the buildings flanking the street have approximately the same height, or asymmetric which there are significant differences in building height.*

Street canyon causes multiple reflection of solar radiation, restricts the view of the sky dome (characterized by the sky view factor SVF) and generally limits the free movement of air (Harman et al., 2004). For long urban canyons aspect ratio - that is the height of building/width of street (H: W) - have been used customarily in order to identify the geometry (Emmanuel, 2005, p.23). Wind flow in street canyons, wind vertical and wind parallel to the canyon alignment or undisturbed wind have been studied by many investigators.

2.8 Wind speed in street canyon

Most designers attempt to explain the air motion inside the urban layout. They usually begin their design of air motion at city level, particularly in its street layout pattern. (Emmanuel, 2005, p. 118) argues that 'streets should be aligned to obtain the maximum benefit from macro-level wind directions'. In other words, this would usually mean aligning the streets according to the main wind directions. Although a city street layout parallel to the major wind directions will be useful at the urban scale, it can cause wind flow problems at a building scale, Givoni (1994) indicates that the street layout should be at an oblique angle (between 30 and 60 degrees) to the prevailing winds (Givoni, 1994 cited in Emmanuel, 2005, p.118). See figure 15.

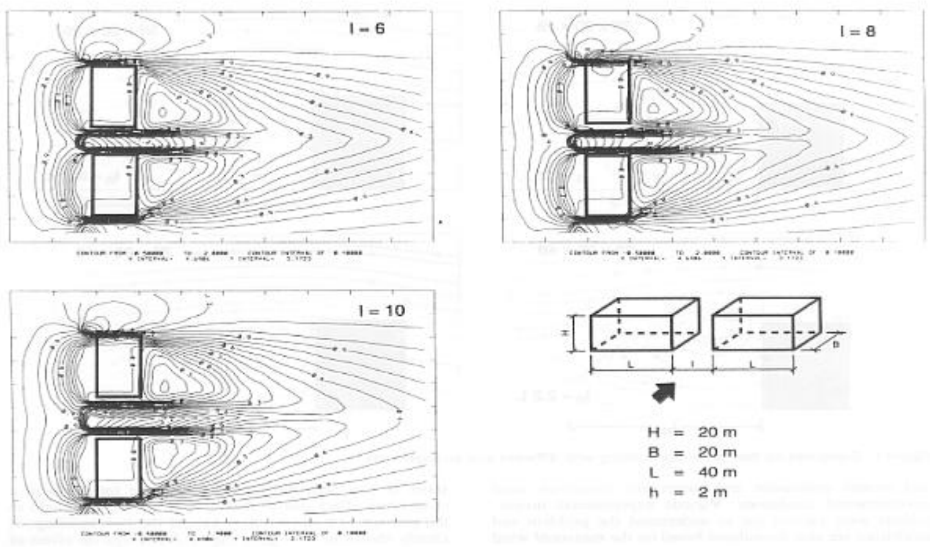


Figure 15: Street canyon and air flow (Baskaran & Kashef, 1996)

The wind speed in street canyons has a lower value than undisturbed wind. The results of investigations by Ghiausa et al. (2006) show that when the undisturbed airflow has values larger than 2–4 m/s, a connection exists between undisturbed wind and the wind in the street canyons. When a 2 m/s or stronger wind blows perpendicular to a street canyon, a vortex results in the canyon. If the wind is parallel to the canyon axis, the vertical speed in the canyon is very low. When the airflow speed is lower than 4 m/s, the temperature measured inside the canyon streets is about 5 C lower than that of the canopy layer as shown in figure 16.

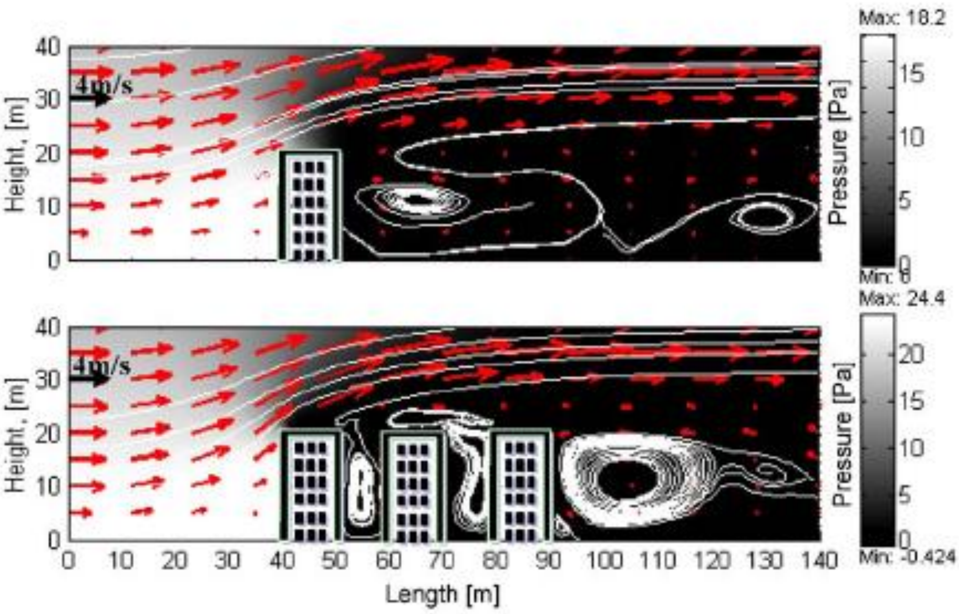


Figure 16: Wind velocity and wind-induced pressure are reduced in urban environment (Ghiausa et al., 2006)

Also Giridharan & Ganesan (2004) point to a similar result which is weak winds are 5% to 20% more frequent in a city than in the countryside. However, the wind velocity is higher in the centre than in the periphery of the city when the wind velocities are less than a threshold of 4 m/s. Therefore, in the case of weak wind, Emmanuel (2005) suggests to utilize the thermal differences that take place at the edges of water bodies in order to induce wind flow.

2.9 Air Pollution

The air flow, and therefore the air pollution are influenced by the street geometry, climate characteristics, and traffic-produced turbulence because street canyon builds up pollutants between the buildings. For example vehicle exhaust fumes cannot easily disperse and thus prevent wind penetration into the street canyon as shown in figure17.

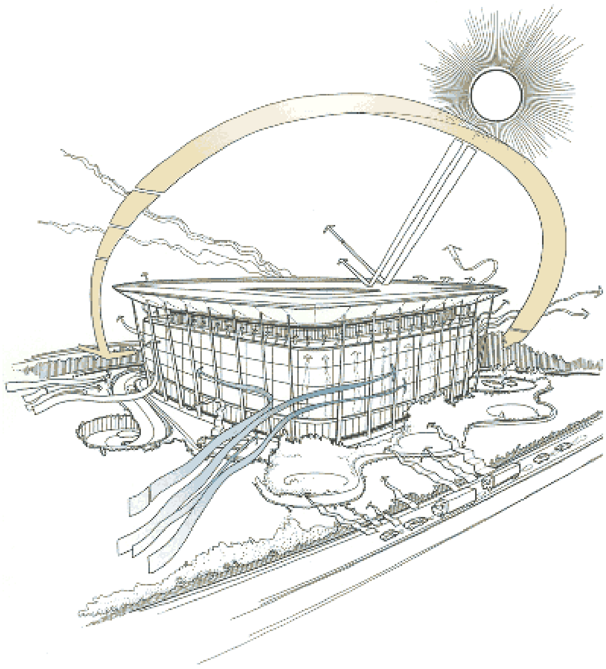


Figure 17: Air pollution source around buildings (Carthy, n.d.)

Outdoor air pollution is a great obstacle to natural ventilation for the reason that filters can not be utilized as in mechanical ventilation system. In other words, air pollution trapped in open spaces makes these spaces unhealthy and thereby make natural ventilation of indoors less desirable. Outdoor air pollution may affect the indoor air quality via exchanging the air and taking in the air pollutant. According to Ghiaus, et al. (2005), 'The facade air tightness, as a characteristic of the building, represents a key factor in this relation because it is the main link between the indoor and outdoor environments, being at the same time an important characteristic of the natural ventilation property of the building'. In other words, indoor pollutant concentration depends on the outdoor absorption of the pollutant as the air tightness link between the indoor and outdoor. Furthermore, different building arrangements and the spacing between the buildings have a major effect on air pollution concentrations. Wind tunnel experiments by Theurer (1999) indicate that 'dispersion depends much on the angle between the orientation of the buildings and the approach flow direction'. Furthermore a study by Flassak et al. (1996) shows that the number of vehicles and the composition of a car fleet have a greater effect on the pollution concentration than the building parameters (Flassak et al., 1996 cited in Theurer, 1999).

2.10 Pedestrian level wind flow

High wind speed and outdoor air pollution have a great influence on the pedestrian comfort. Comfort or discomfort is an abstract phenomenon. There is no exact definition of comfort or discomfort level as they depend on many factors such as age, sex, type of activity, and psychological state. Hence, temperature, wind speed and humidity conditions are very subjective terms which may comfort some people and simultaneously discomfort others. In other words, under the same conditions, some people may feel quite comfortable whereas other may complain. According to Ahuja et al. (2006), it is not only a particular value of wind speed, which may cause discomfort, but there are other parameters which altogether affect comfort and they include gustiness, duration, and wind speed. An air velocity (V) above 8 m/s is seen as uncomfortable air velocity. Wind speed above 10 m/s causes unpleasantness while a speed above 20 m/s is considered to be hazardous. See appendix 3.1. For that reason information on the wind flow field is crucial for the evaluation of counter measures to improve the current comfort condition.

2.11 Heat- islands

Heat islands rise when natural ground is replaced by buildings that catch the arriving solar radiation throughout the day and then re-radiate it at night. This slows the cooling procedure, consequently maintaining nighttime air temperatures higher than the temperatures in suburban areas (William, et al., 2004). This phenomenon is called the heat island effect which is an increase of temperatures in an urban area to more than the temperatures in surrounding suburban and rural areas as shown in figure 18. Ghiausa et al. (2006) share the same view that is 'temperature in urban areas is higher than in rural surroundings thus affecting the potential for stack effect. Tamura & Wilson (1968) indicates that stack action occur as result of pressure difference that depends on the building height and the difference between temperatures inside and outside building. However, the shadow and the thermal inertia of buildings partly balance the urban heat island effect.

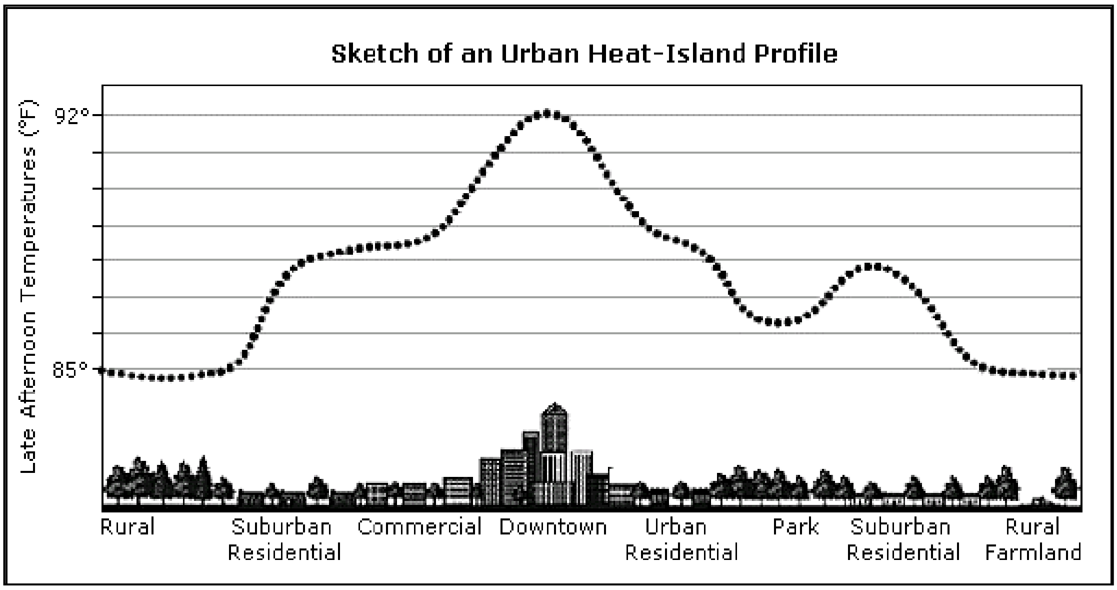


Figure 18: Sketch of a heat island profile (Giridharan & Ganesan, 2004)

Heat islands were first noticed by meteorologists more than a century ago and they are the most obvious climatic sign of urbanization. Emmanuel (2005) portrays that heat islands have been observed in practically all parts of the world except in the Polar Regions. The effect of UHIs is related to summer temperatures in urban areas as they are higher than in rural surroundings (Allard, 1998, p.22). Therefore, a higher urban temperature increases the demand of the electricity in urban area on account of its importance for the air conditioning of buildings. In addition, it increases the emission of pollutants such as sulpur dioxide, carbon monoxide, nitrous oxides and suspended particulates via smog production and power plants (Santamouris, 2001, p.48). It is influenced by many factors including climate, topography, physical layout and short-term weather conditions (Allard, 1998, p.22). (Emmanuel, 2005, p. 22) indicates that 'a heat island is best visualized as a dome of stagnant warm air over the heavily built-up areas of cities'. Heat islands are extreme at night, taking place a few hours after sunset. This has far-reaching implications for urban design in the tropics where night-time them stress is relatively low. The heat island power is relative to the degree of urbanization. Giridharan & Ganesan (2004) argue that the UHI worsens both indoor and outdoor thermal discomfort and enlarge the space conditioning energy consumption.

2.12 Causes of UHI

Giridharan & Ganesan (2004) have found that heat island effect is influenced by the following physical properties and phenomena in an urban environment:

- Canyon radioactive geometry.
- Thermal properties of material.
- Anthropogenic heat.
- The urban green house effect.
- Reduction of albedo by canyon geometry.
- Reduction in evaporating surface.
- Reduced turbulence transfer.
- Manmade factors or the *design variables* that contribute to the above physical properties and phenomena are:
- Urban structure.
- Size of the city, population and density of built-up area.
- Ratio of the height of buildings to the distance between them.
- Width of the streets.
- Building materials.
- Surface materials.
- Sky view factor.

Oke (1987) has effectively associated height to width ratio (canyon geometry) and sky view factor to UHI. In addition, Knowles (1977) has recognized that 'thermal mass of the built environment is a function of height to floor area ratio of the built environment' (Oke, 1987 & Knowles, 1977, cited in Giridharan & Ganesan, 2004). Thus, height to floor area ratio have an effect on the UHI. From previous discussion, it can be argued that urban heat island may transpire in R.A.K city, particularly in the study area on account of the occurrence of some factors that cause heat island. These factors are size of the city, population and density of built-up area, ratio of the height of buildings to the distance between them, width of the streets.

2.13 Heat- island parametric models

Heat island studies are principally intended towards an understanding of the role of the indispensable parameters influencing the temperature increase in cities. Studies have emphasized the role of city size and population, weather conditions such as cloud cover, wind speed humidity, urban canyon characteristics, etc.

There is a relationship between heat island intensity with the size of the urban population. Oke (1988) found that heat-island intensity for North American cities is greater than European cities. The reason behind this as clarified by Oke (1988) is that North American cities have higher-rise buildings and higher densities than typical European cities (Oke, 1988 cited in Santamouris, 2001). Figure 19 demonstrates that RAK city has a similar situation to American cities in which both of them have high-rise buildings and high densities. In the study area, there are eight high-rise buildings in one row of plots with 260 m in length and around 8 m between buildings.

Figure 19: The study area with high rise buildings and high density

2.14 Treatment

The previous discussion shows that improving the ventilation condition of urban spaces, taking the pollutants produced by forms of transport (cars, lorries etc.) away from the street canyons and treatment the UHIs requires the following

- Taking control of the urban parameters such as changing the proportions of buildings (length and width), choosing another type of urban pattern, modifying the height of buildings, using different shapes for buildings or adjusting the width of street canyon.
- Considering the main climate characteristics and the irregular layout before the stage of street or urban planning. Architects can rely on the main wind direction as the real wind direction is always variable.
- In all conditions, there must be a street aspect ratio (H/W) of less than 3, if possible much lower in order to avoid having tall buildings beside narrow streets with busy traffic. According to Allard (1998), the ratio of the length to the width should be not too high in order to avoid a significant decrease in the

pressure in the middle of the windward façade with possible suction effects at the edges. (p.22) see figure 20.

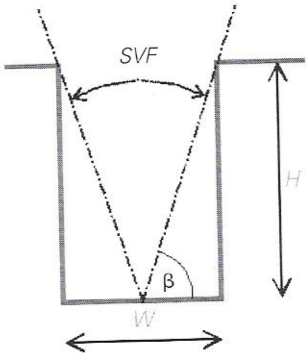


Figure 20: Street canyon geometry (Emmanuel, 2005, p.23)

- The flanking buildings should not be continuous and uniform to allow gaps in the building geometry in order to improve ventilation as shown in figure 21.
- Garden plots can be constructed to attain better effects.

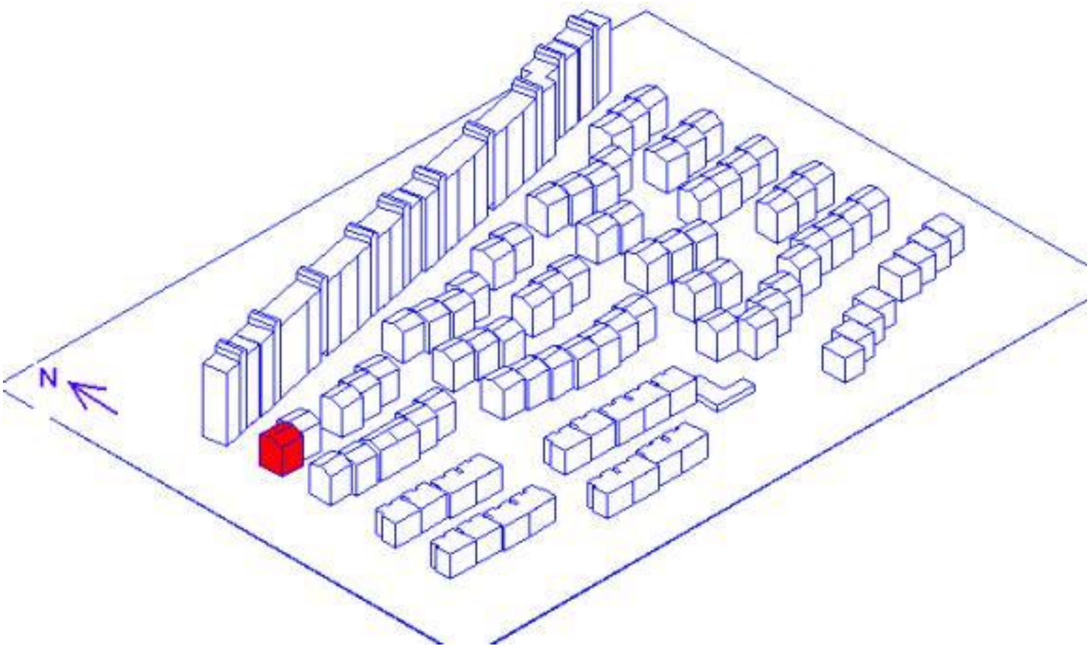


Figure 21: Poor ventilation with this type of flanking building geometry (Chen, 2007).

Strategic planting of deciduous trees at urban exposures can considerably decrease the effect of urban heat island. Miller (1988) suggests that trees affect urban microclimates on two levels which are human comfort and building energy budget (Miller, 1988 cited in Emmanuel, 2005, p. 88). William et al. (2004) take Miller's (1988) point but they assert that 'the effectiveness of trees as a cooling element is limited under conditions of heightened humidity because the rates of evaporation transpiration drop by ~50% '. Improvement potential in a city is hindered significantly by paving over traditional street tree planting sites. As a consequence, the number of sites to plant trees on city blocks is very few (William et al., 2004). Planting trees is an inexpensive strategy to have a noticeable impact on the quality of life.

2.15 Conclusions of chapter 2

In this chapter, a review of literature has been summarized on the fields of natural ventilation, buildings arrangement, air pollution, the shape of the buildings, wind pressure, air regimes, street canyons, wind in street canyons, , pedestrian level wind flow, heat-islands, heat-island parametric models, causes of UHIs, treatment of UHIs. Some final remarks are given below:

- The particular design details of the buildings and the streets, the height of the buildings related to one another, and the direction of the buildings with respect to the wind, seriously influence the actual wind flow inside the urban canopy layer.
- Several studies have recently shown that improving ventilation necessitates architects to be aware of the following:
    - Location of a town within a region,
    - The overall density of the urban area
    - The particular design details of the buildings and the streets
    - Orientation and width of streets
    - The height of the buildings related to one another
    - The direction of the buildings with respect to the wind
    - Availability, size and distribution of open areas and green belts

Chapter 3

3.0 REASEARCH METHODOLOGY

Different research problems demand different research approaches. There are two types of research methods which are quantitative and qualitative research. Quantitative research is ‘based on testing a theory composed of variables, measured with numbers and analyzed using statistical techniques' (Dobbin & Gatowski, 1999). By contrast, qualitative approach aims to understand the situation from multiple perspectives in order to get a holistic picture of the situation. Laboratory approach, measurement tools are not used in the current investigation since the simulation, experimental approach and case study are more suitable for measuring airflow around the buildings.

3.1 Laboratory approach

Laboratory approach provides highly controlled conditions for test and measurement. The laboratory offers a greater reliability and comparable results through controlling over the variables. Cause and- effect relationship can be easily accomplished via isolating a factor of a complex system. It is commonly used in order to choose between options for components. On the other hand, there are some disadvantages of the laboratory approach such as isolating a component of complex system is not always efficient because sometimes the whole system is more than a collocation of component. In addition, any problem in the test facility may affect the reliability of the results. Furthermore, it is not appropriate for analyzing large real scale outdoor. Therefore laboratory approach is not suitable for the current investigation because the aim of the investigation is to analyze the outdoor airflow in the high density zone.

Wind tunnel tests may offer more relevant results for the reason that changes in building shapes or patterns can be made simply. Design team can use a wind tunnel to simulate and calculate the airflow around buildings and an environmental chamber to determine natural ventilation. Furthermore, this tool enables the study of a specific so as to examine diverse hypothesis. However, the disadvantage of wind tunnels is the shortage of tunnels large enough for investigation on urban models.

3.2 Measurement tools

Measurement tools such as real scale measurement, parametrical models and field measurement are the preferred techniques used by many researchers. Real scale measurements are the most accurate tool on account of their giving an exact concept of pressures on a particular building in a specific environment. However, they provide less efficient results about a particular building's shape and especially about a unique environment (Moeseke et al., 2005). Another negative aspect of real scale measurements are related to time and cost limitations.

As wind tunnel tests are impractical, expensive and time-consuming, parametrical models are a solution to promote natural ventilation particularly for architects who are unable to afford expensive or technical scientific work. These models offer relationships between some factors in order to evaluate wind speed. However, Moeseke et al. (2005) find that the results produced by wind tunnels are more reliable than those of parametrical models.

The field measurement is used to collect hourly climatic data in different periods around the year in the real field of the study area. Furthermore, this measurement can examine the effect of various parameters on the outdoor air quality. However, this type of measurements takes a long time test period that largely exceeds the scope of this master thesis see figure 22.

Surface Stations

Canyon masts

Figure 22: The instrument that is used to measure the urban heat island (Eliasson et al., 2006)

3.3 Experimental approach:

Experimental approach is the main research method used in this study. It is "an attempt by the researcher to maintain control over all factors that may affect the result of an experiment". In doing this, the researcher attempts to determine or predict what may occur. In this investigation, an evaluation of the outdoor air flow between buildings in the urban area will be conducted. Experimental design is a plan of the procedure that enables testing the hypothesis by reaching valid conclusions about relationships between independent and dependent variables. It involves two alternative scenario of increasing outdoor airflow between buildings in the study area in R.A.K. The first scenario, involve evaluating the current situation of the study area in terms of the airflow movement around the buildings. The second scenario, involve determining solutions by taking control over the urban parameters which can increase the air flow around the buildings.

This experimental research involves observing the effect of the manipulation of the independent variable on the dependent variable. Furthermore, an attempt will be made to control all other variables except the dependent variable constant. For this investigation, the independent variables are the urban parameters such as building proportion, width of street canyon, the high and the shape of the buildings. Dependant variables are wind speed and wind direction. It can be argued that the experimental research is valid in terms of the ability to generalize the effect of the factors.

The methodology used to evaluate the second scenario described above consists of two overall steps:

1. Using the Envi-met software to simulate both cases in order to analyze the affect of changing the urban parameters on increasing the wind speed and direction

2. Comparing the results of the first scenario and the second scenario to be able to make recommendations regarding natural ventilation and pedestrian comforts.

3.4 Numerical simulation

Simulation research is 'characterized by the generation of data, in a propositional form, that can be returned to the real-world context for its benefit' (Groat & Wang, 2002, 275). It demands controlled replication of real-world situation or events in order to examine the dynamic interactions within that situation.

Computational fluid dynamics (CFD) technique is a type of simulation that was used in this research to calculate the airflow distributions in and around a building. CFD modeling is a general term used to 'describe the analysis of systems involving fluid flow, heat transfer and structured around numerical algorithms that can tackle fluid flow problems' (Vardoulakis et al., 2003).

Vardoulakis et al. (2003) indicates that CFD modeling is a powerful technique that deals with complicated shaped walls and other surrounding situations. CFD technique has been effectively used to calculate airflow in and around buildings, even though it necessitates a considerable amount of computing time.

As there is nowadays rapid progress in computer speed and capacity, the CFD technique appears to be a good approach and is therefore used in the current investigation.

3.5 Envi-met software

In this investigation, Envi-met software will be used to simulate the study area. According to Chen (2007), ENVI-met is a three-dimensional model that is able to calculate different processes in, at and between different urban elements with a high resolution. The major advantage of ENVI-met is that it is one of the first models that seeks to 'reproduce the major processes in the atmosphere that affect the microclimate on a well-founded physical basis such as the fundamental laws of fluid dynamics and thermodynamics' (Toudert, 2005). According to the objectives of the present study, ENVI-met presents several advantages:

1. Simulating the urban areas with daily changes and operating wind speed, wind direction and wind pressure.
2. Presenting a complex urban area with buildings of different forms and sizes.
3. Providing a high resolution of the time and place which allows a fine reading of the microclimatic changes by concentrating on the urban geometry.

4. Requiring a small amount of input parameters and providing a large number of outputs.
5. Calculating many variables of output.

After the Envi-met software was used to simulate the study area in order to check airflow around the buildings, any problem that might occur in the current situation is going to be analyzed. Finally, certain strategies will be followed to improve the air quality of this area.

3.6 Case study

In this investigation, a certain area in R.A.K has been chosen as a case study in order to find out a solution for a particular problem which is improving the airflow as a factor influencing air quality and natural ventilation in high density areas. The main purpose of choosing a case study method is to concentrate on an area with high-rise buildings to apply the appropriate strategies for improving air quality which depend on the natural setting of this city. A case study has many advantages such as its applicability to real-life and contemporary human situations and its public accessibility through written reports. Case study results relate directly to the ordinary reader's everyday experience and facilitate an understanding of complex real-life situations.

The case study is complex because it involves multiple sources of data such as landscaping, climatic data, population, land use, topographic, high, shape, materials and arrangement of the buildings. Therefore, it produces large amounts of data for analysis.

Data gathered is normally largely qualitative, but it is also quantitative when the climatic data and urban area measurement were taken in consideration. Furthermore, data gathered from the simulation was analyzed in terms of describing a value that relates to an urban area such as airflow. In addition, according to the findings, the relationship between urban form and air quality can be assumed. Data gathered from the case study will include the following:

1. A reliable work for improving the air quality in a selected city.
2. The micro-climate for the location of the case study to calculate the airflow.

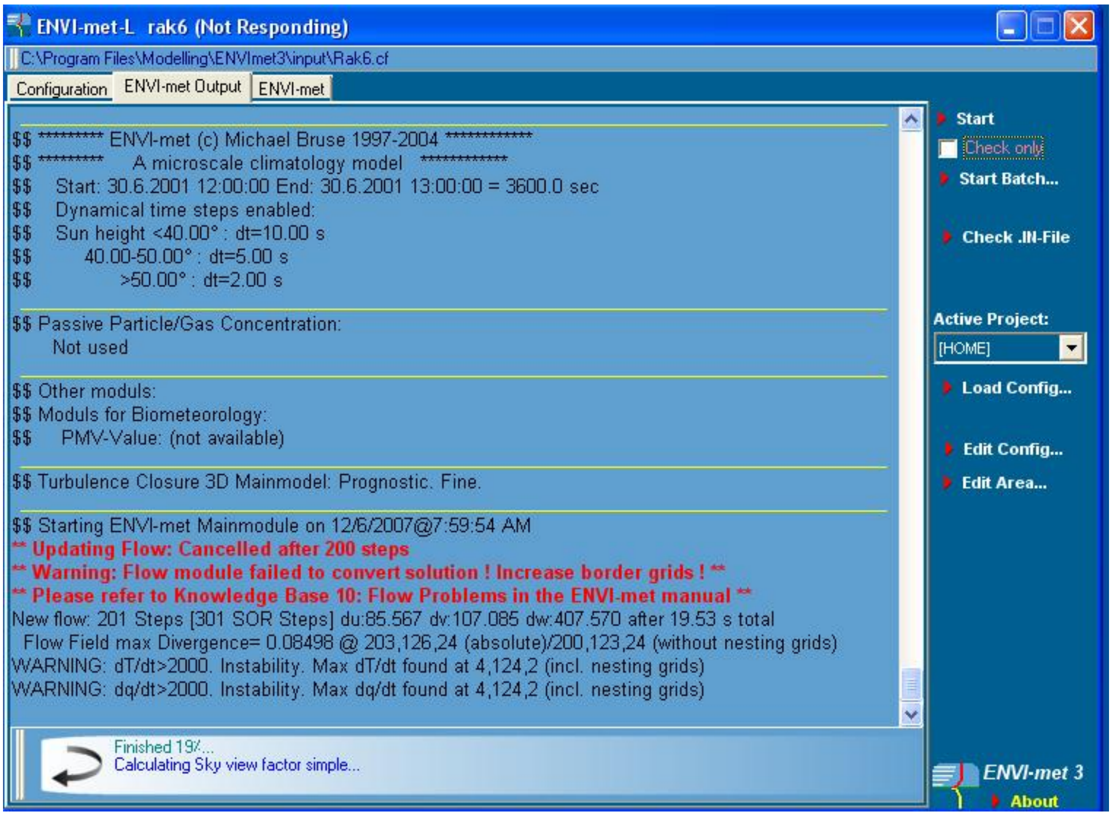
3.7 Validity& Reliability

Validity can be defined as the degree to which a test measures what it is supposed to measure. There are two basic approaches to the validity of the experimental approach: these are internal validity, and external validity.

- Internal Validity: asks if the experimental treatment make the difference in this specific instance rather than other extraneous variables. This is depends on the quality of numerical simulations which is based on extremely accurate input data (Moeseke et al., 2005).

A serious of errors in simulation stage occurred due to the large size of the site of the study area as compared to the maximum size of the Envi-met software grid. As a consequence a lot of modification was necessary and a lot of time was consumed in order to reach to the current model as shown in figure 23.

On the other hand, the output of the simulation is similar to what has been expected, in addition, the changes that have been made to the variables treated the target problem which is increasing the airflow around the buildings, particularly the modification of the buildings proportion (length and width) and changing the width of street canyon.



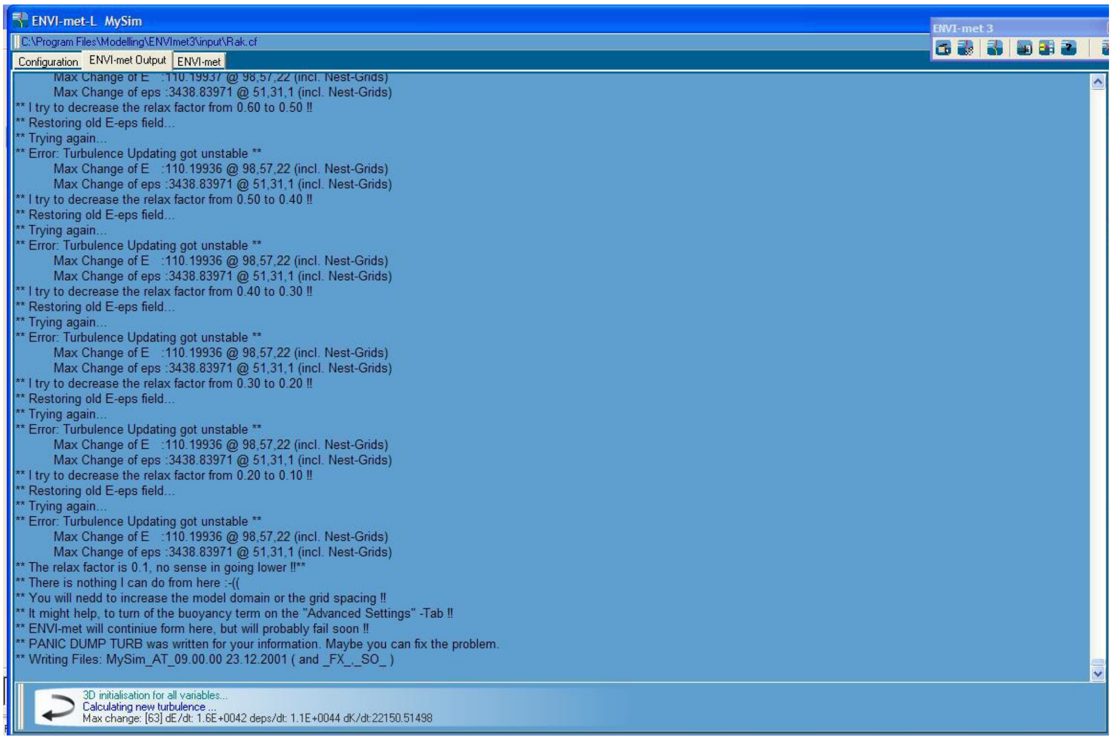


Figure 23: The errors message in simulation stage

- External Validity: asks to what extent that the populations, settings, treatment variables, and measurement variables can be generalized.

Aiming for studying the entire of the study area and the effect of the surroundings on each other, the resolution of the output map is not high as the size of the study area is too large. Furthermore, as the simulation takes a long time, few times were only taken on account of the time available for this investigation. The time to simulate one hour needs 24 hours in reality. Simulated one hour in reality takes approximately seven hours computation time and thereby it would be complex to simulate twenty-four hours.

According to Key (1997), the reliability of a research instrument 'concerns the extent to which the instrument yields the same results on repeated trials'. Simulation results are not reliable to some extend since the input data are not accurate 100%, particularly the buildings and landscaping dimensions. In addition, the available computer power is small for high simulation accuracy.

Although unreliability is always present to some extent, there is a good deal of reliability in the data gathered by means of repeated measurement. The simulation was repeated many times in different hours in order to maintain accuracy. As in the findings stage, the simulation was repeated seventeenth time in different hours in a day. The modification stage was repeated three times in different hours of each parameter and the results are the same. According to Key (1997), 'The tendency toward consistency found in repeated measurements is referred to as 'reliability'.

Chapter 4

4.0 IMPLEMENTATION OF ACTION

In this part of the work, the field experiment being simulated will be described. The Envi-met software was used to simulate the field experiment conducted in RAK city in the UAE in June 2006. After initializing the design, the CFD technique was used to calculate the airflow in and around the buildings. Based on the calculated results, the designs were modified. Several alterations will be necessary until a satisfactory outdoor air quality for the building is achieved. In order to provide an easy user-access, Chen (2007) states that most commercial CFD packages include the sophisticated input and output interfaces. They contain three main elements:

i. The pre-processor, which serves to input problem parameters at the ENVI-met editor, make the grid of the computational domain, decide on the physical phenomena that need to be treated such as air pollution, identify the fluid flow properties, and finally define the appropriate boundary conditions such as wind turbulence.
ii. The processor, which first estimates numerically the unknown flow variables, then simulate the input area air flow using the ENVI-met default configuration, and finally get the output file with the results.
iii. The postprocessor, which demonstrates the grid of the domain, plots vectors such as wind velocity and contours such as pollutant concentration by LEONARDO software.

The purpose of the simulation is to evaluate the air flow around the buildings in the study area using the Envi-met software. The simulation by CFD package includes the following input parameters:

The site was chosen with an area of 376025 m^2 that overviews on Al- Quasim Cornish. It is located in the center of RAK city which is considered as the main developing area in RAK Emirate. The area contains many buildings with heights in the first two lines ranging from 25 m to 90 m. The second rows of buildings have heights a round 15 m as shown in figure 24.

The model of the study area provides various types of one input such as: wind direction, orientation, air temperature, relative humidity and the surrounding areas such as: water surface, green areas, urban areas, open areas. The study area includes some landscaping features such as asphalt, sandy soil and pavement. All the above data were input in Envi-met software in their exact places.

Figure 24: The study area

The design of the study area is a large grid pattern, containing many smaller grids so there are many types of access. The size of the buildings differs depending on the plot area. Additionally, the shapes of the buildings vary from square to rectangle. The general shape of the study area is rectangular as shown in figure 24. The proportion of the buildings in the study area is divided into two types. The first type is length equals width while the second one is length equals double the width. In addition, the proportion with the height of the buildings varies in the first two rows while it is equal in the next rows.

The second parameter is the weather data of RAK city which is indispensable in attaining a precise result. The third parameter is the different distances between the buildings that also need to be indicated in order to get more accurate result. This parameter depends on the nature of the study area for the existing buildings as well as for the proposed buildings. This parameter has a strong effect on the air quality as shown in figure 24.

The above parameters were carefully selected, as well as the phenomena that need to be treated: for example, the discomforts of pedestrian level wind flow, heat islands, air pollution and the poor air quality and natural ventilation. This would help in defining the passivism in the study area and applying the appropriate strategies to solve this passivism. The properties of the flow are velocity, pressure, density, and temperature. The velocity of the air flow in the case study is 4.3 m/s and the mean air temperature is 26.55 C^{o}. The air flow boundary conditions such as objects, time, geographical location, surface orientation and air temperature are very important in achieving accurate simulation.

The study area has a grid arrangement. The benefit of this arrangement comes from the possibility of modeling a wide range of the building arrangements through changing the height of the building or the distances between the buildings. An equally important benefit is the accessibility of the measured wind velocities around the buildings for the normal arrangement. Another important input is selecting the size of the computational domain to form such a configuration which mainly relies on the expected air flow patterns and wakes around the buildings under examination. The size of the computational domain grid is 220 X 120. Air flow, in turn, depends on the size of the buildings and local land configuration. Researchers have indicated that 'the size of the domain as a multiple of building dimensions, taking into consideration that the rise in the domain not only increases the number of grid nodes but also demands more CPU time'(Baskaran & Kashef, 1996). Therefore, the size of the domain must be selected so that a certain level of precision is maintained.

4.1 Simulation procedures of existing situation:

Depending on the Envi-met software, the study area was modeled in the actual setting. The buildings with different heights, sizes and shapes were also modeled. The actual places of each building were located. After that, the landscaping tools (soil, trees, pavement, asphalt and water) were situated in their places. See appendix 4.1. Configuration files were be prepared using the following data: see appendix 4.2

Start Simulation at Day (DD.MM.YYYY):	=30.6.2001
Start Simulation at Time (HH:MM:SS):	=12:00:00
Total Simulation Time in Hours:	=3.00
Wind Speed in 10 m ab. Ground [m/s]	= 4.3
Wind Direction (0:N..90:E..180:S..270:W..)	=315
Initial Temperature Atmosphere [K]	=293
Relative Humidity in 2m [%]	=72%

Checking the file by using the Envi-met default configuration window is the next step in checking the simulation process. This step is a pre simulation step. See appendix 4.3. After that, the simulation was started to get an output file with the wind flow patterns. The duration of each simulation was about 24 hours depending on extract and the required data from the output file and displays it in the form of maps. Then, Leonardo software was used to get the final output. This software explains the different wind velocities, air flow patterns and air behavior. See appendix 4.4

Chapter 5

5.0 FINDINGS AND ANLAYSIS OF CURRENT SITUATION

In this chapter, the results of the simulations by Envi-met software are discussed. It summarizes the most significant findings related to wind speed, air pollution, poor natural ventilation and discomfort pedestrian level wind flow. This chapter is divided into four zones which are illustrated in figure 25. First zone expresses the area with different wind speed**.** The second zone defines the air pollution as a result of high-density of built up area which reduces the airflow in the space between the buildings. The third zone defines poor natural ventilation because of the dense of the buildings which affect the speed of the airflow. Also, some buildings block the air to reach to the other buildings. On the other hand, the perpendicular of air flows in the street canyon decrease the wind speed. Finally, the last zone discusses the pedestrian level wind flow.

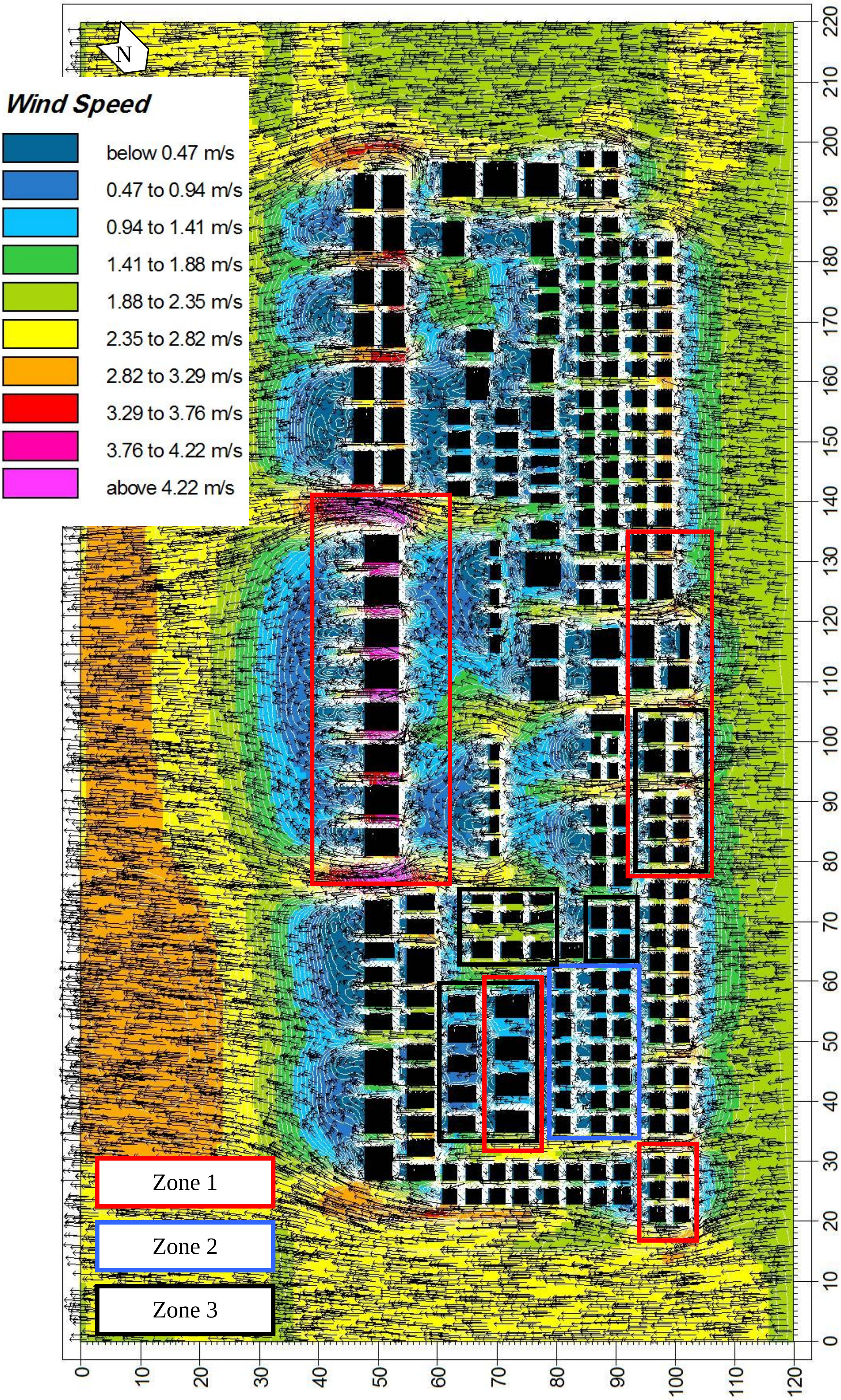


Figure 25: Output simulation file z=0 m at 20:00:00

5.1 Zone 1 problem: <u>Wind speed</u>

In zone 1, different wind speed can be analyzed in the study area. Wind speed has a considerable effect on air pollution and weather turbulence. At the same time, wind speed can effectively drive the air flow through the openings of the buildings in zone1.

From figure 25, it will be noticed that the blue color with below 0.47 m/s and high dense of contour lines which define law wind speed. This type of problem occurs between the buildings as there is a small distance between them.

In some places, the row of buildings prevents the flow of the airflow into other buildings. Airflow behavior depends on the local flow between the buildings and obstacles. Flow direction and velocity are a result of interaction of the outer flow and the type and arrangement of the buildings in their surroundings

This type of air flow does not have a strong effect on the buildings and the pedestrians for the reasons that the maximum wind velocity around the year is approximately 4.3 m/s. This finding supports what Giridharan & Ganesan (2004) maintain which is that weak winds are 5% to 20% more frequent in a city than in the countryside. On the other hand, it can be seen that there is a high wind speed on the corner of some buildings as shown in figure 26. This type of speed may be inconvenient for pedestrians as mentioned by Ahuja et al., (2006). The wind which hits the surface of tall buildings touches the ground causing high velocity winds on the windward side and near the corners of the buildings at street / pedestrian level.

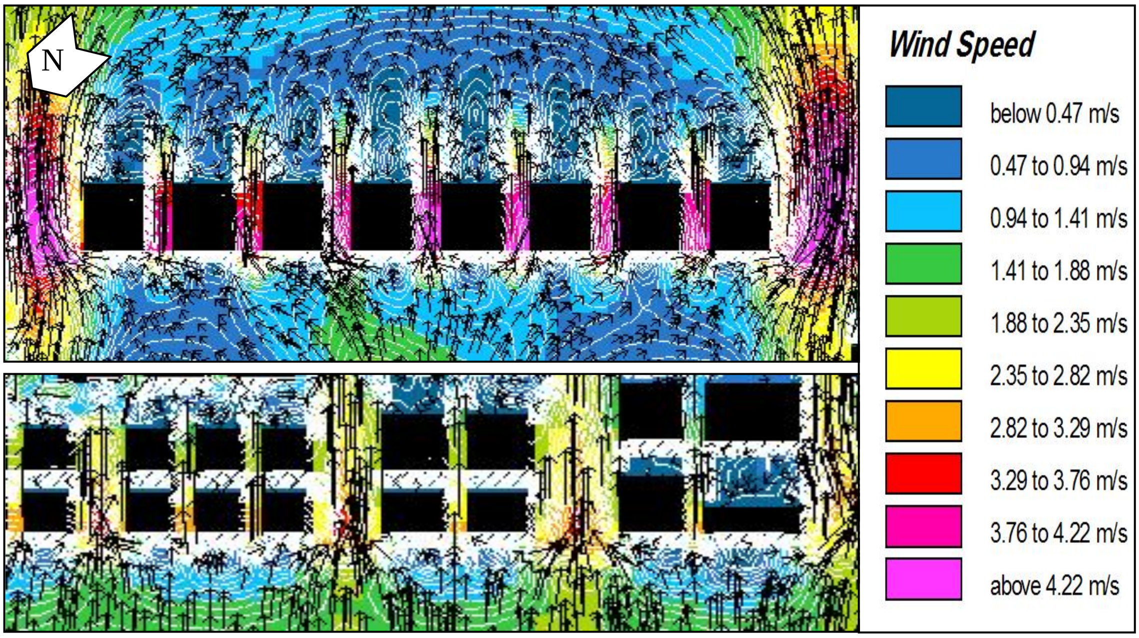


Figure 26: Wind speed in the existing situation

Wind flow parallel to the long facade causes almost low wind speed on both the opposite long facades of the buildings as shown on the map in figure 27.

Figure 27: Low wind speed parallel to the long façades

The patterns of the wind speed distribution were unequal for the reason that almost all buildings are long flat-faced. Fluctuations in the wind speed values can be seen noticeably in the map as shown in figure 28.

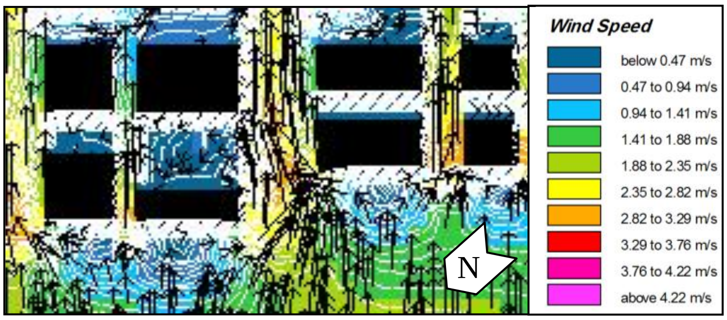


Figure 28: Unequal wind speed on the flat-faced

The differences in wind speed are found to be capable of generating a good cross-flow of air. Figure 29 show the wind speed produces difference airflow across the windward and leeward facades.

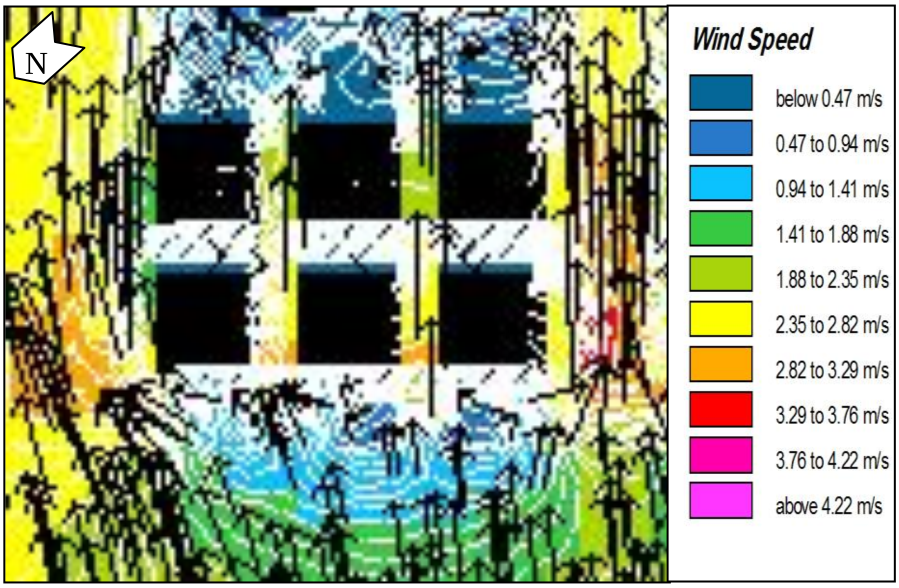


Figure 29: Wind speed difference across the windward and leeward facades

5.2 Zone 2 problem: Air pollution

The windward façade of the buildings block the airflow from other buildings. The lower wind speed in this zone prevents getting rid of existing air pollution, for the reason that the air in these areas can not be refreshed since there is a lack of air motion. There are many causes of air pollution in these areas such as smoke sources and mechanism equipments outlets. A study by Flassak et al. (1996), shows that the number of vehicles and the composition of a car fleet have a greater effect on the pollution concentration than the building parameters (Flassak et al., 1996 cited in Theurer, 1999).

This type of problem can be seen marked in blue and dark blue on the map as shown in figure 25 with wind speed ranging from 0.47 to 1.41 m/s. High density zones reduces the flow of air between the buildings. This may clarify the reason behind selecting these areas as air polluted areas.

According to the literature review, air pollution transpires in these areas on account of high-density zones, and long walls of building fabric which prevent deeper penetration of wind as can be noticed on the map in figure 25. Another equally important reason for selecting these areas as air polluted areas is that the configuration of buildings does not allow gaps in the building geometry and, as a consequence, it prevents airflow around the buildings. The map as shown in figure 30 illustrates that the flanking of buildings is continuous and uniform which reduces the airflow in the space between the buildings.

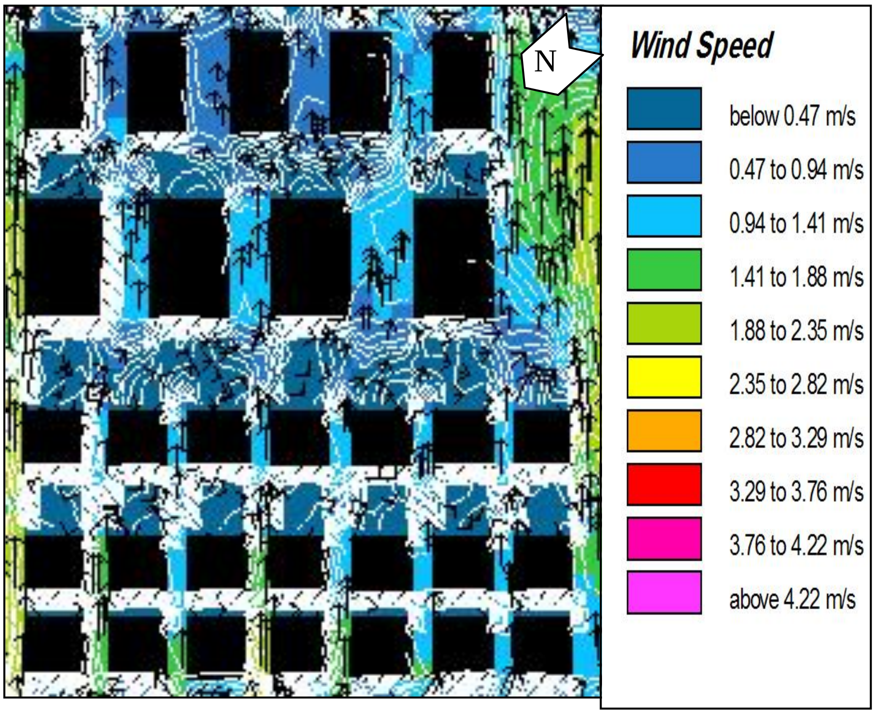


Figure30: High-density zones reduces the airflow in the space between the buildings

5.3 Zone 3: Poor natural ventilation

The airflow around the buildings is weak in some areas and this problem has a great effect on the natural ventilation in the buildings. Some buildings have good natural ventilation in some elevations while other buildings have poor ventilation. This phenomenon is marked in blue and dark blue on the map as shown in figure 25. Wind velocity measurement ranges from 0.47 m/s to 1.41 m/s.

The narrow spacing between the buildings has a significant impact on the microclimate of the study area. Narrowly spaced buildings will shelter each other from the wind. Hence, the spaces between the buildings, as well as the buildings themselves, will have poor natural ventilation as shown in figure 25. The map illustrates the vital features of natural ventilation that help to drive the ventilation to the buildings. The blue areas as shown in figure 31 show how airflow is utilized to drive the ventilation by wind speed.

Figure 31: Drive the ventilation by wind speed

A variety of wind speeds occur on the building façade causing wind driven ventilation. These wind speed differences force the air into the buildings through the openings of the building facade on the windward side and expel polluted air out of the buildings through the openings of the building facades on the leeward side. Green and yellow color (from 1.88 to 2.82 m/s) as shown in figure 32 represent the ventilation principle utilized to take advantage of the natural driving forces to ventilate a space. This can be done by single-sided ventilation, cross ventilation, or stack ventilation.

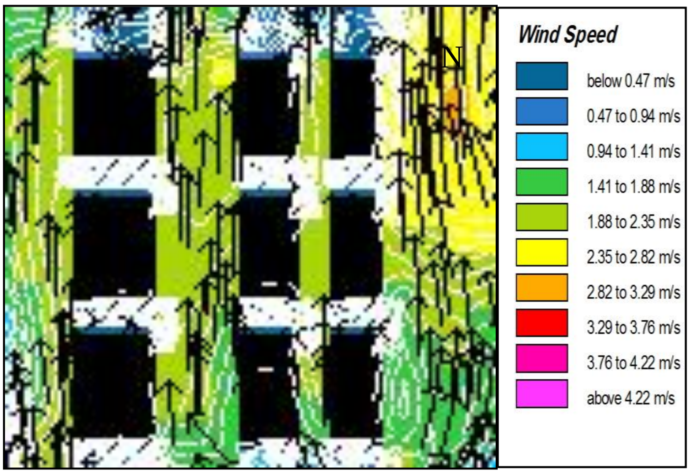


Figure 32: Natural driving forces to ventilate buildings

A maximum airflow comes from the northwest direction. Envi-met results show a more sophisticated pattern with airflow flowing through the whole building from downward wind depression parts to upward wind strong depression parts. This flow emerges on each side, leaving weak ventilated parts on the middle part of the building.

The airflow velocity in the canyon is strongly related to its aspect ratio and the wind velocity above the canyon. Orange color as shown in figure 33 demonstrates that some places have good ventilation as the wind velocity above the canyon ranges from 2.82 - 3.29 m/s and nearly parallel to the canyon axis.

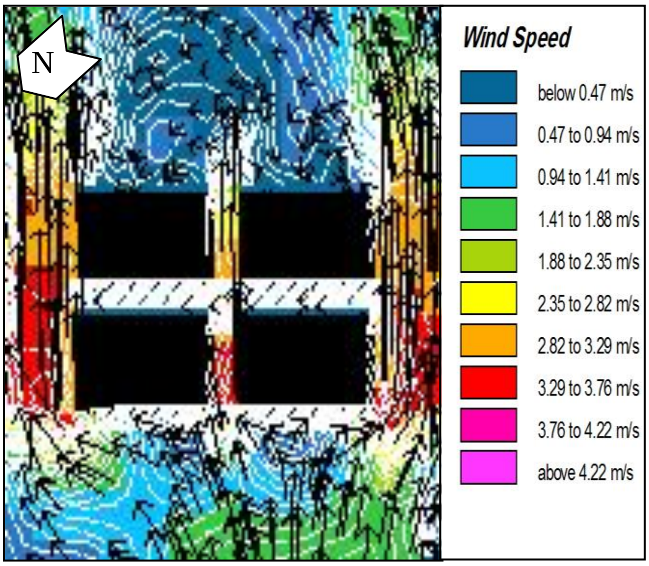


Figure 33: Good ventilation parallel to the canyon axis

This is in sharp contrast to what appears in blue and dark blue areas as shown in figure 25. It illustrates weak ventilation as the wind speed parallel the street canyon is 1.41 and below m/s. A vortex phenomenon appears which causes poor air exchange when the wind speed perpendicular to the canyon axis as shown in figure 34.

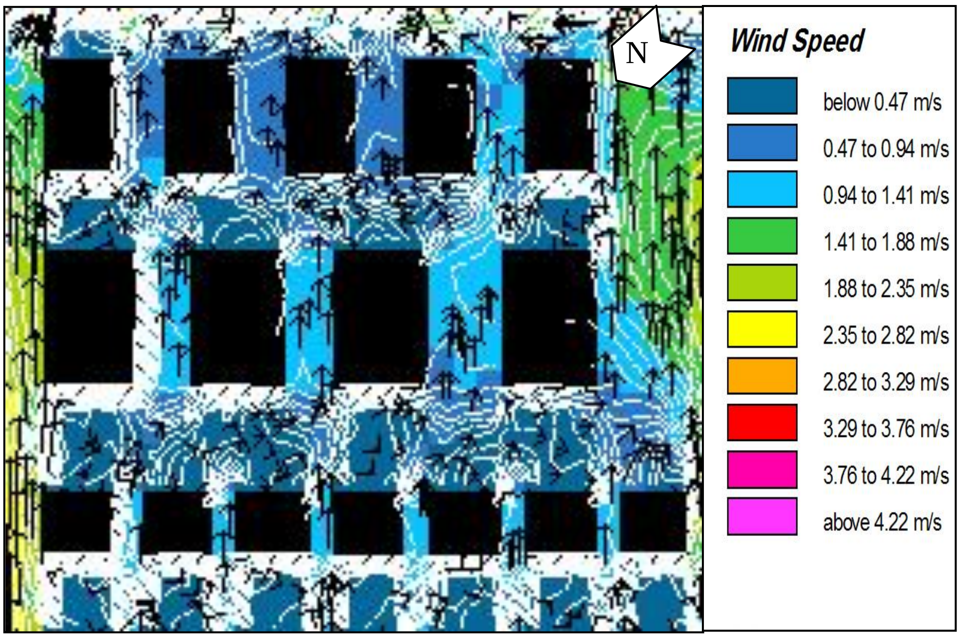


Figure 34: Weak ventilation perpendicular to the canyon axis

5.4 Zone 4: <u>Pedestrian level wind flow</u>

From table 2 below, and as shown in figure 25, it can be seen that the discomfort caused by pedestrian level wind flow does not appear to be a serious problem in the study area for the reason that the maximum value of wind speed measurement in the study area is in the range of pink and dark pink areas from 3.76 m/s and above. According to the table below, this value of wind speed causes a gentle breeze. This type of wind does not have a serious effect on the pedestrians due to the limited effect of a slight breeze wind on extending a light flag. A gentle breeze in the study area is suitable for human beings, but high speed winds such as gales and cyclones are not.

Table 2. Summary of wind effects (Ahuja et al., 2006)

Description of wind effects	(m/sec)	Description of wind Speed
No noticeable wind.	0.4-1.5	Light airs
Wind felt on face	1.6-3.3	Light breeze
Wind extends light flag.	3.4-5.4	Gentle breeze

According to the literature review, Ahuja et al. (2006) believe that it is not only a particular value of wind speed, which may cause discomfort, but there are other parameters which altogether affect comfort such as gustiness and duration of wind. The actual effect of the wind on pedestrians in the study area is very subjective, depending on many factors such as age, sex, type of activity, and psychological state.

Another important case is the presence of high rise buildings beside low-rise buildings which causes uncomfortable wind conditions around high rise buildings. This leads to discomfort for the pedestrian but comfort or discomfort are abstract phenomena and there is no exact definition of comfort or discomfort level. Hence, temperature, wind speed and humidity conditions are very subjective terms which may comfort some people and simultaneously discomfort others.

Chapter 6

6.0 URBAN PARAMETERS

Analyzing the findings involves answering the research question which is, how can we increase the performance of natural ventilation in the case of high density of buildings in the urban area in RAK? Based on the summary of the Envi-met simulation outcomes, three significant themes emerge which is air pollution, weak natural ventilation and wind speed.

Based on the above themes, this chapter tries to find some solutions in order to improve the outdoor air quality in the study area by controlling the urban parameters in the study area. These parameters include the following:

- Changing buildings proportion (length and width)
- Choosing other types of urban layouts
- Modifying the height of buildings
- Constructing buildings of different shapes
- Adjusting the width of the street canyon

6.1 Modification of simulation procedures

To change the parameters, the design of the input file was modified and then the same procedure was used in order to simulate the new situation. As done previously, the same Envi-met default configuration window was utilized in the simulation process. After that, the simulation was started to get an output file with the wind flow patterns. This step took a long time in view of the configuration file data and the size of domain. Then, Leonardo software was used to get the final output that includes the wind velocities, air flow patterns and air behavior. The input file was redesigned to change the parameters. This change involved the width and length of the buildings, the width of street canyon, urban pattern types and the height and the shape of the buildings.

6.2 Changing buildings proportion and adjusting the width of street canyon:

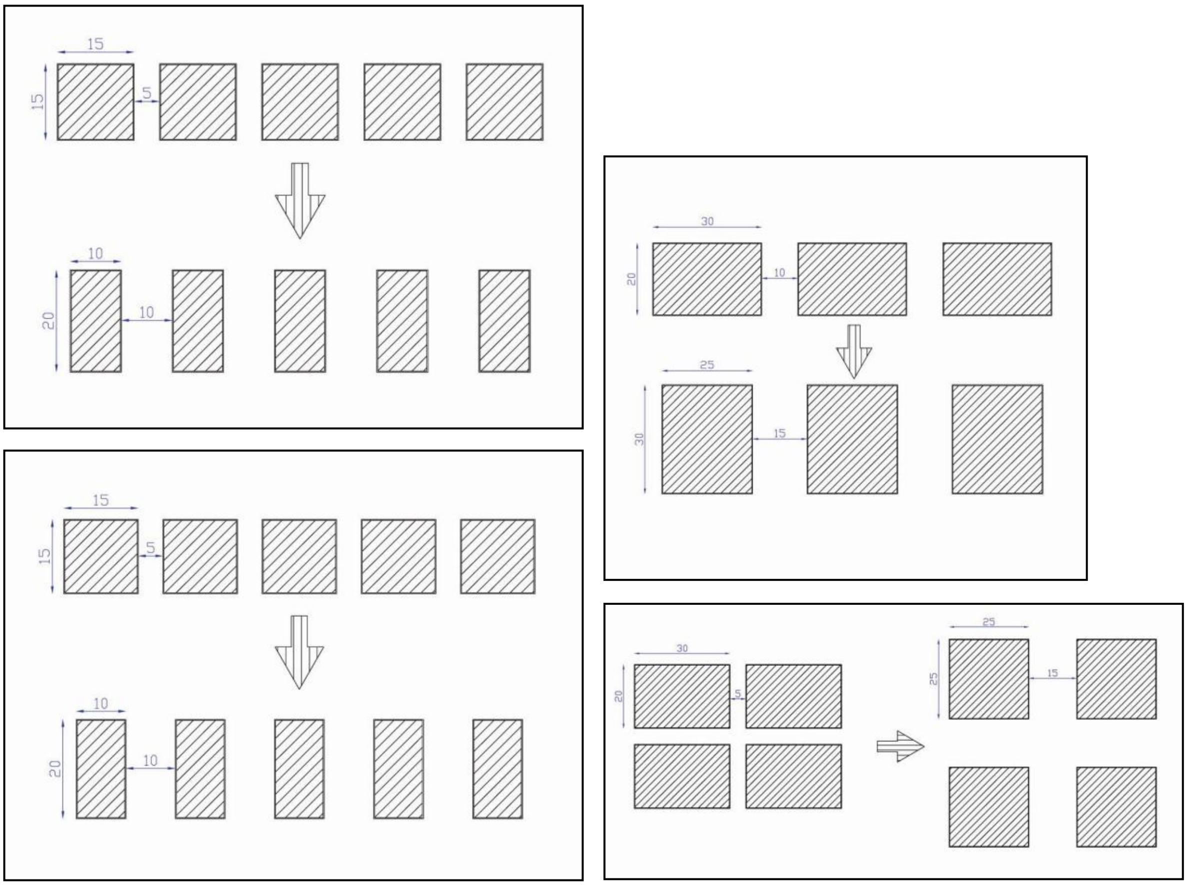


Figure 35: Changing buildings proportion in the study area

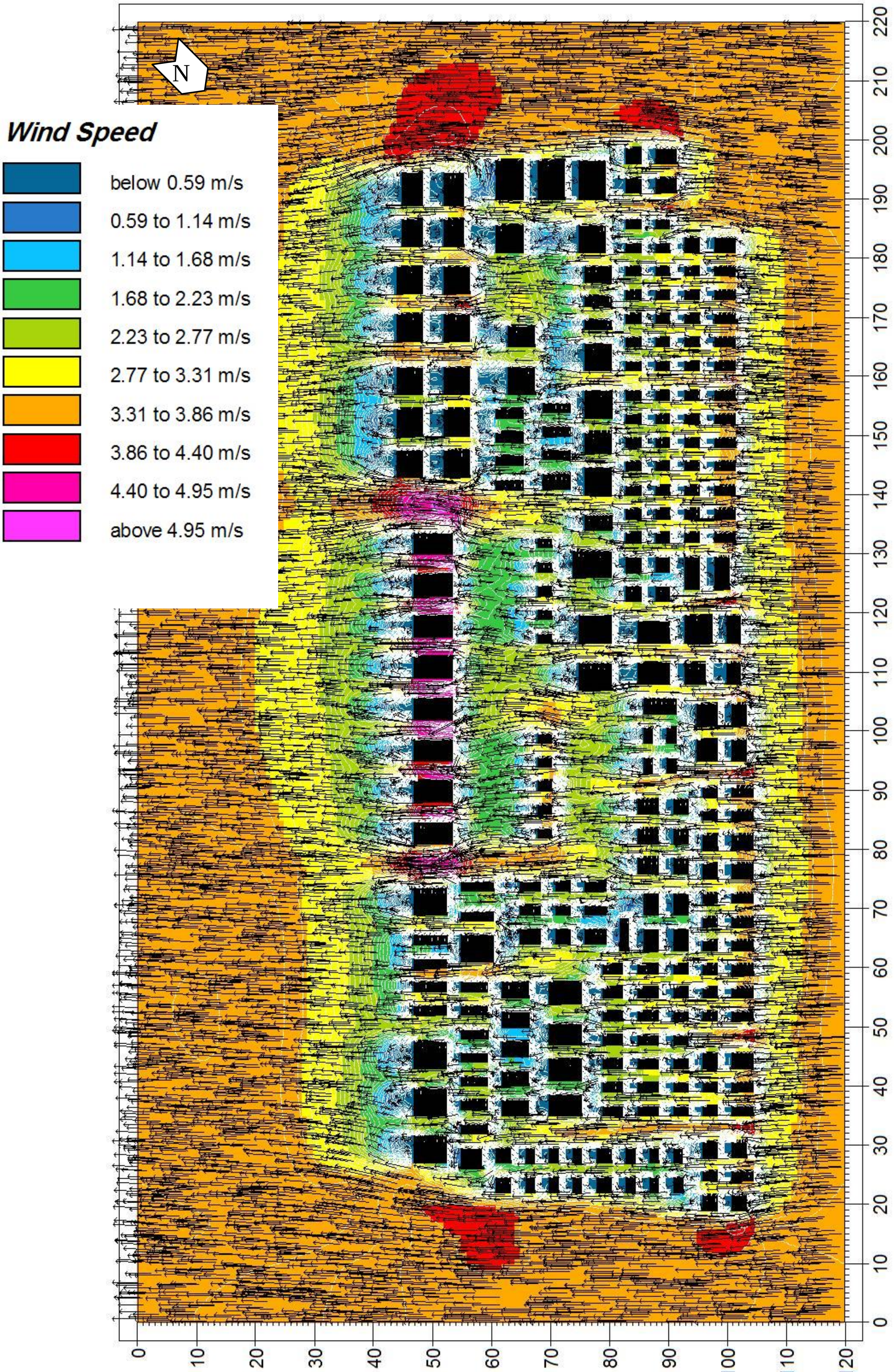


Figure 36: The airflow movement around buildings was improved clearly on account of the changes in buildings proportion (length and width) and Adjusting the width of street canyon

According to the literature review, the ratio of the length to the width of street canyon should not be too high in order to avoid a significant decrease in the wind speed in the middle of the windward façade with possible suction effects at the edges (Allard, 1998, p.22). Figure 36 illustrates that the differences in the proportion between length and width from building to another raises the flow of air between the buildings. The floor area of the building was not changed but the length and width were changed. As a consequence, the distance between the buildings was increased; therefore, the airflow was also increased in the study area as shown in Figure 37.

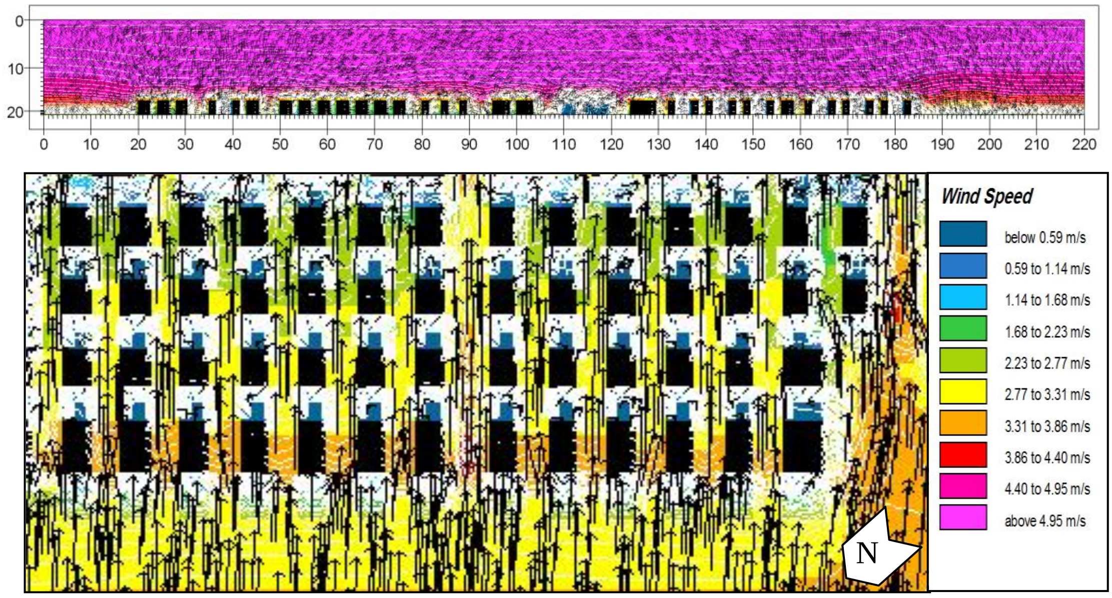


Figure 37: Airflow increases due to increase the distance between buildings

Furthermore, the measurement of the wind speed demonstrates that there is a dramatic increase in the value of the wind speed as shown in the table 3. The previous value of the wind speed is from 0.47 m/s to 1.41 m/s as indicated in blue and dark blue in figure 25. The new value of the wind speed is range from 2.23 m/s – 3.86 m/s as clarified in green, yellow and orange in figure 36. Also, the differences in the proportion between length and width allow the wind flow to move smoothly into the buildings as shown in figure 38.

Figure 38: Increasing of wind speed

Adjusting the output file of the buildings proportion parameter is useful at this stage. The reason for this is that change in the buildings proportion in order to improve the airflow in the study area resulted in increasing the width of the street canyon as shown in figure 36.

According to the literature review, concerns about attaining the maximum environmental benefits by optimizing the layout of the urban street canyon become an important concept for contemporary urban design and planning. Improving the urban ventilation condition and taking the traffic pollutants away from the street canyons requires considering the main climate characteristics and the irregular layout before the stage of street or urban planning. Architects can rely on the main wind direction as the real wind direction is always variable. From output file, the following improvements can be observed:

- Wind speed is increased which is helpful in driving the natural ventilation into the buildings as shown in figure 39
- The distance between the buildings is increased so the wind flows smoothly between the buildings as shown in figure 40
- The size of the long façade is decreased as well as the blocking of the airflow as shown in figure 41

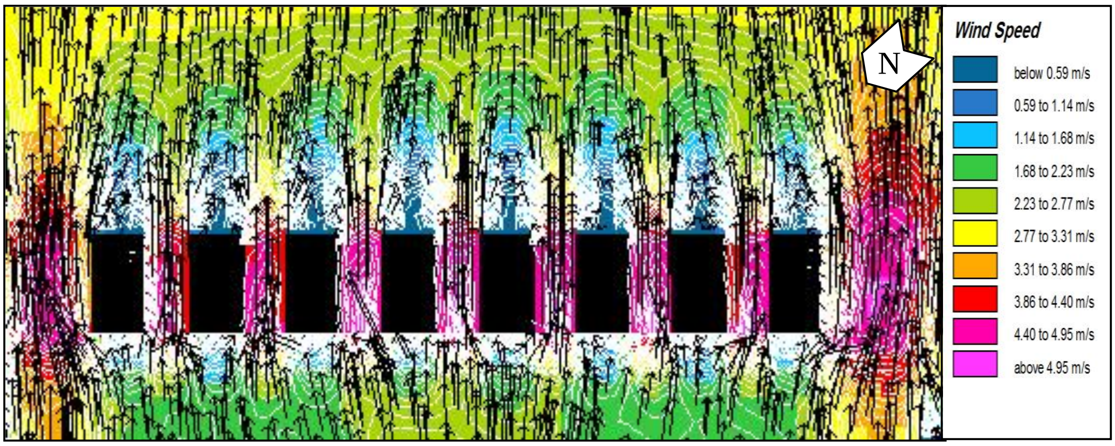


Figure 39: Increasing the wind speed with short wall façade

Figure 40: Increasing the distance between the buildings

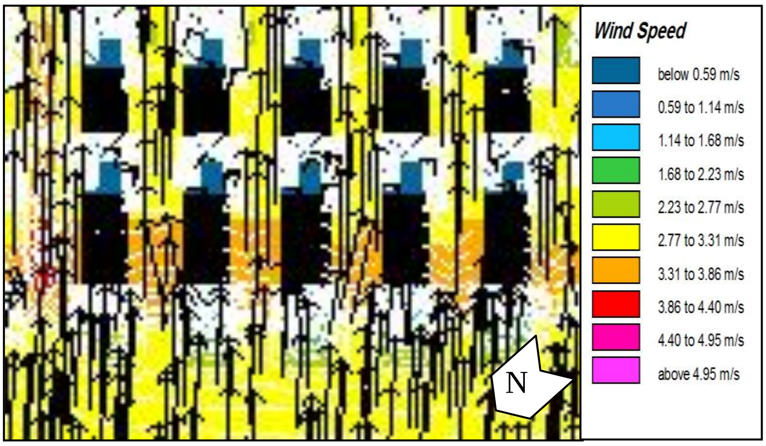


Figure 41: Decreasing the size of the long façades and reduce the blocking of air flow

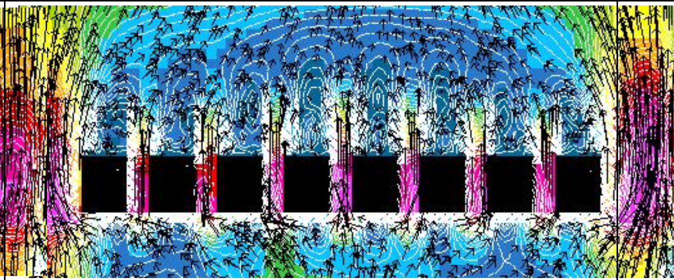
These improvements occur because of the following:

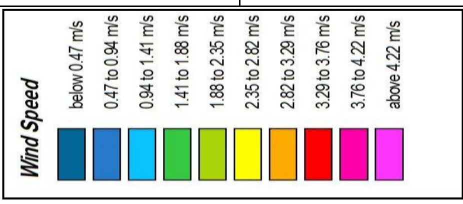
- The width of street canyon is modified
- The street layout of the study area is parallel to the major wind directions
- The flanking buildings are not continuous which allows gaps in the building geometry

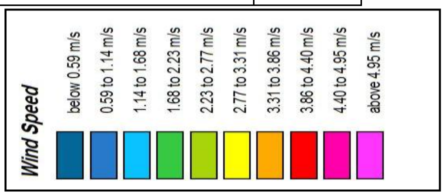
For that reason, most architects begin their design of air movement at city level, particularly in its street layout pattern. According to the literature review, Emmanuel (2005) argues that 'streets should be aligned to obtain the maximum benefit from macro-level wind directions'. (p. 118)

Envi-met results indicate that there is a considerable increase in the value of wind velocity as a result of changing the buildings and canyon proportion which is demonstrated in the table 3 below.

Table 3: Comparison between the old reading and new readings after changing the buildings and canyon proportion

New readings	Old readings	Zone
		ne 1
		Zone #2
		Zone #3
From the figures, it can be noticed the significant improvement of air flow around the buildings as indicated in green, yellow and orange with values (1.68 m/s – 3.86 m/s)	From the figures, the weak air flow around the buildings can be noticed. It is indicated by blue and dark blue color with values (1.47 m/s and below)	Com-ment





The differences in the proportion between length and width decrease the long façade and allow air movement around the buildings as well as distribute equal wind speed on the buildings as shown in figure 42. Long facade buildings without openings cause the largest wind speed differences, particularly when the building is perpendicular to the prevailing wind

Figure 42: Increasing of wind speed

6.3 Choosing other urban patterns types:

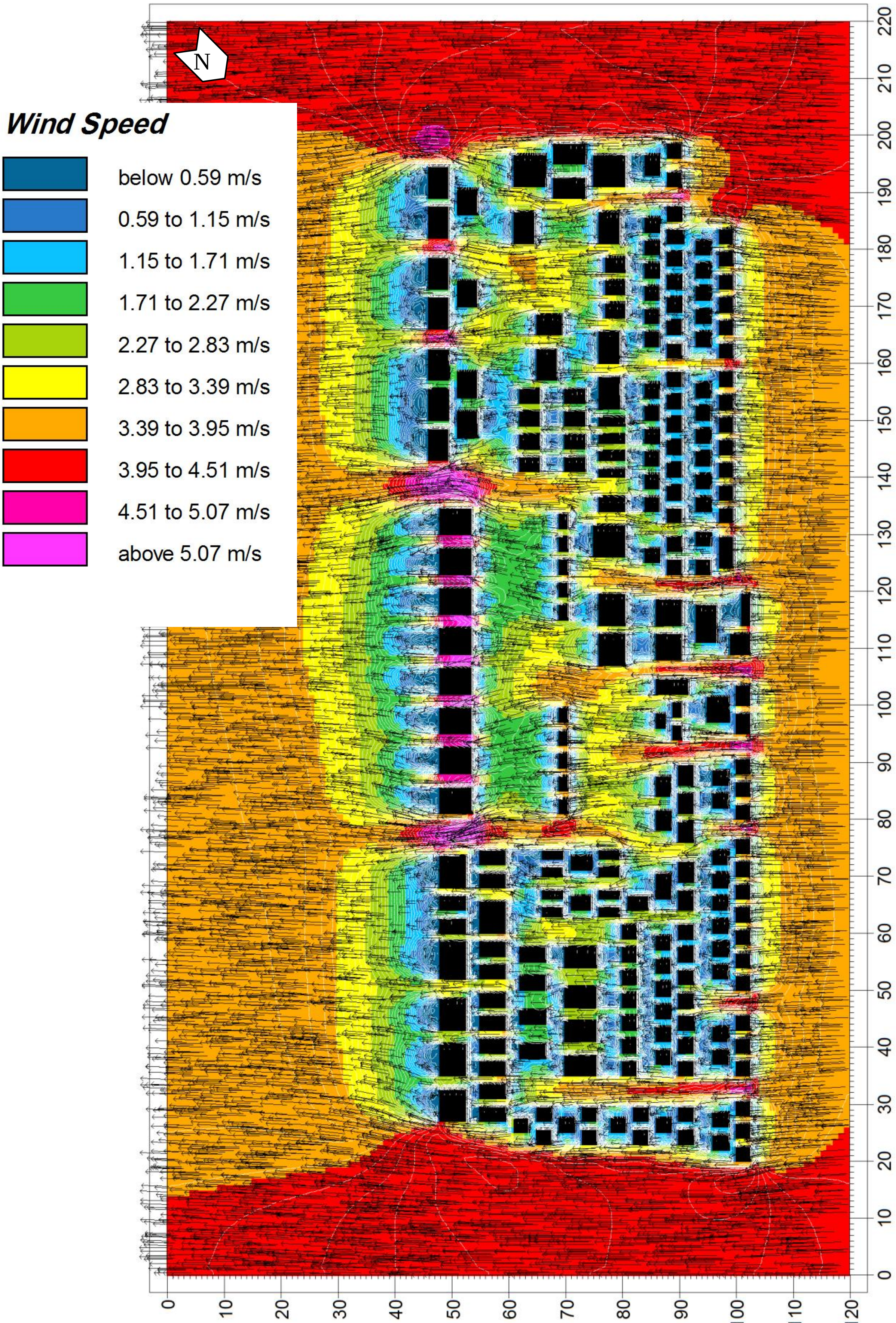


Figure 43: The airflow movement around the buildings was slightly improved on account of the changes in the staggered urban parameters

The layout of building patterns was changed in the input file in order to simulate the file. Staggered pattern was chosen as recommended by the literature review. As a consequence, figure 43 shows that the airflow in the street canyon was increased. This is because the high wind speed occurred in the first rows of the buildings which allow the air flow to reach the maximum number of the buildings as shown in figure 44. A staggered pattern layout increases the airflow within the buildings, because the configuration provides less sheltering from the wakes. (Allard, 1998 p.22) indicates that 'a building should be designed to be high enough to overcome the wind sheltering obstructions, subject to considerations related to other requirements and building regulations'. Allard's proposal will be appropriate when the density and configuration of the surrounding buildings do not allow for proper wind exposure.

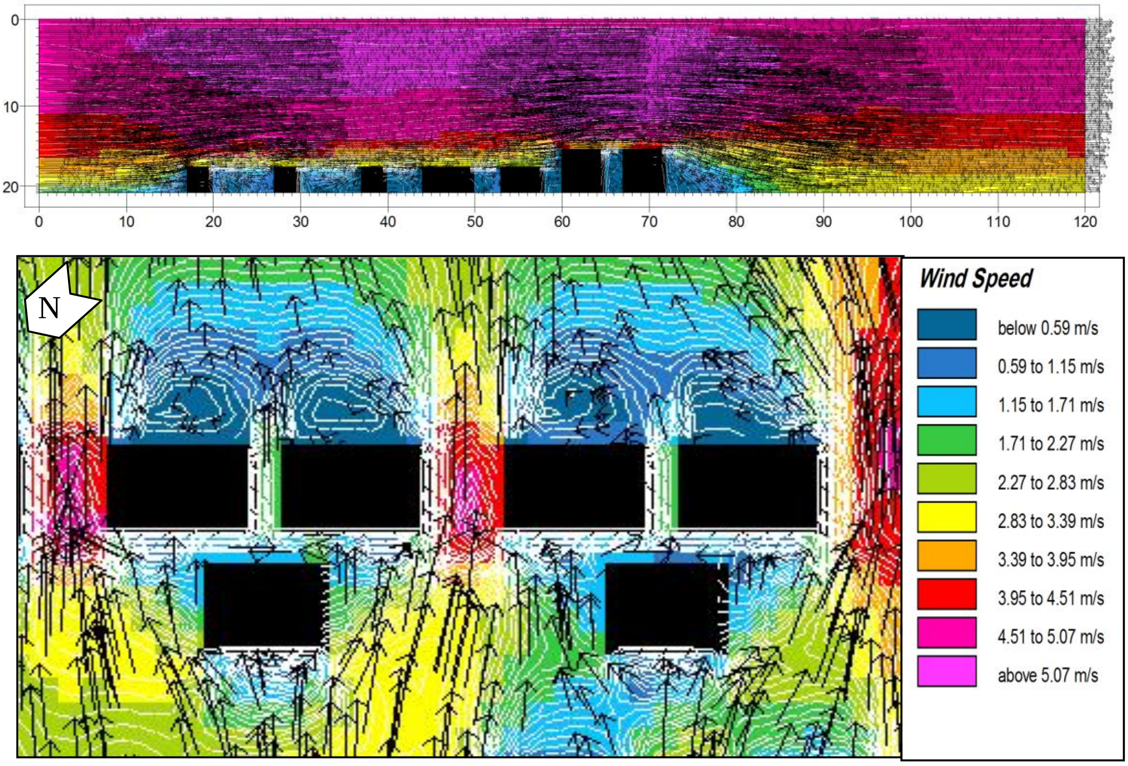


Figure 44: High wind speed on the corner of some buildings

Envi-met results indicate that there is a considerable increase in the value of wind velocity as a result of changing the buildings patterns which is demonstrated in the table 4 below.

New readings	Old readings	Zone

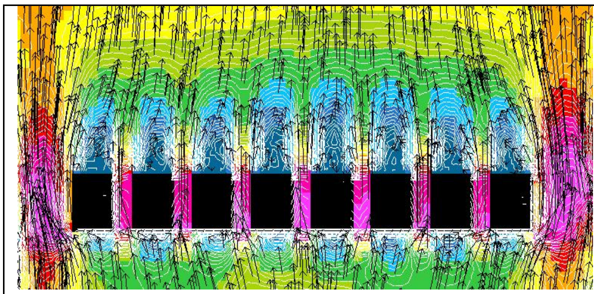
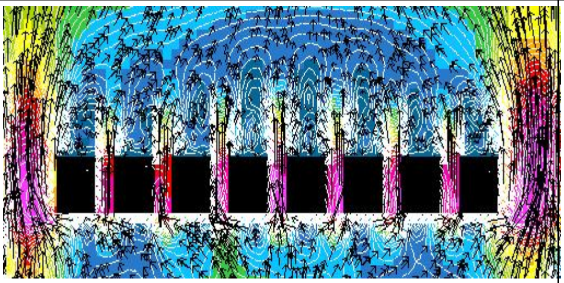
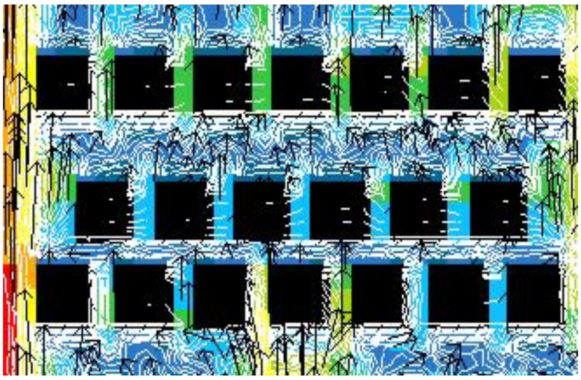
		Zone #1
		Zone #2
		Zone #3
From the figures, it can be noticed the significant improvement of air flow around the buildings as indicated by green and yellow color with values (1.71 m/s – 3.39 m/s)	From the figures, it can be noticed the weak flow of air movement around the buildings which is indicated by blue and dark blue color with values (1.47 m/s and below)	Comment

Table 4: Comparison between the old readings and new readings after changing urban pattern

6.4 Modifyi

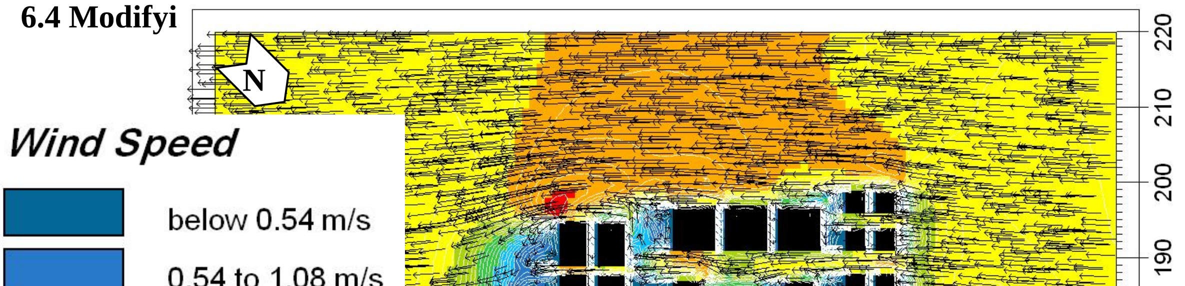


Figure 45: The airflow movement around the buildings was slightly improved on account of the changes in the heights of the buildings

The height of the buildings was modified in the input file design, and then the new file with the same configuration file was simulated. The heights of the buildings range from 6m to 90 m from the windward row to the last row. This type of hierarchy of buildings allows the airflow to reach most floors in each building as shown in figure 46.

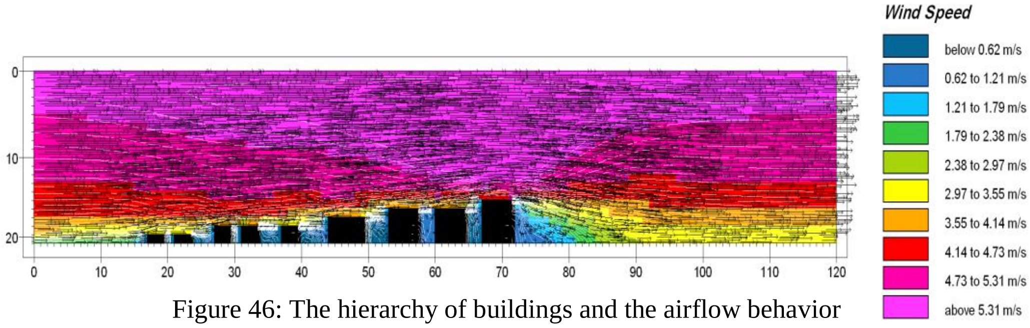


Figure 46: The hierarchy of buildings and the airflow behavior

According to the literature review, changing the height of a building while keeping the length and width unchanged will result in increasing the depth of the downwind wake and the shape will remain the same. In addition, the wind velocity increases at higher levels including an increased airflow rate through the windward openings of the top floors and higher suction at the side walls as shown in figure 45.

As the buildings increase in height, the distribution of airflow paths changes around the building and within it. There is a direct proportion between the amount of air passing around the sides of the building and the amount of air traveling over it. According to Allard (1998), this causes less upward air movement through the openings placed on the lower two-thirds of the building windward façade; however, the top one-third of the building windward façade will face more upward airflow, regardless of the height of the building.

Allard (1998) shows that above a certain height, stratification of air density and temperature may cause an excess in temperature differential between the bottom and top of the building, which may not be easily eliminated by passive means (p.22). Modifying the height of the buildings does not make a great improvement in the flow of the air movement in the lower part of the buildings. This is because the airflow is being blocked due to the presence of the narrow rows of buildings. On the other hand, the upper parts of the buildings have a better air flow as a result of the hierarchy of the buildings and the relationship between the wind direction and the method of hierarchy as shown in figure 47. According to the literature review, Givoni (1994) states that 'an urban profile of variable building height, where buildings of different heights are placed next to each other, and when the long facades of the buildings are oblique to the wind enhances urban ventilation' (Givoni, 1994 cited in Emmanuel, 2005, p.118).

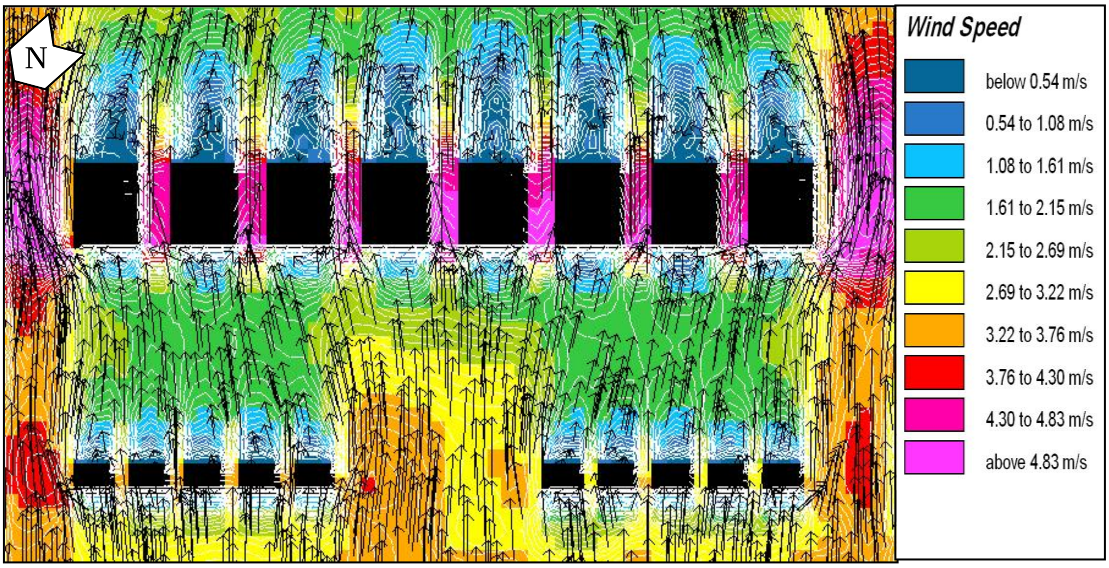


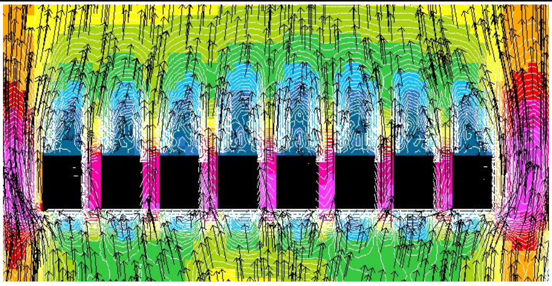
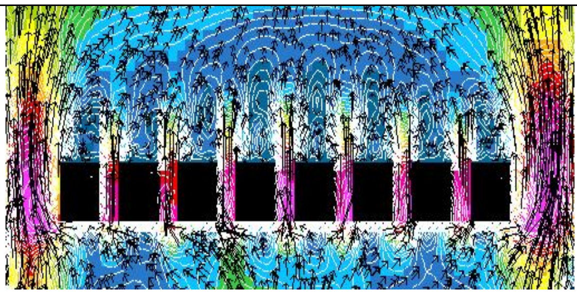
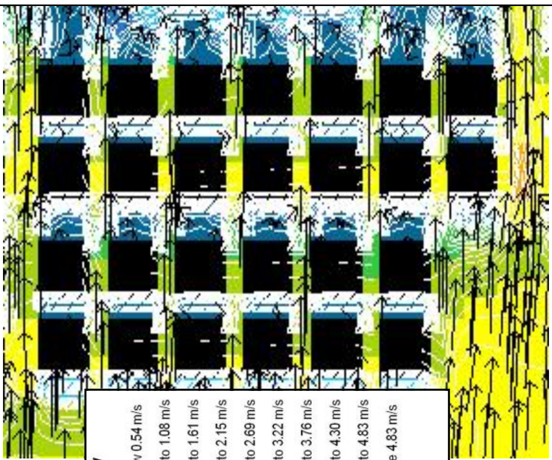
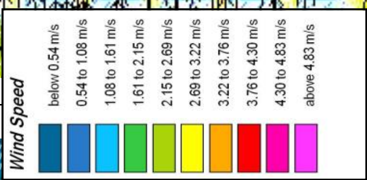
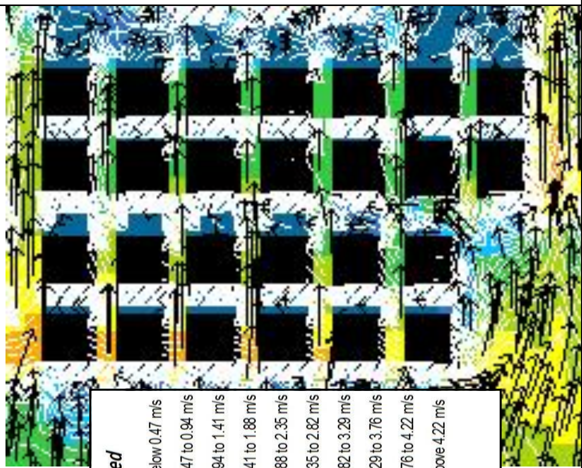
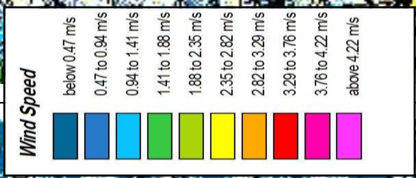
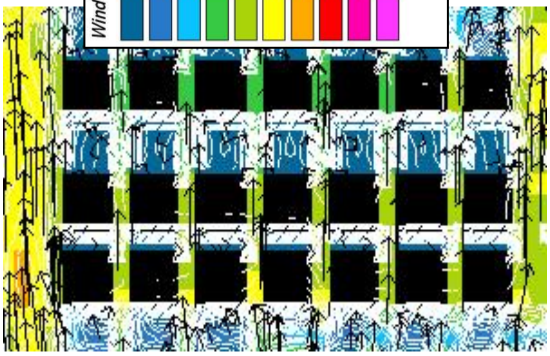
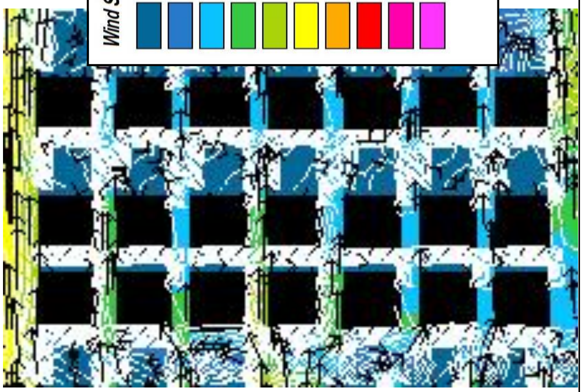
Figure 47: The upper parts of the buildings have a better air flow at 10 m in height

The wind speed was decreased in the study area so the air flow has a relative improvement as shown in the table below. In addition, the wind velocity and wind direction are steadier in the higher level than at the ground level for the reason that the wind is less influenced by surrounding buildings and vegetation. A tall building in the first two lines of the study area receives more airflow than a low building. The variations in ventilation between tall and low buildings are because of the different building types face. A high-rise building, for instance, faces a higher wind speed as shown in figure 45 than a low-rise building as shown in figure 48. This driving force can be used for ventilation.

Figure 48: Low wind speed with low-rise buildings

Envi-met results indicate that there is a slight increase in the value of wind velocity as a result of changing the heights of the buildings which is demonstrated in the table 5 below.

Table 5: Comparison between the old readings and new readings after modifying the height of the buildings

New readings	Old readings	Zone
		Zone #1
 	 	Zone #2
		Zone #3
From the figures, it can be noticed the significant improvement of air flow around the buildings as indicated by green and yellow color with values (1.61 m/s – 3.22 m/s)	From the figures, it can be noticed the weak flow of air movement around the buildings which is indicated by blue and dark blue color with values (1.47 m/s and below)	Comment

6.5 Using different shape of buildings:

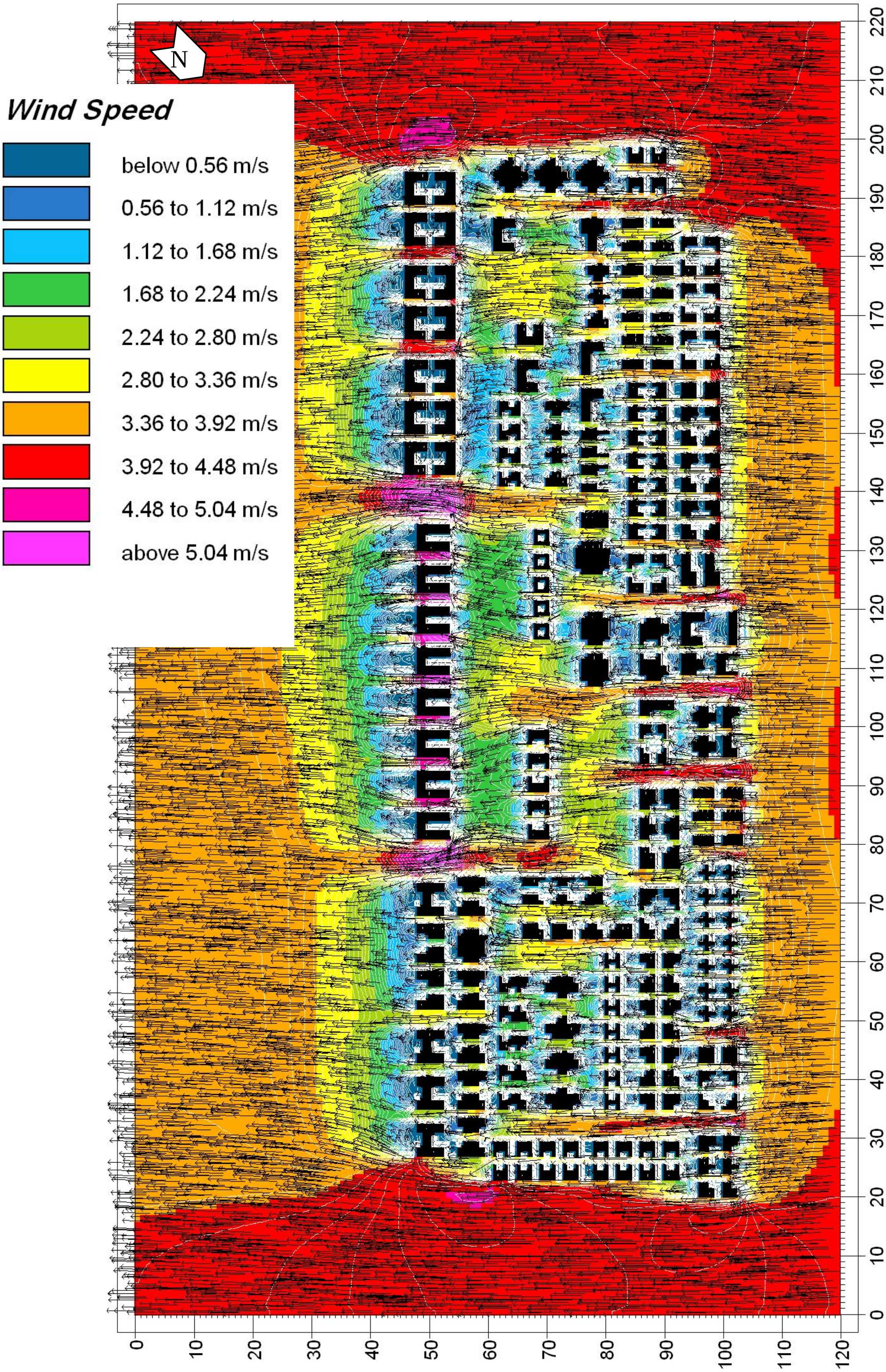


Figure 49: The airflow movement around the buildings was slightly improved on account of the changes in the shapes of the buildings

Various shapes of the buildings are another parameter that may improve the outdoor air quality in the study area. The input file has been changed to start the simulation technique again with the new modification. Leonardo software was then used to evaluate the new modification and the improvement of the outdoor air quality as shown in figure 49.

Several shapes of the buildings in the study area have made some improvement, but also reveal some weaknesses in the airflow. The changes of the building shape based on two concepts which are creating some courts between the buildings in order to increase the ventilation and increasing the windward façades to enter the airflow into the buildings by openings. The main improvement is an increase of the wind speed in the places as shown in figure 50. This type of improvement drives the air flow into the buildings.

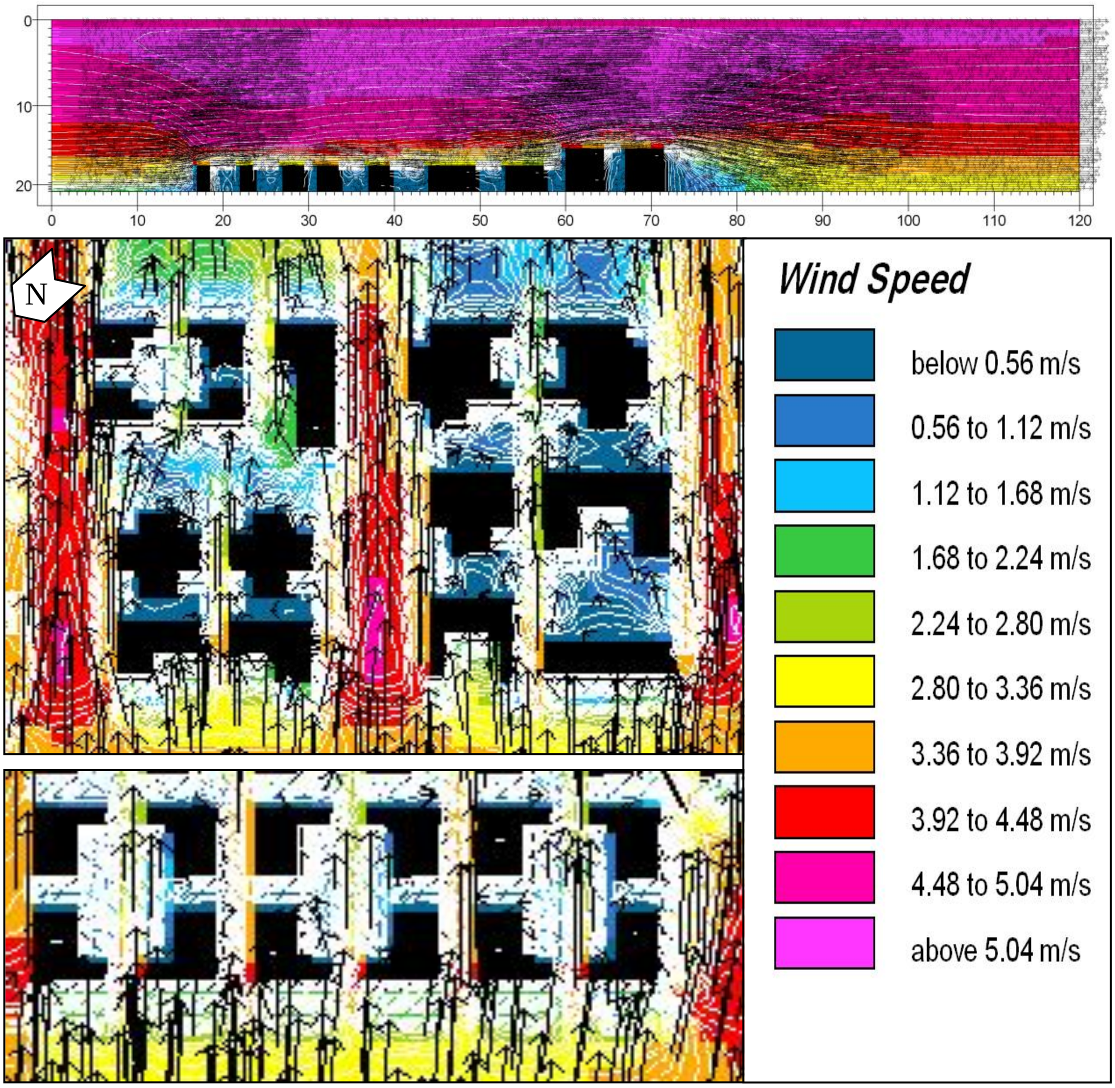


Figure 50: increasing of wind speed by changing the shape of the buildings

From the literature review, the differences in the shape of buildings are essential to get a high performance of natural ventilation. The shape of buildings can change the wind speed distribution considerably. This is because the shapes of the buildings affect the way wind flows around the building, and therefore influence the distribution of wind speed on buildings.

Building shape is crucial in creating the wind speed that will drive the air flow through its apertures. On the other hand, high wind speed made a negative effect on the buildings users and pedestrian comfort. Figure 51 indicates a similar result to what have been mentioned in the literature review which is wind speed will vary considerably, creating complex air flows and turbulence by their interaction with elements of the natural environment (trees, hills) and urban context (buildings, structures).

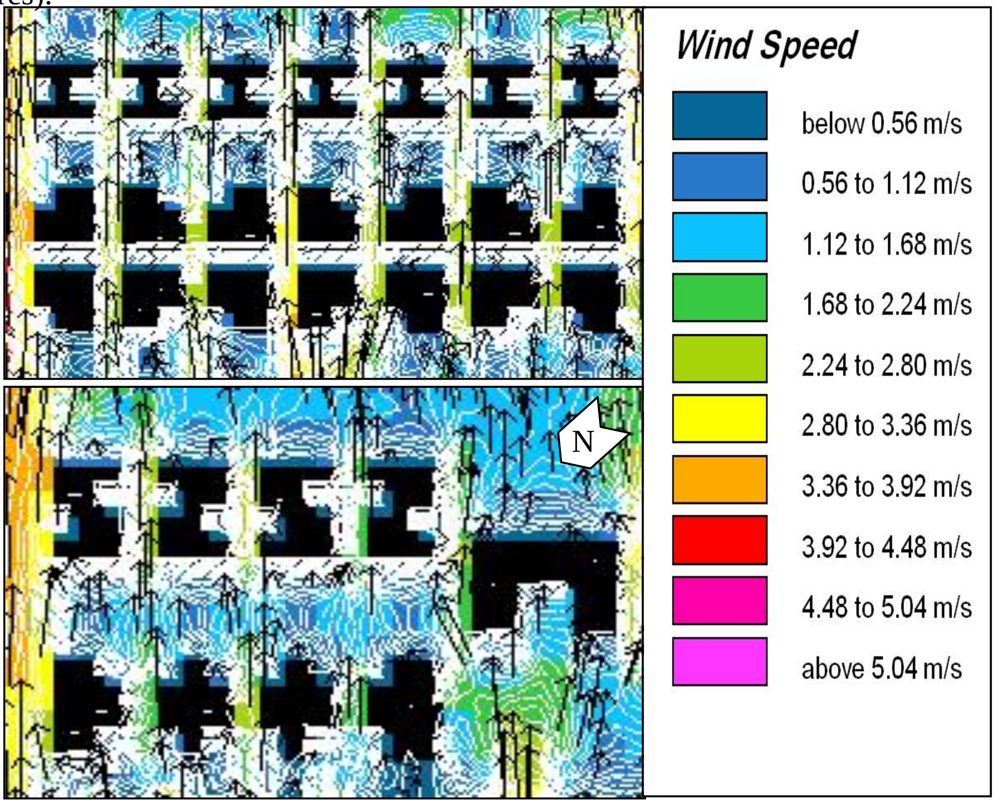
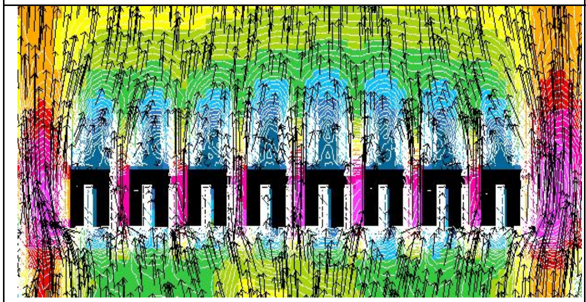
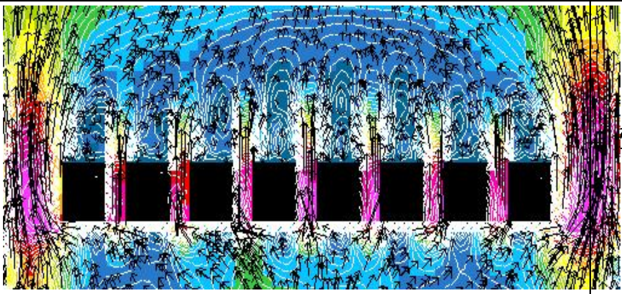
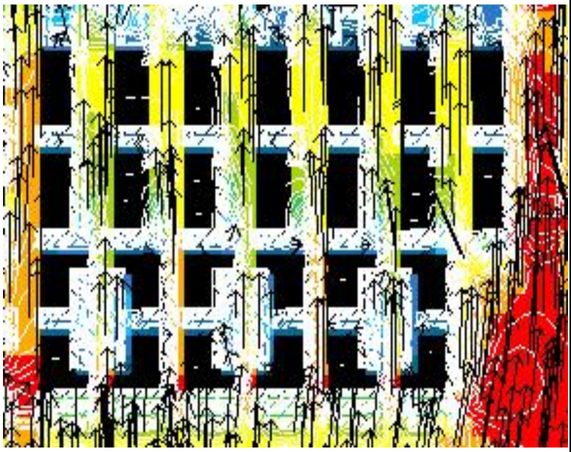
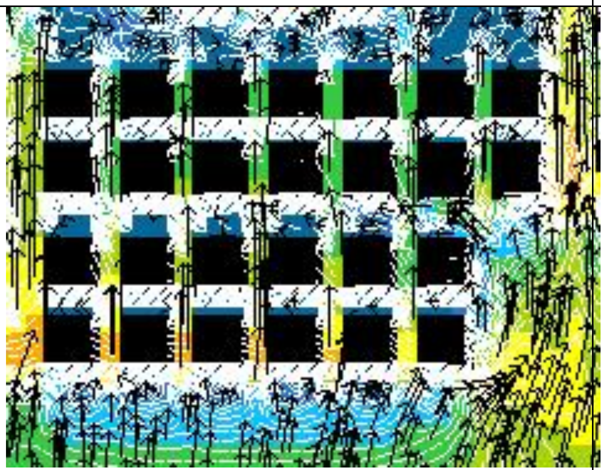
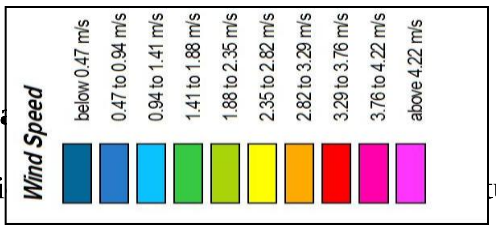


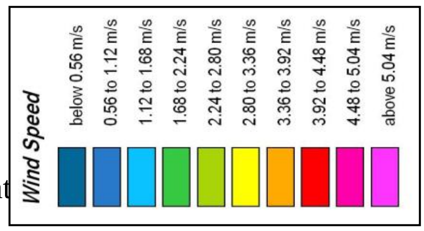
Figure 51: Poor natural ventilation

Envi-met results indicate that there is a considerable increase in the value of wind velocity as a result of changing the shape of buildings which is demonstrated in the table 6 below.

Table 6: Comparison between the old readings and new readings after changing shape of the buildings

New readings	**Old readings**	**Zone**
		Zone #1
		Zone #2
		Zone #3
From the figures, it can be noticed the significant improvement of air flow around the buildings as indicated by green and yellow color with values (1.68 m/s – 3.36 m/s)	From the figures, it can be noticed the weak flow of air movement around the buildings which is indicated by blue and dark blue color with values (1.47 m/s and below)	Comment





6.6 Summa

In conclusi … tural vent … be achieved through the following:

- Varying the proportion between length and width in order to decrease the long façade that blocks the airflow and unequally distributes the wind speed on the buildings with a flat façade
- Increasing the distance between the buildings to allow airflow to move smoothly between the buildings while decreasing the size of the long façade
- Designing a staggered pattern layout which is more effective than a grid pattern in contributing to the air movement within the buildings. This is because the configuration of scattered pattern provides less sheltering from the wakes
- Considering the hierarchy in heights of the buildings to allow the airflow to reach most floors in the buildings
- Varying the shape of buildings because they influence the airflow behavior around the buildings, and thereby affect the wind speed distribution on the buildings

Modification of the five urban parameters which are building proportions (length and width), the width of street canyons, urban pattern types, height of buildings as well as their shape play a significant role in increasing the performance of the natural ventilation.

7.0 CONCLUSION

The aim of this investigation is to analyze the outdoor air quality and natural ventilation in a hot and humid region, specifically in the city of RAK in the UAE. It is an attempt to improve the quality of air flow around the buildings by examining the effect of parameters of urban design. A review of literatures provides a theoretical framework to achieve outdoor air quality and natural ventilation. The Envi-met software was used to simulate the study area. Validation of simulation was sought by repeating the process in order to avoid inaccuracies in the interpretation of the results. The numerical simulation was used to calculate the airflow around the buildings after initializing the design. Based on the calculated results, the designs were modified.

The results of the preliminary simulation show that high wind speed around buildings appears to be the most obvious problem in the study area which resulted in several serious problems such as poor natural ventilation. These problems occur in the study area on the account of high-density zones, narrow spacing between the buildings and long walls of building fabric that may prevent deeper penetration of the wind. Another equally important reason is the configuration of buildings does not allow gaps in the building geometry; as a consequence, it prevents airflow around the buildings. Another important outcome of the research is that the discomfort to pedestrians regarding the wind flow level does not seam to be a serious problem in the study area. This is mainly because the maximum value of wind velocity in the study area ranges from 4.5 to 5.06 m/s. However, wind speed is not the only factor that might affect pedestrians since the discomfort for pedestrians is very subjective, depending on many factors such as age, sex, type of activity, and psychological state. Nevertheless; high-rise buildings cause high wind speed on the corner of some buildings which may discomfort pedestrians. The reasons behind this is that the air which hits tall building surface turns aside the ground sourcing high-wind velocity on the down-wind and near the corners of the buildings at street / pedestrian level.

For that reasons, investigation was carried out along with the modification of the five urban parameters which are buildings proportion (length and width), width of street canyon, urban patterns types, height of buildings as well as the shape of buildings. Regarding the research question, increasing the performance of natural ventilation in the study area necessitated varying the proportion between length and width and increasing the distance between the buildings as well as varying the shape and the height of the buildings for the following reasons:

- Decreasing the long façade that blocks the airflow and unequally distributes the wind speed on the buildings with flat-façade
- Allowing the airflow to reach to the most floors in the buildings
- Moderating the wind speed distribution on the buildings

- Allowing the airflow moving smoothly between the buildings.

After the above changes were applied in modifying the urban parameters of the study area, the major findings indicate that there is a considerable improvement in airflow movement around the buildings. In other words, the new modification of the urban parameters plays a significant role in increasing the outdoor air quality.

7.1 Final design recommendation

- Design the urban areas taking into consideration the building proportion by:
    - Considering the proportion of the plots which are distributed to people.
    - Providing each site a specific building regulation to ensure that the new building will not affect the old one and decrease the distance between buildings.
- Design the urban areas taking into consideration the heights of the buildings by:
    - Considering the hierarchy in heights of the buildings to allow the airflow to reach most of the floors in the buildings
- Designing the urban areas taking into consideration the shape of the buildings by:
    - Creating some courts between the buildings in order to increase the ventilation and increasing the windward façades to enter the airflow into the buildings by openings
- Designing the urban areas taking into consideration the pattern of the buildings by:
    - Staggering the buildings according to the prevailing wind direction in order to decrease the wind shadow area at the back of each building and provide the maximum wind flow to the downstream buildings.
- Designing the urban areas taking into consideration the width of street canyon by:
    - Paralleling the main street canyon layout to the prevailing winds and increasing the width of street canyons because of the wind speed and the heights of buildings.

7.2 Further work

Similar field inquiries should be undertaken in the Arabian Gulf in order to assure the results that were found in the current investigation and therefore have a wider picture of the hot and humid region.

Numerous basic studies have been undertaken on airflow and wind speed distribution around simple or regular building geometries. Further research must therefore be done in more sophisticated building and urban environments by using the most accurate simulation tools such as CFD simulations and wind-tunnel experiments. A further investigation of the airflow interaction between the outdoor space and indoor space is necessary. Further research is also needed in order to study the effect of landscaping on the airflow pattern.

Further work concerning air flow conditions inside different spaces must be studied taking into account solar radiation on walls and floors. This will enable researchers, engineers and architects to obtain a comprehensive overview of the different thermal conditions between night and daytime and an in-depth parameter study should be undertaken for this subject.

8.0 APPENDICIES

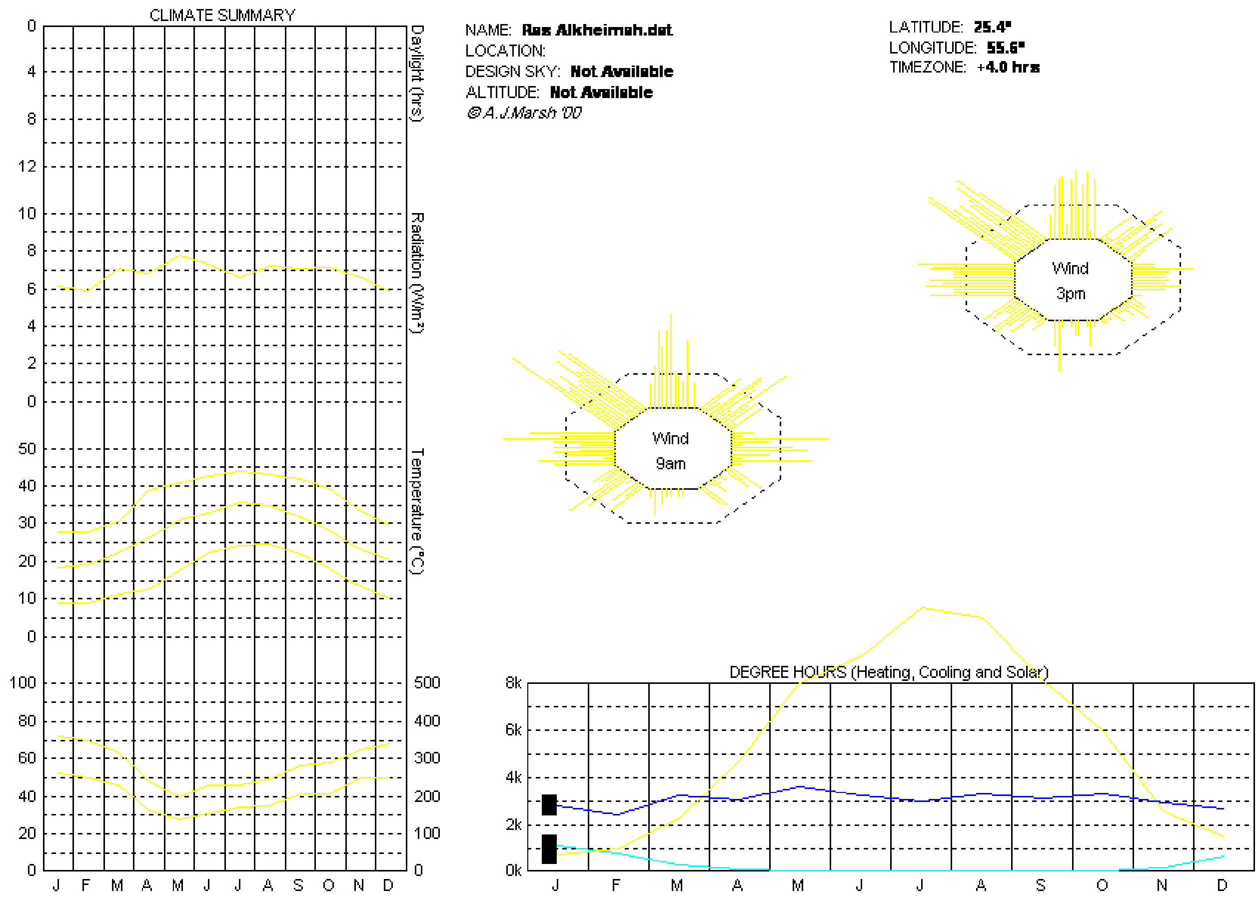
Appendix 1.0:

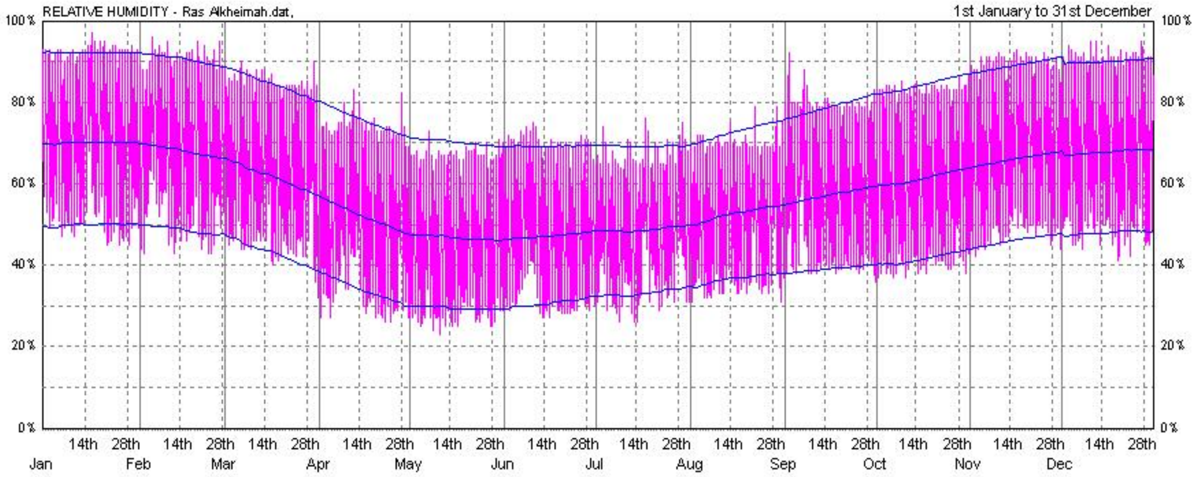
Appendix 1.1: Key Economic Indicators for Ras Al Khaimah

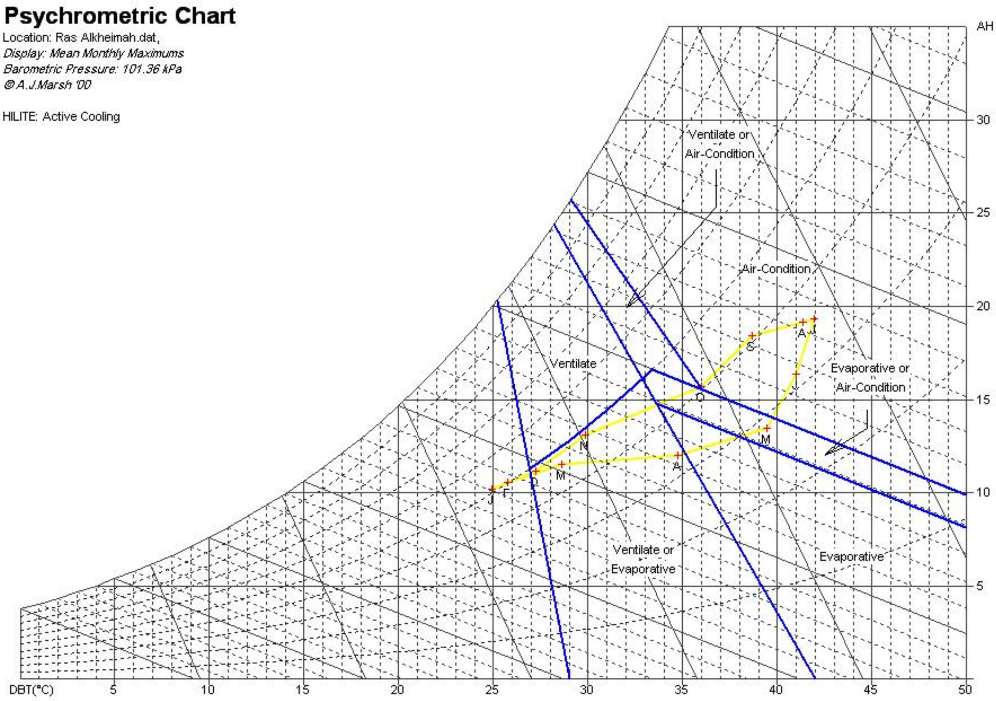
2005	2004	2003	2002	2001	2000	1999	1998	Indicator
197	208	195	187	181	172	165	159	**Population (000s)**
9,253	7,834	6,963	6,622	6,225	5,940	5,636	5,218	**GDP (m; AED)**
5.0%	6.7%	4.3%	3.3%	5.2%	4.2%	3.8%	-	**Growth**
3180	5752	1172	1205	747	627	740	848	**Imports (m; AED)**
876	606	1242	1856	258	259	489	281	**Exports (m; AED)**

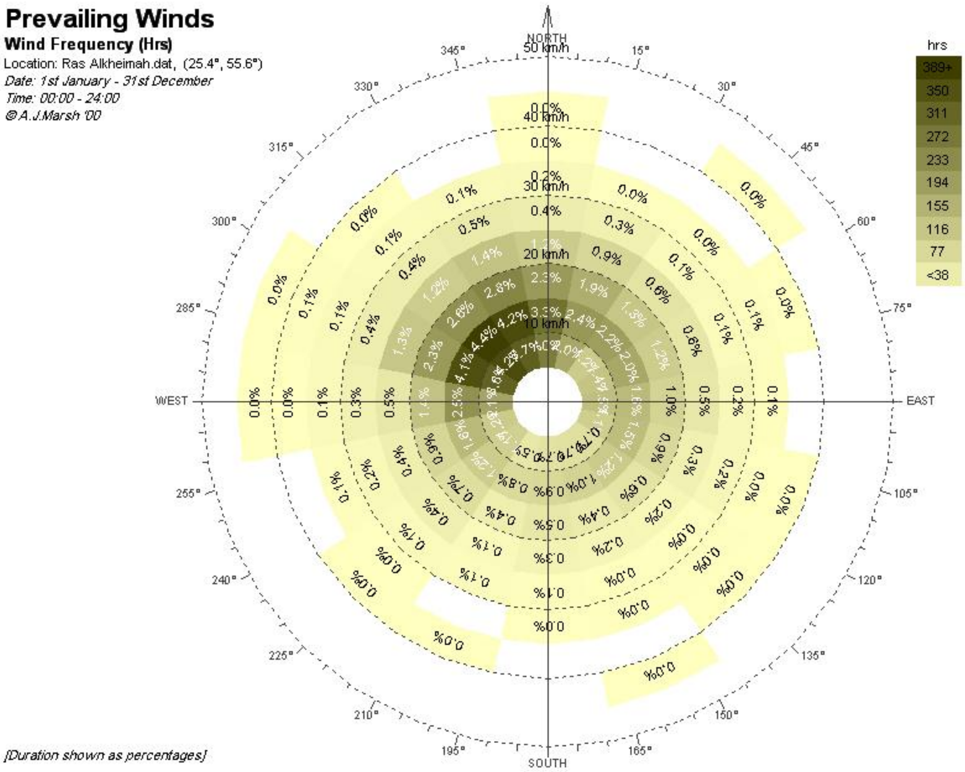
Source: Economic Department of Ras Al Khaimah. (Government of Ras Al Khaimah, 2007)

Appendix 1.2: Climatic data

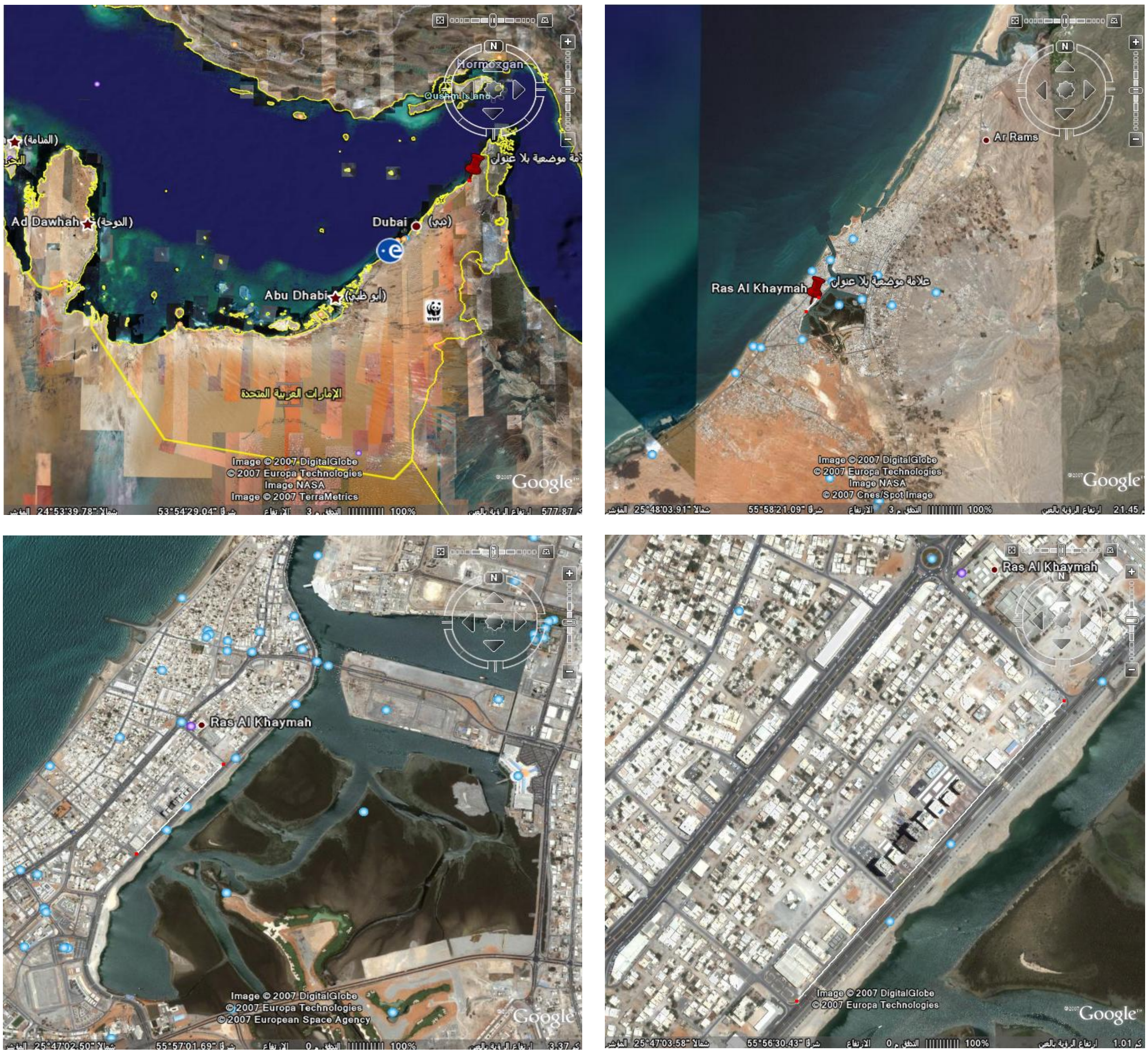



RELATIVE HUMIDITY - Ras Alkheimah.dat,
1st January to 31st December
100%
80%
60%
40%
20%
0%
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Psychrometric Chart
Location: Ras Alkheimah.dat,
Display: Mean Monthly Maximums
Barometric Pressure: 101.36 kPa
© A.J.Marsh '00
HILITE: Active Cooling
Ventilate or Air-Condition
Air-Condition
Ventilate
Evaporative or Air-Condition
Ventilate or Evaporative
Evaporative
AH
DBT(°C)

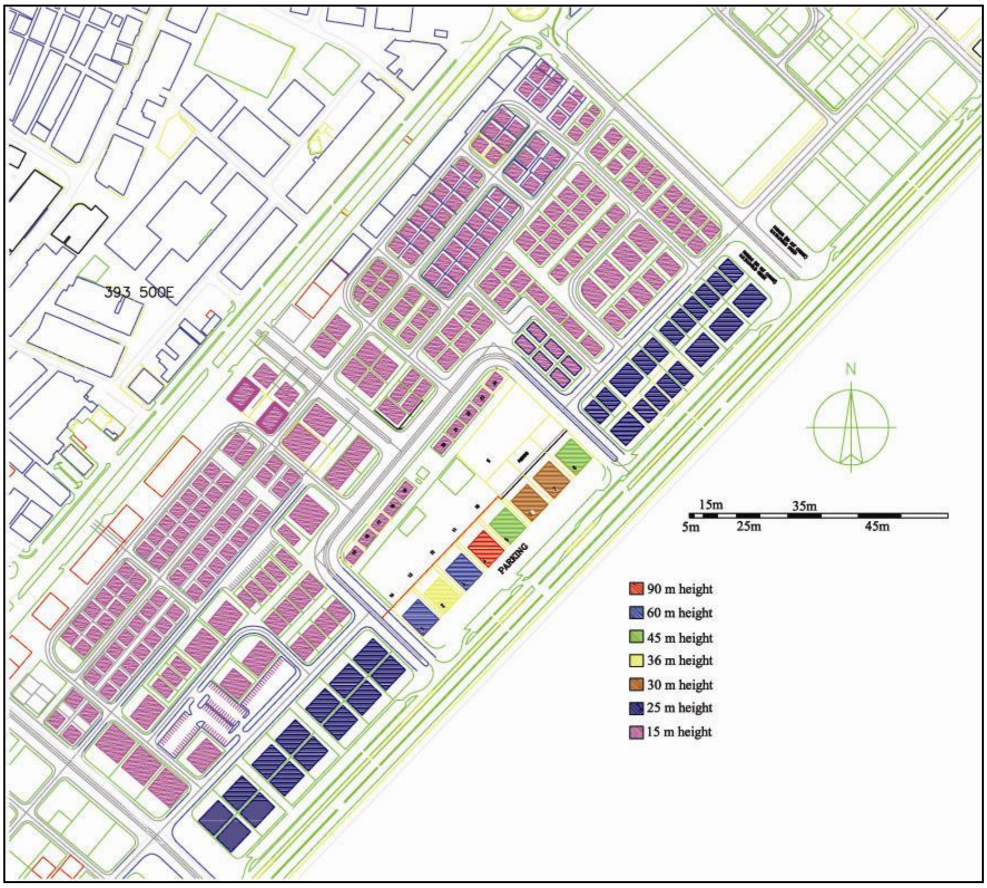

Prevailing Winds
Wind Frequency (Hrs)
Location: Ras Alkheimah.dat, (25.4°, 55.6°)
Date: 1st January - 31st December
Time: 00:00 - 24:00
© A.J.Marsh '00
NORTH
SOUTH
EAST
WEST
50 km/h
40 km/h
30 km/h
20 km/h
10 km/h
hrs
389+
350
311
272
233
194
155
116
77
<38
[Duration shown as percentages]

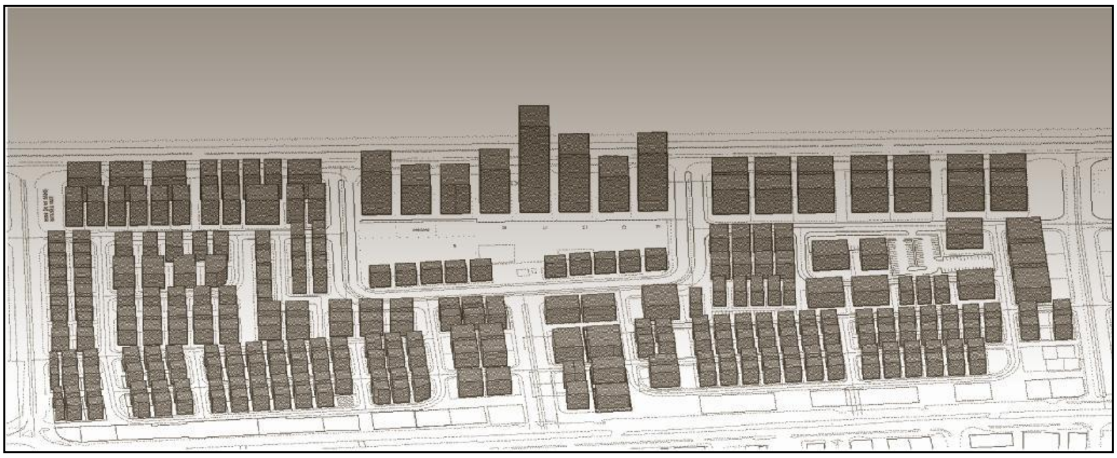
Appendix 1.3: Study area location

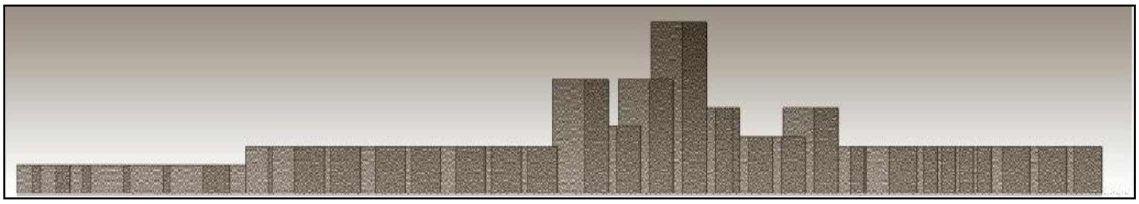


Appendix 2.0

Appendix 2.1: The design of the study area



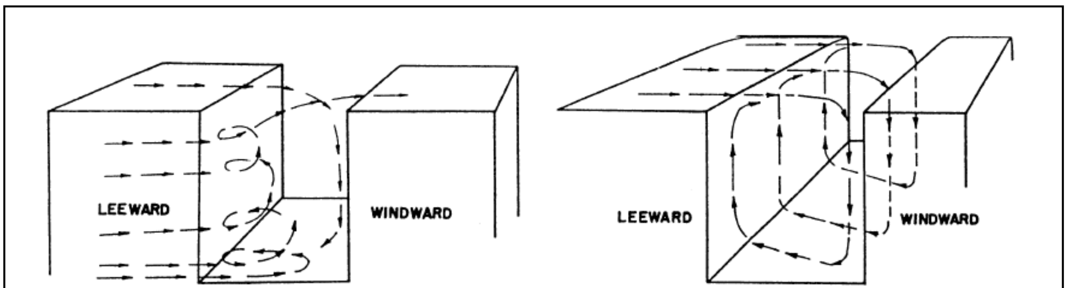





STRABAG
TRADE CENTRE




Appendix 2.2: Wind pressure behavior in the street canyon



3D interaction of corner and cavity vortex near the edges of a short street canyon

recirculation in a 2D street canyon

Appendix 3.0

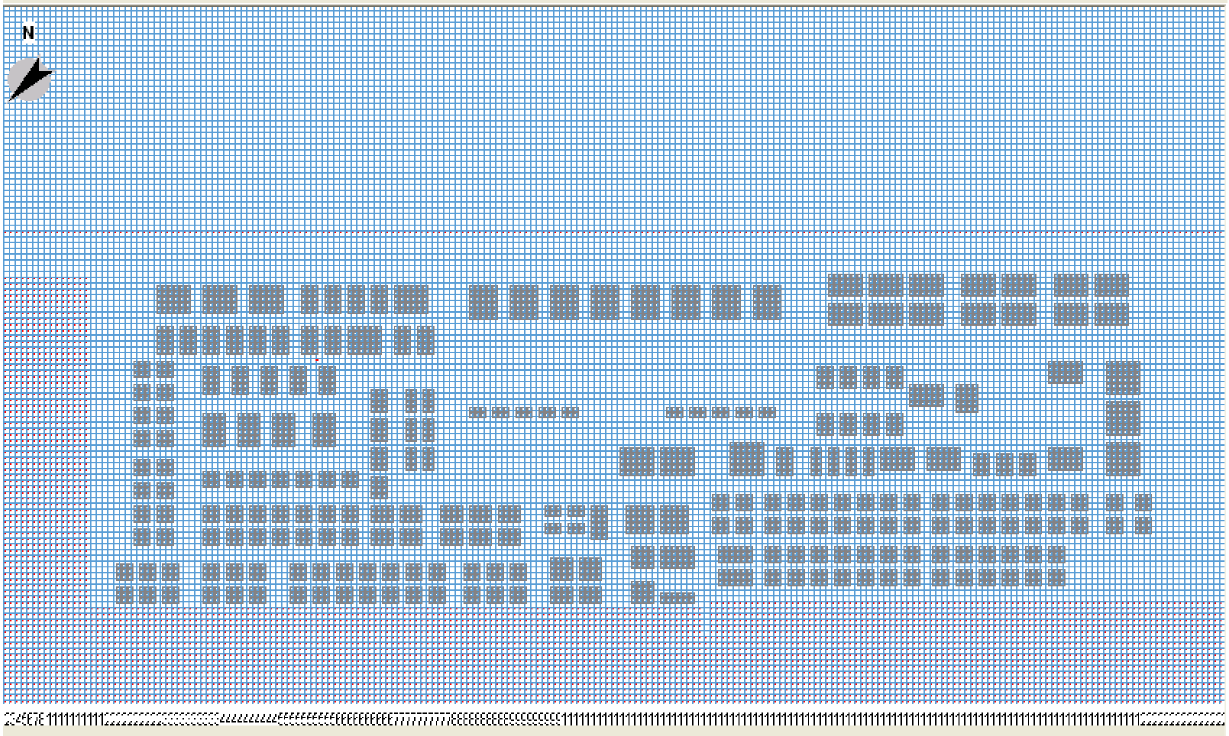
Appendix 3.1: Description of wind Speed (m/sec) Description of wind effects

No noticeable wind.	0.4-1.5	Light airs
Wind felt on face	1.6-3.3	Light breeze
Wind extends light flag.	3.4-5.4	Gentle breeze
		Hair is disturbed
		Clothing flaps.
Wind raises dust, dry soil, and loose paper. Hair disarranged.	5.5-7.9	Moderate breeze
Force of wind felt on body.	8.0-10.7	Fresh breeze
		Drifting snow becomes airborne
		Limit of agreeable wind on land
Umbrellas used with difficulty.	10.8-13.8	Strong breeze
		Hair blown straight.
		Difficulty to walk steadily.
		Wind noise on ears unpleasant.
		Windborne snow above head height (blizzard).
Inconvenience felt when walking.	13.9-17.1	Moderate gale
Generally impedes progress	17.2-20.7	Fresh gale
		Great difficulty with balance in gusts.
People blown over by gusts	20.8-24.4	Strong gale

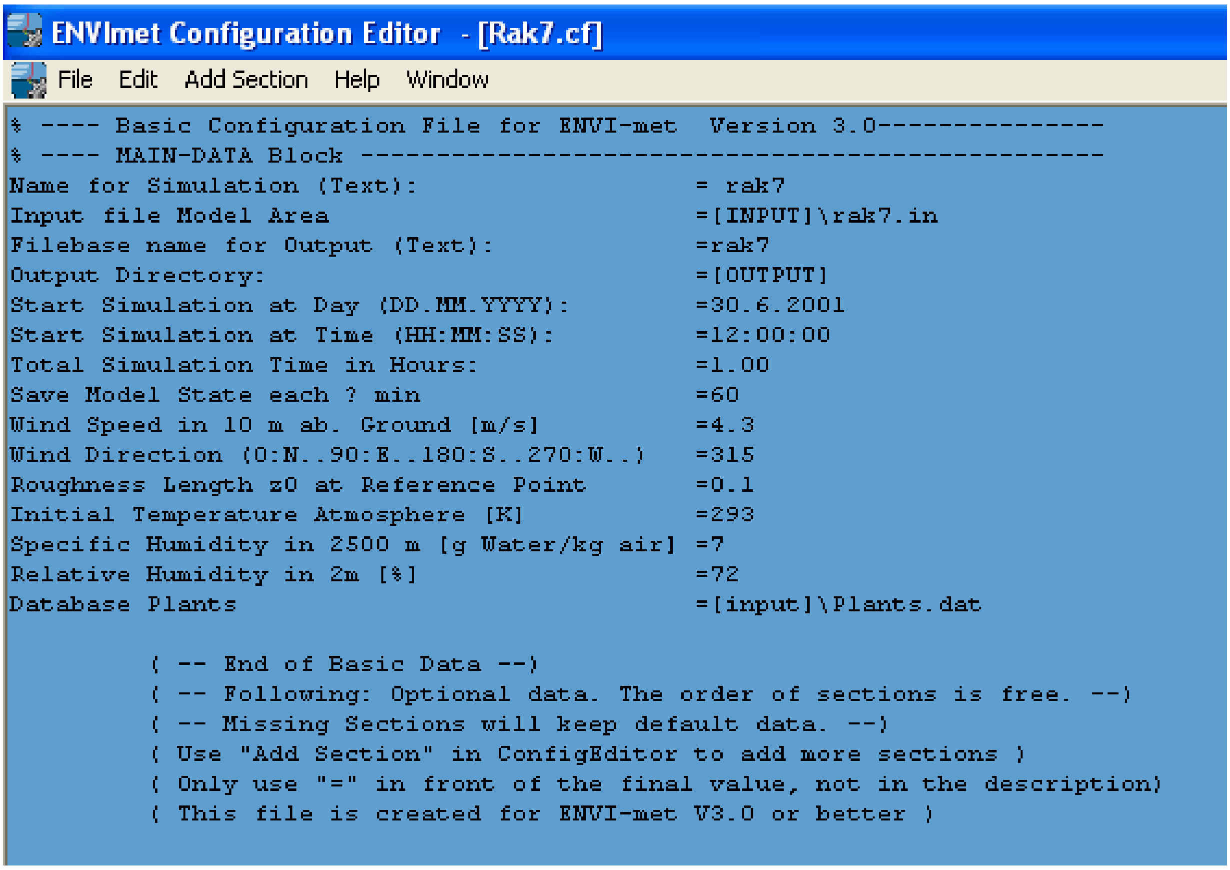
Summary of wind effects (Ahuja et al., 2006)

Appendix 4.0

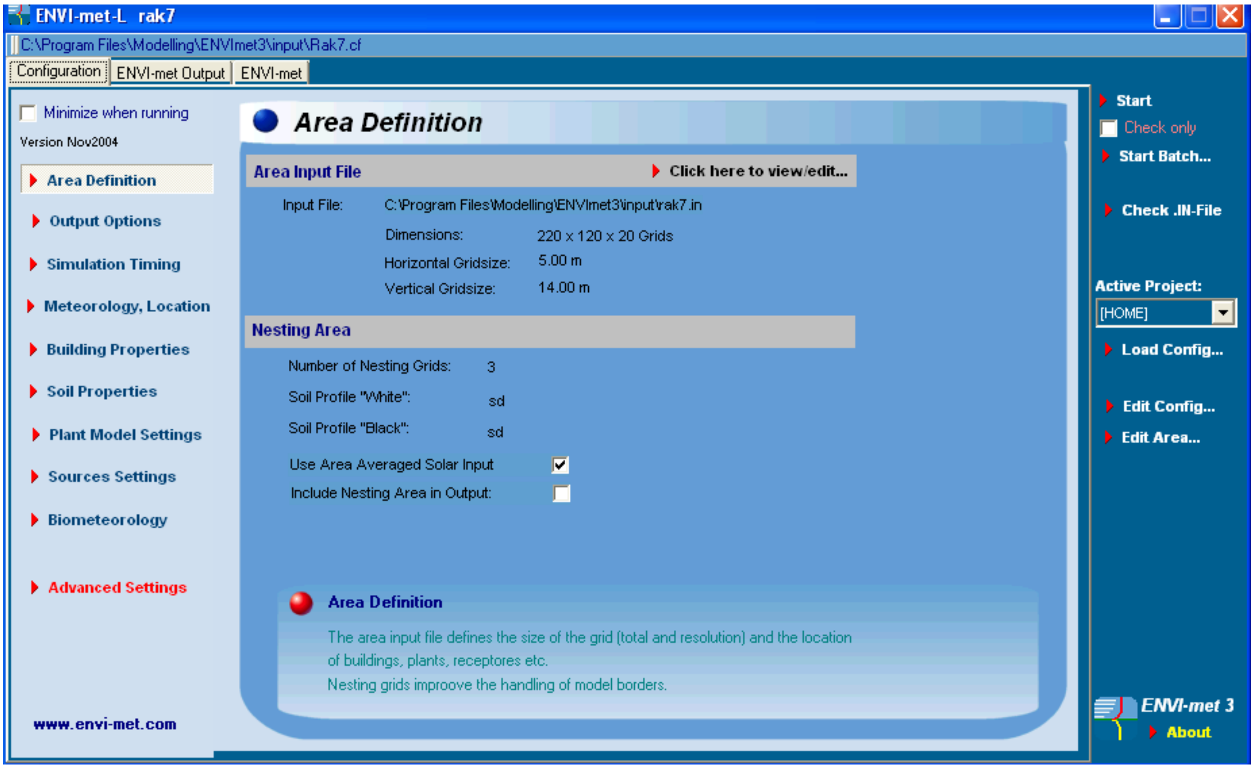
Appendix 4.1: Input files design (Domain 220 X 120)



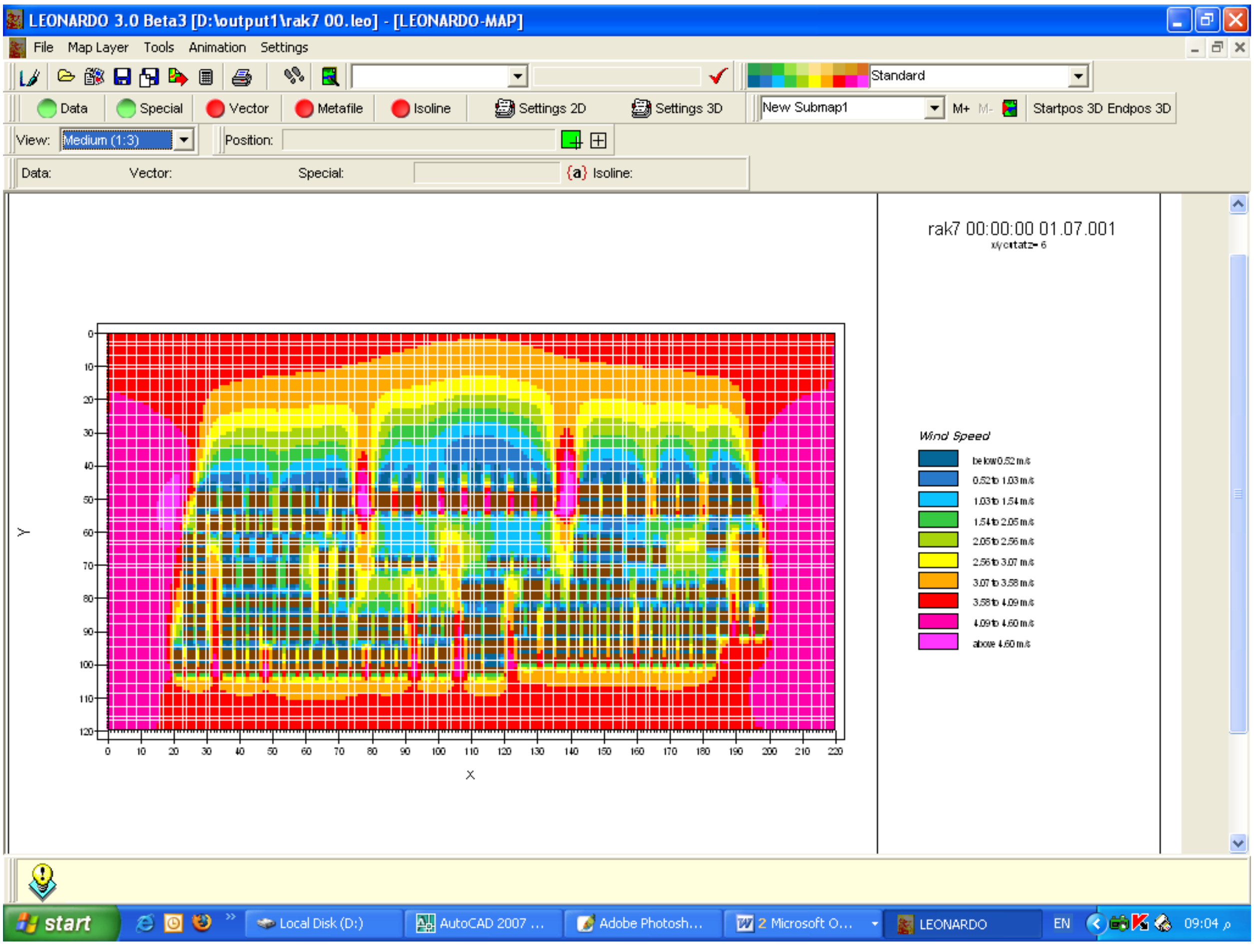
Appendix 4.2: Configuration editor



Appendix 4.3: Simulation interface



Appendix 4.4: Leonardo software interface to the data set in the output files



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