University of Dundee
College of Art, Science & Engineering

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EVALUATING AND ENHANCING DESIGN FOR NATURAL VENTILATION IN WALK-UP PUBLIC HOUSING BLOCKS IN THE EGYPTIAN DESERT CLIMATIC DESIGN REGION

By
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A thesis submitted in partial fulfilment of the
Requirements for the degree of
Doctorate of Philosophy

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DECLARATION

I hereby declare that this dissertation and the research work described in it are my own, unaided except as may be specified below, and that the dissertation has not been presented in any previous application for a higher degree.

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……………………….

CERTIFICATE

This is to certify that Medhat M. A. Osman has done his research under my supervision, and that he has fulfilled the conditions of Ordinance 14 of the University of Dundee, so that he is qualified to submit the following thesis in application for the Degree of Doctorate of Philosophy in Architectural Engineering.

Principal supervisor
Tamer Gado

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Second supervisor
Michael Spens

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To …

My beloved country Egypt

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ABSTRACT

This work is concerned with evaluating and studying the possibilities of enhancing natural ventilation performance and its use as a passive cooling strategy in walk-up public housing blocks within the Egyptian desert climatic region. This research attempts to maximize the benefits from the vast investments made in housing projects in Egypt through providing thermally comfortable housing prototypes that could use by contrast less energy for cooling purposes. This is considered essential in the light of the current concerns about energy all over the world. Egypt was divided to seven different climatic regions by the Egyptian organization for energy conservation and planning. The Egyptian desert climatic region, which was chosen as the research context, is the largest climatic region of Egypt. Most of the Egyptian new cities that accommodate the majority of the recent public housing projects are located within this desert climatic region that represents the typical hot arid climate characteristics. Nationally, the problem of the misuse of the housing prototyping was spotted. According to previous researchers, the same basic prototypical designs are being built all over the country without giving enough consideration to the actual effects of different climates and the diversity in the residents social needs. Regionally, within the Egyptian desert climatic region, the harsh climatic conditions rate the problem of achieving thermal comfort within these housing prototypes as the most urgent problem that needs to be examined in depth.

A pilot study that used observation and monitoring methods was conducted in the New Al-Minya city (*The representative city of the desert climatic design region*) in order to closely investigate this problem and identify its dimensions. The results confirmed thermal discomfort conditions of the housing prototypes built there, especially during the hot summer period. The passive design strategies analysis of the climatic context indicated that night purge ventilation is the most effective passive strategy that could enhance thermal comfort. These results go along with the role of natural ventilation in reducing the used energy for cooling and the actually massive national income spent on these housing prototypes to encourage this work so to concentrate on natural ventilation. Different studies using multi-approaches research techniques were employed in order to achieve the main aim of the research. These techniques included; literature review, monitoring, questionnaire and computer simulation.

A critical literature review was conducted including; the physical science of natural ventilation, its strategic design as well as the design measures that control natural ventilation and the airflow in; the macro, intermediate and micro design levels. The results of the investigations were discussed and interpreted in the light of this review.

A representative case study was chosen for the study. The natural ventilation performance in the case study was quantitatively and qualitatively evaluated through conducting field objective and subjective assessment respectively. In this evaluation study, the thermal performance of the case study under different ventilation scenarios was monitored, the airflow inside it was simulated using CFD (*computational fluid dynamics*) software "*FloVent*" and a sample of residents were questioned. This study identified many problems associated with natural ventilation uses and indicated its poor performance within the case study. A number of natural ventilation design measures were formulated based on the literature review and considering the evaluation study results along with the research context nature.

The proposed natural ventilation design measures were applied to the case studies and their effectiveness in terms of enhancing the natural ventilation performance was quantified using "*FloVent*". Results reported that the proposed natural ventilation design measures could significantly enhance the natural ventilation performance inside the case study quantitatively and qualitatively. This in turn maximizes the potential of providing thermal comfort by using both natural ventilation strategies; comfort ventilation and night purge ventilation. However, all the applied measures could not achieve neither an acceptable airspeed at any of the case study spaces nor a good airflow circulation at some of its spaces. It can be concluded that the current design of the case study can not achieve quality airflow without the use of the mechanical assisted ventilation. In general, it seems very difficult to optimize the air velocity within all spaces in a very dense multi-space design like this case study. A new design that considers natural ventilation and its drivers has to be introduced.

THESIS ORGANIZATION

To reach the research goals and proceed using its methodology, the thesis is organized in nine chapters divided into three parts in addition to the preliminaries; abstract, thesis organization, declaration, acknowledgment, dedication, table of content, list of figures, list of tables, and the appendices. The appendices were enclosed in a CD as they contain media files. Figure 1 illustrates the research organization in terms of parts, chapters, tasks, and main aim.

Chapter one is the introductory chapter that gives an overview of the whole research contents. In it, the overview of the whole research project, the research context, the research background, the research problem, the research objectives and its main aim are all presented. Finally the research general methodology is outlined.

Chapter two presents the related science to natural ventilation and airflow through reviewing the state of art related to this subject. Firstly, the interlink between natural ventilation and thermal comfort is clarified. Then the related physics to natural ventilation and the associated airflow are summarised. Finally, strategic and techniques design for natural ventilation is explained. In general, this chapter aims to build up a scientific background on which the discussion and interpretation of results throughout this work will be based on.

Chapter three presents a critical review of literature on the design measures and their parameters that are believed to control the air movement in and around the buildings and, in turn, affect natural ventilation performance. The design measures are comprehensively classified and their effect is discussed and explained. This chapter forms the base, from which the proposed enhancement design measures in the third part will be formulated.

Chapter four presents detailed preparatory steps of the evaluation study. In general, it aims to identify the research case study and the properties of its design's elements in terms of natural ventilation. In this chapter, the criteria, based on which the main case study of the research was chosen, are presented. Also, a detailed analysis of the chosen case study is conducted through highlighting the current settings of the case study's design elements that could be possibly related to the air movement and natural ventilation performance.

Chapter five presents the first part of the evaluation study (*The quantitative objective assessment of natural ventilation performance*). Firstly, the objective assessment methodology including the monitoring experiment design and the *CFD* simulation study are set out. Secondly, the results of the objective assessment are shown, discussed and analyzed according to the explained methodology.

Chapter six introduces the second part of the evaluation study (*The qualitative subjective assessment of using natural ventilation in the case study*). Firstly, the detailed methodology of the subjective assessment including methods, techniques and analysing method are illustrated. Then the discussion of the results of the occupants' subjective response towards using natural ventilation is presented.

Chapter seven is the first part of the natural ventilation enhancement in the case study. In it, the proposed design measures and their parameters, which are believed to have positive effect on the air movement in and around the buildings, are drawn from the review introduced in chapter three. A list of possible measures for optimizing natural ventilation performance will be then formulated.

Chapter eight presents the detailed methodology of conducting the enhancement process. Then the results of the natural ventilation enhancement process are shown. This chapter aims to quantify the effectiveness of the proposed natural ventilation design measures in terms of enhancing the natural ventilation performance inside the case study using *FloVent* computational fluid dynamics simulation software.

Chapter nine summarizes the research conclusions, presents the research general findings, as well as highlights the proposed further work.

At the end of the thesis the appendices and the publications are presented as an enclosed CD.

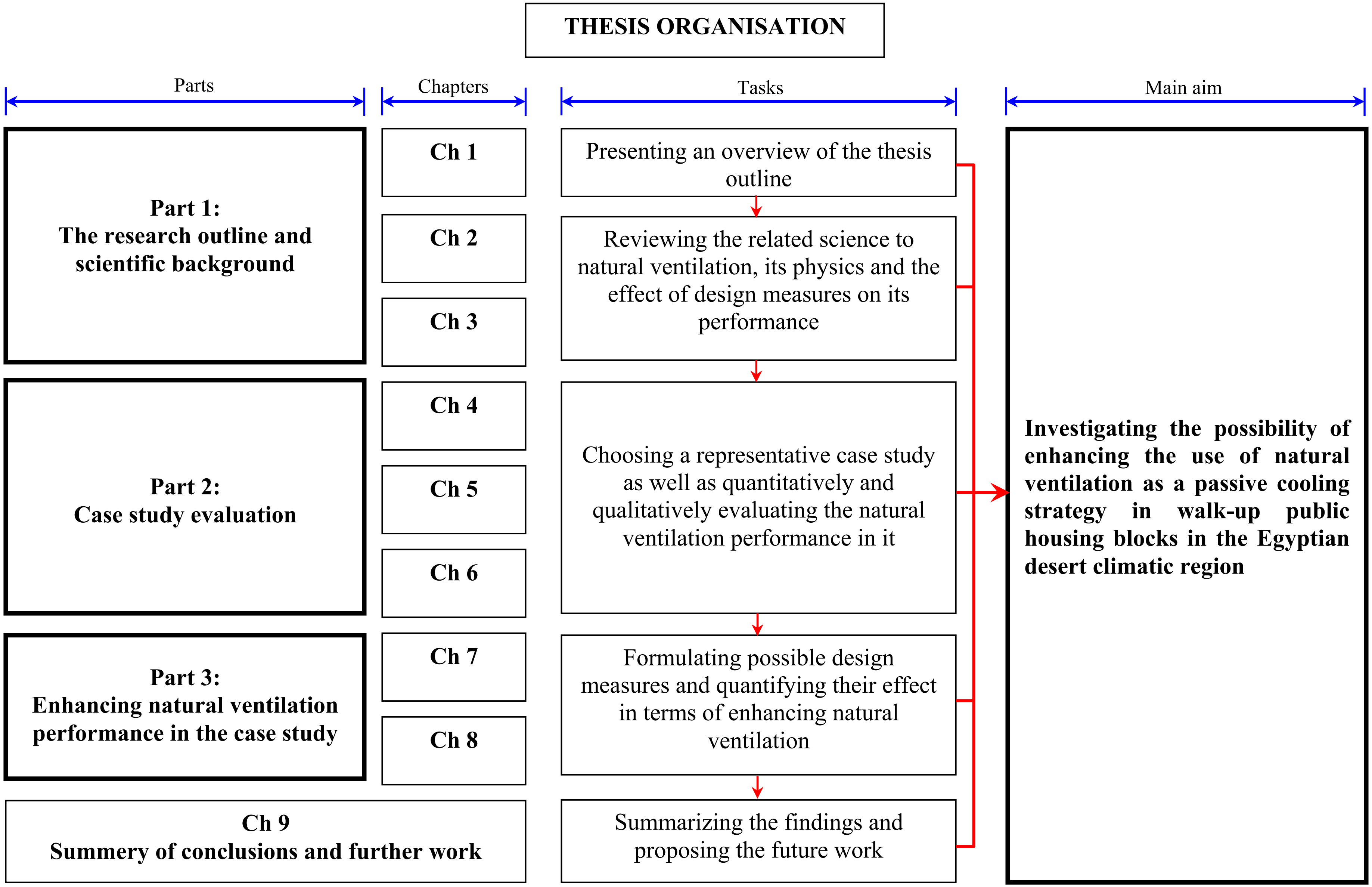


Figure 1: Thesis organization

Part 1:
The research outline and scientific background

Chapter 1:
Research context, problem, aims and previous work

1.1. Chapter one introduction

In this chapter, the overview of the research project is presented, the research geographical and climatic context are explained, the research background is shown, and the research problem is identified. In addition, the chapter reviews the previous literature relevant to the research problem within the Egyptian context. Finally, the research general methodology is outlined. In general, this chapter aims to present a preliminary understanding of the whole research project.

1.2. Research geographical context

The Arab Republic of Egypt is a part of the world's hot arid climatic zone and is used as the geographical context of this research. Egypt occupies the North Eastern corner of Africa continent and Sahara. It presents a unique location settling at the crossroads between East and West, Africa and Asia (Figure 1-1). It lies in the area between the northern latitudes of 23˚ and 32˚, and eastern longitudes of about 25˚ and 36˚ [1]. It has a total area of 1,010,000 sq km with only 3.3% of the total area inhabited in the Delta and Nile valley [2]. The rest of the area is desert with some scattered small settlements. This area consists of; Western desert, Eastern desert and Sinai peninsula. The *New Al-Minya city*, one of the Egyptian new cities built in the desert to the east of the *Al-Minya city* (Figure 1-2), was chosen to be the specific research geographical context. This choice was driven based on its representation to the research climatic context.

Figure 1-1: Location of Egypt in relation to the world and Africa's deserts, after Worldatlas [3]

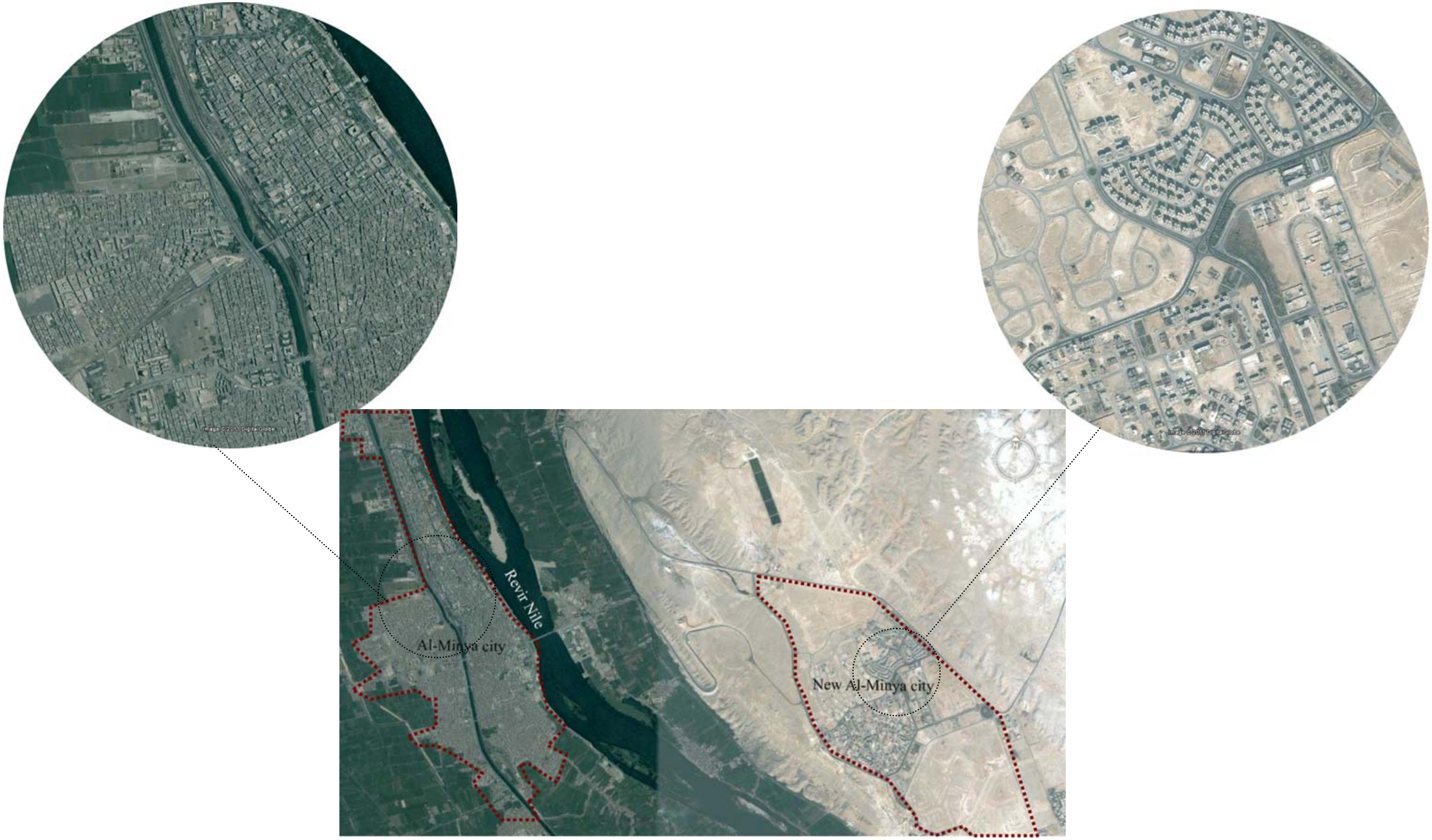


Figure 1-2: A satellite image shows the location of the *New Al-Minya city* in regard to *Al-Minya city* and the urban pattern of each

1.3. Research climatic context

In terms of climate, Egypt has a significant variation in the climatic conditions. It is divided by the Egyptian Organization for Energy Conservation and Planning (*EOECP*) [4] into seven different climatic design regions based on analyzing the climatic data observed at 45 meteorological station across the county by using Mahoney tables (Figure 1-3) (*Quoted from [5]*). According to Gado [5], climatic design region is defined as "*The region that demonstrates the same climatic design needs all over its area*". Those seven climatic design regions are; Mediterranean sea coast region, Red sea coast region, Semi-moderate region, Semi-desert region, Desert region, Very dry desert region and Mountain region. These regions are significantly varied in the climatic conditions. This in turn creates a great variation in the requirement of buildings' design in terms of being climatically responsive. The largest climatic design region among them is the desert region that includes most of the Upper Egypt governorates and most of the Egyptian western desert (Figure 1-3). Therefore, it was particularly chosen to be the climatic context of this research. According to Mohamed [6], the desert climatic design region is considered to be the most ruling bioclimatic design region in Egypt. The *New Al-Minya city*, one of the Egyptian new cities built in the desert to the east of the *Al-Minya city* (Figure 1-2), was employed as a representative location for the largest climatic design regions of Egypt (*the desert region*). This choice was based on the selection of *Al-Minya city* as a representative city for the desert climatic design region by the Egyptian Organization for Energy Conservation and Planning (*EOECP*).

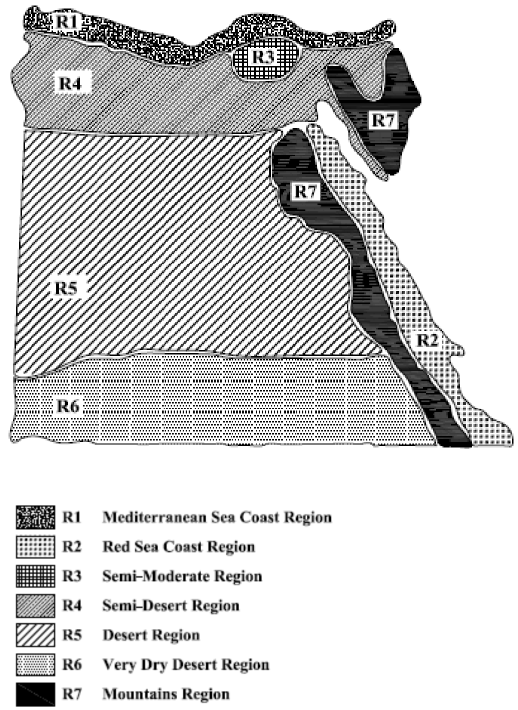


Figure 1-3: Climatic design regions of Egypt, reproduced after Gado [5]

Table 1-1: The Egyptian climatic design regions classification and properties, after Mohamed [6]

Climatic designs Regions	*Region description*	*Areas included*	*Average temperature (˚C)*	*Extreme temperature*		*Relative Humidity (%)*	**Rainfall Total** (mm/year)
				Max (˚C)	Min (˚C)		
Mediterranean Sea Coast Region	It is affected by the sea, thus It has the smallest diurnal range among all Egyptian regions. It also has the highest frequency and speed wind. The humidity levels are the highest in the summer. And it is the rainiest region in Egypt.	All the cities of the north coast of Egypt from the Libyan to the Palestinian borders; Al-Sallum, Matruh, Alexandria, Kafr al Shaykh, Domiatta, Port Said and Al Arish, Sedy Barany and Al Dabaa, (representative city is Alexandria)	20.38	38.8	5.7	69.16	197.4
Red Sea Coast Region	It has the effect of reducing temperatures of the coastal cities but less than the Mediterranean Sea. The winter humidity is higher than the summer humidity due to the presence of the mountains in the west of the region that hold the water vapor.	This region is on the same latitude of Upper Egypt cities from Al-Minya to Aswan. The coastal strip between the Red Sea and the Red Sea Mountains. (representative city is Hurgada)	25.17	40.8	3	42.42	4
Semi-Moderate Region	The Nile River and the wide cultivated area increase the humidity. But the Nile River has a very weak effect on lowering the temperature. In general the climate of this region resembles that of the Mediterranean region.	The Delta zone. It includes Al Gharbiyah, Al Sharqiyah, Ad Daqahliyah and parts from Al Minufiyah and Al Buhayrah. (representative city is Tanta)	21.2	36.0	7.5	61.75	45.5
Semi-Desert Region	It is considered as a transitional region between the semi-moderate region and the desert region.	Cairo, Giza and El Dakahlia,Bani-suef, Ismailia and Suez City It extends to the southern coast of Sinai at El-Tur City. (representative city is Cairo)	22.2	44	2.4	57.75	24.8
Desert region	It is considered the largest region in Egypt and the most ruling bioclimatic design region.	The western desert, the Oasis and the biggest part of the Al Wadi Al Jadid and most of the upper Egypt governorates; (representative city is Al-Minya)	21.82	44.7	2.5	53.5	3.7
Very dry desert Region	It is the driest region in Egypt because there is no rain and the annual humidity average is 13.4 percent. It is the hottest region in Egypt; and its winter is considered warm.	Aswan, El Sad El Aly, Lake Nasser, Abu Sunbul and the rest of the Al Wadi Al Jadid. (representative city is Aswan)	26.16	47.5	3	29.16	1.4

Table 1-1 illustrates the main aspects of the different climatic design regions and their representative cities in Egypt with the desert region's characteristics highlighted. As seen from the table, The annual temperature in the desert region ranges between (*2.5^{o}C*) in winter and (*44.7^{o}C*) in summer with annual average of (*21.82^{o}C*). The relative humidity averaged at (*53.5%*) with low level precipitation during winter reaches (*3.7 mm/year*). By analyzing the typical climatic condition of *Al-Minya city* (*The representative city of the desert climatic design region and the research context*), it was found that it has a typical hot-dry climate with hot summers and relatively cold winters. The coldest month is January (*average monthly outdoor temperature is 12.4^{o}C*) and the hottest month is August (*average monthly outdoor temperature is 29^{o}C*). The maximum temperature reaches (*42.1^{o}C*) in June and the minimum temperature reaches (*1.3^{o}C*) in February. Diurnal differences reach (*10.2^{o}C*) during the hottest day of the year (*1st August*) and (*19.1^{o}C*) during the coldest day of the year (*24th January*). The average summer temperature ranges between (*28.1^{o}C*) in June and (*29.8^{o}C*) in August. The average winter air temperature ranges from (*12.2^{o}C*) in January and (*13.8^{o}C*) in February. *Al-Minya* has a clear sunny sky throughout the year with almost no rain and an average daily solar radiation ranging between (*3690 Wh/m^2*) in December to (*10485 Wh/m^2*) in May. On average, the most frequent wind blows from the North and North West with speeds ranging from (*1.4 m/s*) to (*8.3 m/s*). In summer, the prevailing wind blows from the North and North West and reaches (*8.3 m/s*). In winter, the prevailing wind blows from the same directions with speeds reaching (*6.9 m/s*). The cooling degree hours reaches its peak in August (*6438 hours*), while the heating degree hours reach its peak in January (*4157 hours*).

1.4. Research background

From the early 60's, the housing demand in Egypt has started to be an urgent matter as a result of the alarming population growth along with the informal expansion of existing cities [7]. Since then, the Egyptian government has adopted different strategies in order to provide low income families with affordable housing. During the period between 1952 and 1975, the government built mass production housing blocks on the edges of the cities (Figure 1-4). The individual apartment area and design did not meet the residents' desires [8]. These housing prototypes have been halted since 1995, when another designs started to be adopted as explained below.

Figure 1-4: Government housing prototype built between 1952 and 1975: an image from Helwan city

Since 70's the Egyptian government has adopted a new strategy in order to solve the housing problem in the over populated cities on the Nile valley. This strategy was based on developing a number of new cities in the desert. 22 cities have been built in three stages (*generations; as called in Egypt*) since late 70's until now and 38 cities are planned to be built in the future (Figure 1-5) [9].

Figure 1-5: The current and planned new cities in Egypt, after NUCA [9]

From the 90's, the Egyptian new cities have become the main land of accommodating territorially most of the public housing projects in order to encourage people moving into them. In October 1995, modified design housing norms for youth in the new cities have started to replace the old dull blocks. These norms were built in the form of walk-up housing blocks (*apartments' blocks that do not exceed 6 stories height*) with flats' areas of 100, 70 and

63 m^2. This project was known as the "*Youth Housing Project*" [10]. In August 1998, the non-governmental organization (*future association*) started the *"Future Housing Project*". This project aimed to provide dwellings for low income families. The new urban communities' authority in Egypt described this project by reference to its unique architectural prototypes which can contribute with the proposed improvements [11]. Dwellings with area of 63m^2 and well designed building mass as well as facades were adopted in this project.

In October 2005, The Egyptian government began to adopt a massive project to produce over 500,000 dwellings for low income in both old and new cities within a time period of six years. This project is called "*The National Housing Project*". The design of the projects' prototypes has been delegated to the Egyptian housing and buildings national research centre and some universities [12]. The project is working within 7 different approaches. They are [12, 13]:

1- ***Ownership of housing units' approach***[1] to be built in both new and old Cities. This approach is being built in walk-up housing blocks form;
2- ***Investors' lands approach***[2] to be built in new Cities. Also, in walk-up housing blocks form;
3- ***Build your own house approach***[3] to be built in new cities in form of attached three stories apartments' blocks;
4- ***Smaller dwellings (36m^2) for rent approach***[4] for the underprivileged (very poor) people. These are being built in walk-up housing blocks form as well;

Note 1:
Dwellings to be built by the government and sold to low-income people at no profit.

Note 2:
Dwellings to be built by investors on state owned land and sold to low-income people at tiny profit.

Note 3:
Houses to be built by low-income people with governmental financial support in land price and structure.

Note 4:
Dwellings to be built by the government and rented to underprivileged people.

5- ***63m² dwellings for rent approach***[5] within governorates, new Cities and Endowment Authority's plots. They are being built in the form of walk-up housing blocks;

6- ***Family House for rent approach***[6] in 6th of October governorate. they are built in an attached two stories houses form; and

7- ***Ownership of rural house approach***[7] in Governorates.

The "*National housing project*" is considered the largest housing project, which is unprecedented in the number of produced dwellings throughout the country.

Note 5:
Dwellings to be built by the government and rented to low-income people.

Note 6:
Houses to be built by the government and rented to low-income people.

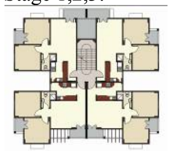
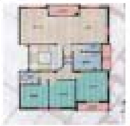
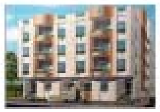
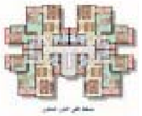
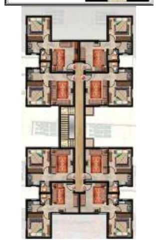
Note 7:
Houses to be built by the government at rural areas and sold to farmers.

Currently, and beside the *National housing project*, there are two other projects that aim to provide dwellings and houses for the middle-class families in Egypt. These projects are; *Free housing project* and *Family housing project*. The free housing project is being built in walk-up housing blocks' forms that contain flats in larger areas than other projects. However, the Family housing project is based on providing large plots to people to be built by themselves and according to eleven pre-designed prototypes. Table 1-2 illustrates all information about the current public housing projects in Egypt and examples of their architectural designs from 1995 onward.

1.5. Identifying the research problem

Nationally, the main problem in the public housing projects is the indiscriminate use of prototyping. In other words, all the housing projects, with no exceptions, are designed as fixed prototypes that are being built all over the country regardless of the differences in; people desires, social life, and climatic conditions.

Table 1-2: Public housing projects classification in Egypt from 1995 onward, acquired from NUCA[13], MHUUD[12], and HBNRC[14]

The project	**Youth housing project (1995 – now)**	**Future housing project (1998 – now)**	**Family housing project (2004 – now)**	**Free housing project (2005 – now)**	**National Housing Project (2005 – 2011)**						
					Ownership of housing units	**63 m^2 dwellings for rent**	**Investors lands approach**	**36 m^2 dwellings for rent**	**Build your own house approach**	**Family houses for rent**	**Ownership of rural houses**
Proposed places to be built in	New Cities	New Cities	New Cities	New Cities	New cities + Governorates	New cities + Governorates + Endowment authority's lands	New Cities	New cities + Old cities in governorates	New Cities	6th of October governorate	Old ruler communities in governorates
Targeted amount to be built	84633 Dwellings in areas of (100 – 70 – 63 m^2) in 4 stages	15636 Dwellings	20,000 plots recently addressed	3500 Dwellings	201233 Dwellings	136925 Dwellings	218931 Dwellings on 5181 Acre	76,000 Dwellings	91736 House with 3 Dwellings each	3020 Houses	7389 Houses
Project description	Walk-up housing blocks contain flats in areas of: Stage 1: 100 m^2, Stage 2: 70 m^2, Stage 3: 63 m^2, Stage 4: 50-57 m^2	Walk-up housing blocks contain Flats in areas of: 63 m^2	Fully equipped plots in areas of (150:350 m^2) to be built according to owners requirements and the relevant (11) models	Walk-up housing blocks contain flats in areas from 63 to 120 m^2 to be sold at no profit	Walk-up housing blocks contain 4:6 flats/floor in areas of 63m^2	Walk-up housing blocks contain 4:6 flats/floor in areas of 63m^2	Walk-up housing blocks contain 4:6 flats/floor in areas of 63m^2	Walk-up housing blocks contain flats in areas of 36 m^2	Fully equipped plots in areas of 150 m^2 to be built in 3 floors height on area of 75 m^2	2 floors attached houses	1 floor attached houses
Architectural prototypes	Stage 1,2,3:   Stage 4:  	   	   	   	 			   	  	 	

Moreover, these prototypes do not provide any kind of flexibility in their designs to fulfil the future requirements of the residents. This in turn has made these prototypes unpleasant for their users and not suitable functionally, socially [8, 15] as well as thermally [16-18].

This work is concerned with the thermal performance and climatic design of the Egyptian housing. Climatically, the problem of indiscriminate use of the prototyping method is against the rule of thumb which states that diversity in climatic conditions creates different considerations that have to be considered in the buildings' design [19]. Gado [16] proved that the thermal performance of the same dwellings' block differs from one climatic region to another in Egypt. Also, he reported that the block design could not be considered as a climatically responsive design at any of the climatic regions. The same problem also was found to be true in the schools' buildings within Egypt, where the prototyping is also being applied [6].

1.5.1. Research problem context

In terms of climate, the harsh climatic conditions of the desert climatic design region (*The research context*) raise the necessity of designing climatic responsive dwellings. Designing climatically responsive dwellings not only can achieve thermal comfort for occupants but also can make a significant improvement in energy conservation. Passive strategies' analysis for *Al-Minya city* was conducted. This analysis was conducted using the Szokolay [20] method of psychometric analysis in order to investigate the effectiveness of different passive design measures on achieving thermal comfort. The Autodesk *Weathertool* software along with the typical metrological year (*TMY*) weather file for *Al-Minya city* were used to perform this analysis. Figure 1-6 to Figure 1-11 show the analysis' results.

It can be seen from the graphs (Figure 1-6: Figure 1-11) that the passive cooling strategies play a significant role in increasing the time spent under thermal comfort conditions in such a climate. All passive cooling strategies can have a significant effect within *Al-Minya* climatic context in terms of thermal comfort, especially during the hottest months of the year (*April to October*). Using direct evaporative cooling (Figure 1-10), natural ventilation (Figure 1-8), indirect evaporative cooling (Figure 1-11) and night purge ventilation along with exposed thermal mass (Figure 1-9) can increase the comfort percentage during the hottest months to reach an average of 34.1%, 51.6%, 68.0% and 83.9% respectively. This asserts that the use of night purge ventilation with exposed thermal mass is the most effective passive strategy able to significantly increase the comfort percentage with its peak 98.0% reached in May.

In terms of the housing projects in the research problem context, seven different walk-up public housing prototypes were identified in the *New Al-Minya city*. Before 1995, two prototypes were built on the edges of the first and the second neighbourhoods of the city. These prototypes are no longer in use by the government. Between 1995 and 2005, three prototypes were used within two projects: The youth housing project and the future housing project. These three prototypes are known as *Asfour Al-Gana* (Figure 1-12), *Al-Bondok* (Figure 1-13) and *Kamar Al-Deen* (Figure 1-14) and they were built in a dedicated site in the fourth district at the northern edge of the city. After 2005 two prototypes were introduced: *Al-Mokhtara* (*Youth housing project*) (Figure 1-15) and the *Al-Talet prototype* (*National housing project*) (Figure 1-16).

The current housing buildings' non-responsive specifications in such harsh climatic conditions in the Egyptian deserts can result in the occupants of public housing blocks there being thermally uncomfortable, especially in the hot summer season.

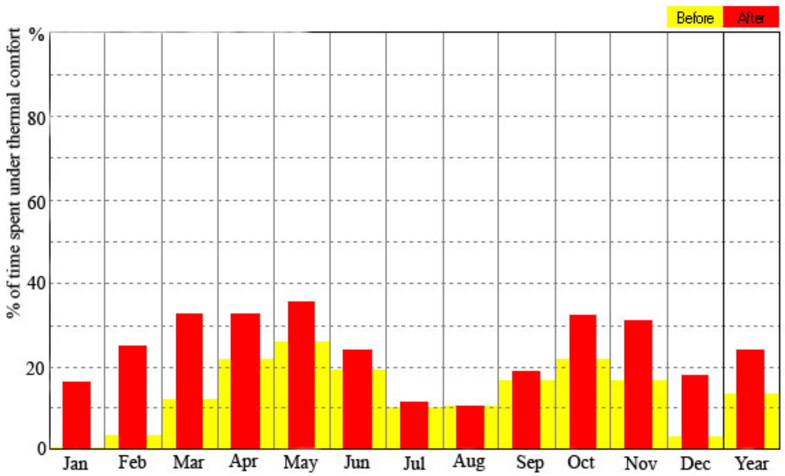


Figure 1-6: Using passive solar heating

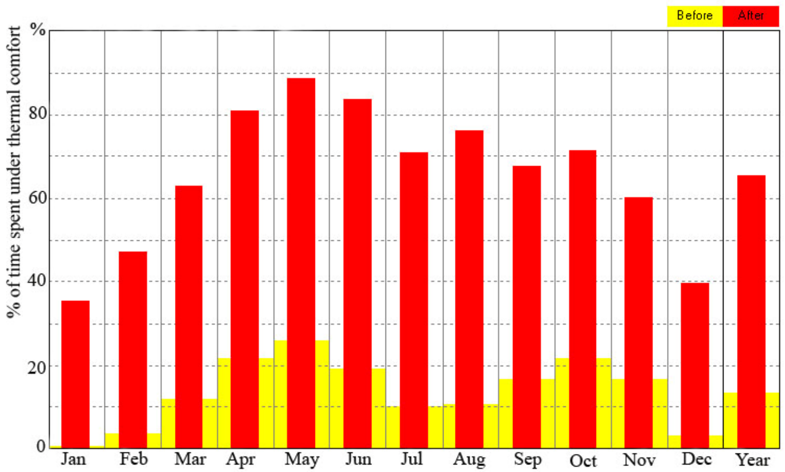


Figure 1-7: Using heavy thermal mass

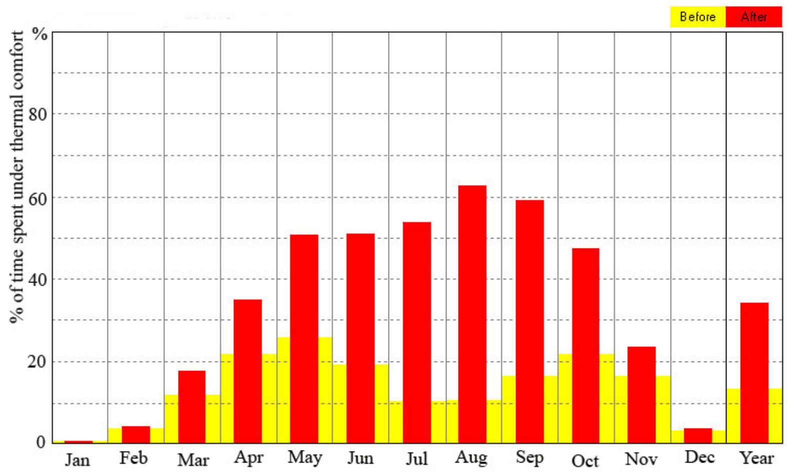


Figure 1-8: Using natural ventilation

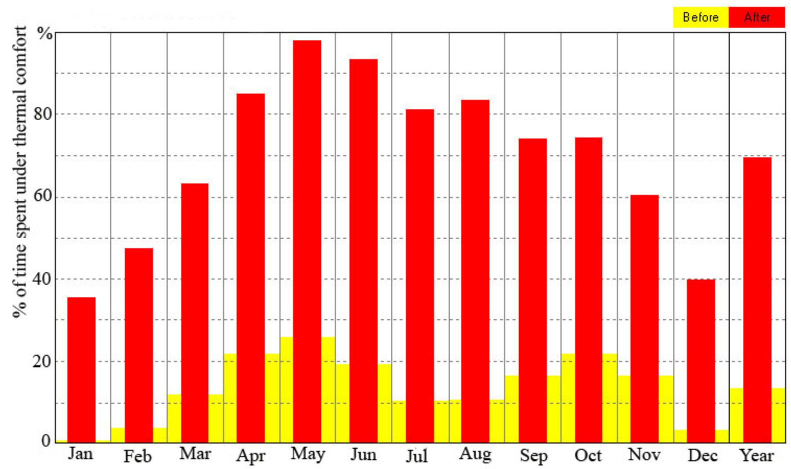


Figure 1-9: Using night purge ventilation + exposed thermal mass

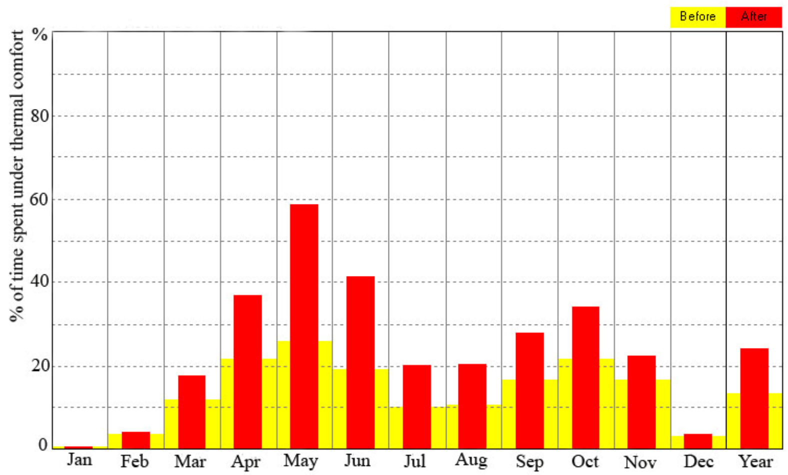


Figure 1-10: Using direct evaporative cooling

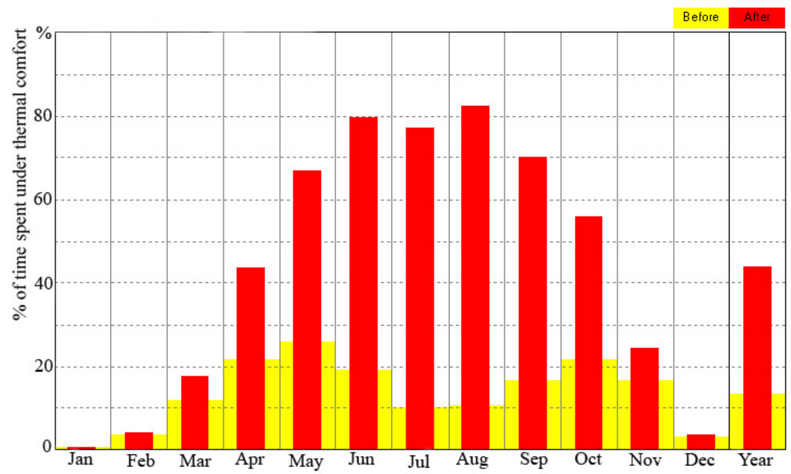


Figure 1-11: Using indirect evaporative cooling

Figure 1-12: Asfor Al-Gana prototype (*Stage 2 – Youth housing project*)

Figure 1-13: Al-Bondok prototype (*Stage 3 – Youth housing project*)

Figure 1-14: Kamar Al-Deen prototype (*Future housing project*)

Figure 1-15: Al-Mokhtara prototype (*Stage 4 – Youth housing project*)

Figure 1-16: Al-Talet prototype (*National housing project*)

A pilot study was conducted in the *New Al-Minya city* during July 2008 in order to closely investigate the truth of this argument.

1.5.2. Pilot study

This pilot study was conducted in two stages. The first stage aimed to identify the occupants' adaptive behaviour and transformation which they have done to their dwellings as a response to the climatic context. This stage was conducted through observing the public housing blocks that were built in the *New Al-Minya city* after 1995.

The second stage aimed to investigate the dwellings' thermal performance through monitoring the air temperature inside one of the existing dwellings. In this stage one dwelling within one of the *Al-Mokhtara* prototype blocks (*Youth housing project*) was employed as a case study (See Figure 1-17). This dwelling was the only dwelling that the researcher had access to at that time. It also was not occupied with no heat sources or thermal loads being introduced. The internal air temperature inside the case study was monitored over a period of four days (from 23-07-08 at 14:00 until 27-07-08 at 14.00. Air temperature data loggers (*Hobo U12*) were installed inside the north east facing living room (*S1*) and the south east facing bedroom (*S2*) (See Figure 1-17).

It was found that the microclimate of this block provided the optimum conditions for air movement inside the interior of the investigated dwelling. This apartment block faces the prevailing wind direction (*north - northwest*) with no obstacles in the wind direction (See Figure 1-17). Therefore, It was found to offer a good chance for studying the effect of applying natural

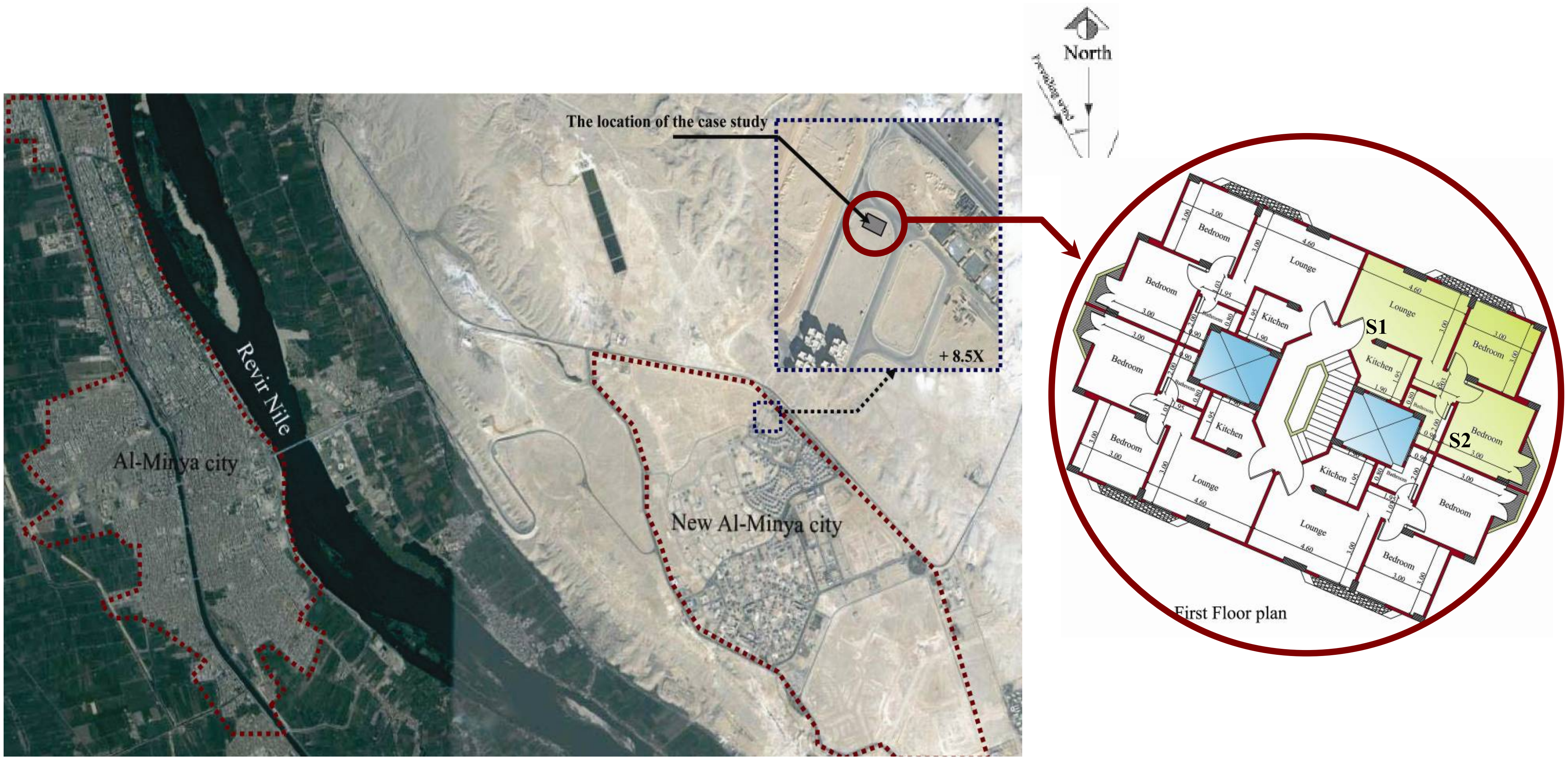


Figure 1-17: The monitored case study location, orientation and plan

Ventilation passive cooling strategies, which advised by the passive strategies analysis in the previous section, to the dwelling. Three possible ventilation cases were applied:

- ***Case (1)*** Infiltration only (*the air only enters the dwelling through fabric cracks and voids between openings shutters*): All windows were closed all the time for 48 hours;
- ***Case (2)*** Day and night natural ventilation: All windows were opened all the time for 24 hours and
- ***Case (3)*** Night purge ventilation only: All windows were opened during the night approximately an hour after sunset (*19:53*) and closed approximately an hour before sunrise (*6:10*) on the next day.

The monitored internal air temperature data were then compared to the comfort temperature calculated using the free running adaptive model's equation introduced by Humphreys [21]:

$$Tc = 11.9 + 0.534*To \qquad \text{(Eq: 1-1)}$$

Where:

Tc = The comfort temperature and

To = The average outside temperature for the monitoring period.

The results of the first stage showed the transformations users adopted to respond to the climate. Most of these transformations gave an indication of the non-responsive design of the observed housing blocks. These transformations can be categorized under three different groups:

a) *Installing external horizontal and vertical solar shading devices:* The majority of the openings are not shaded despite their high exposure to solar radiation. Occupants had to install horizontal solar shading devices in many cases as shown in Figure 1-18 for solar protection. Also, several windows and balcony doors were covered with vertical textile curtains as shown in Figure 1-18. This was done to provide occupants with privacy and to protect external walls and interiors from early morning and late afternoon direct solar radiation.

b) *Altering the windows' design:* The typical window design in residential buildings in Egypt comprises an external timber Venetian shutter and an internal single glazed timber frame shutter. Some housing prototypes' Venetian shutters in *New Al-Minya city* were designed with holes to induce air movement inside the spaces without fully opening the windows. However, in several cases users have blocked these holes with plywood, plastic or paper sheets (Figure 1-19). This was to avoid sun glare, minimize dust as well as provide high level of privacy.

c) *Using air conditioning equipments*: Air conditioning systems and equipments in Egypt are mainly installed for cooling purposes. Although they are relatively expensive for low-income people living in studied public housing blocks, several air conditioning equipments were spotted (Figure 1-20). This indicates that many occupants are suffering from overheated dwellings in summer.

The monitoring results in both spaces (*S1 and S2*) showed that in the first 48 hours of the experiment, when no ventilation was applied (*Case 1*), the internal air temperatures always exceed the calculated comfort temperature. However, when applying both ventilation cases (*Case 2 and Case 3*), few hours at late night and early morning dropped under the comfort temperature as a result of applying ventilation either strategy (Figure 1-21). This happened as a direct effect of opening the windows during the night and the significant diurnal difference.

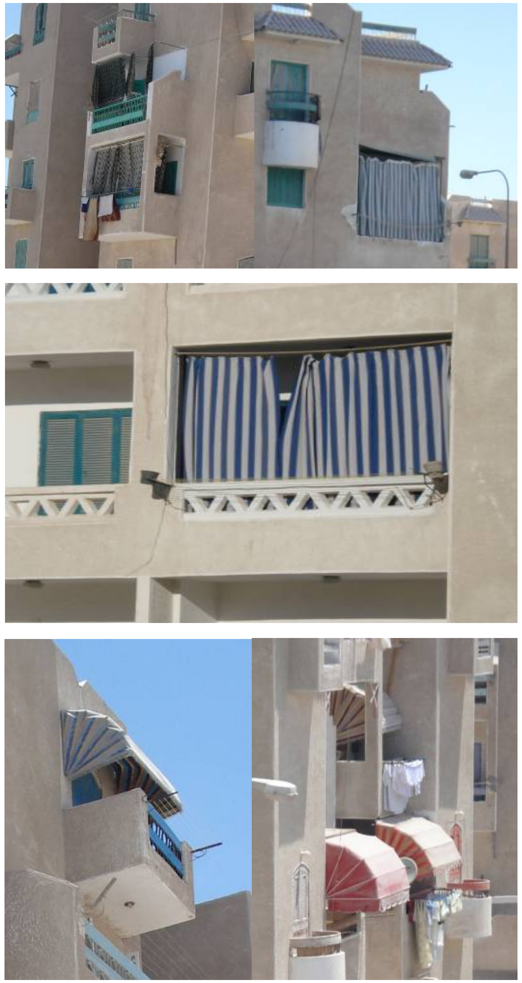


Figure 1-18: Installing external horizontal and vertical shading devices

Figure 1-19: Altering windows' design

Figure 1-20: Using air conditioning equipments

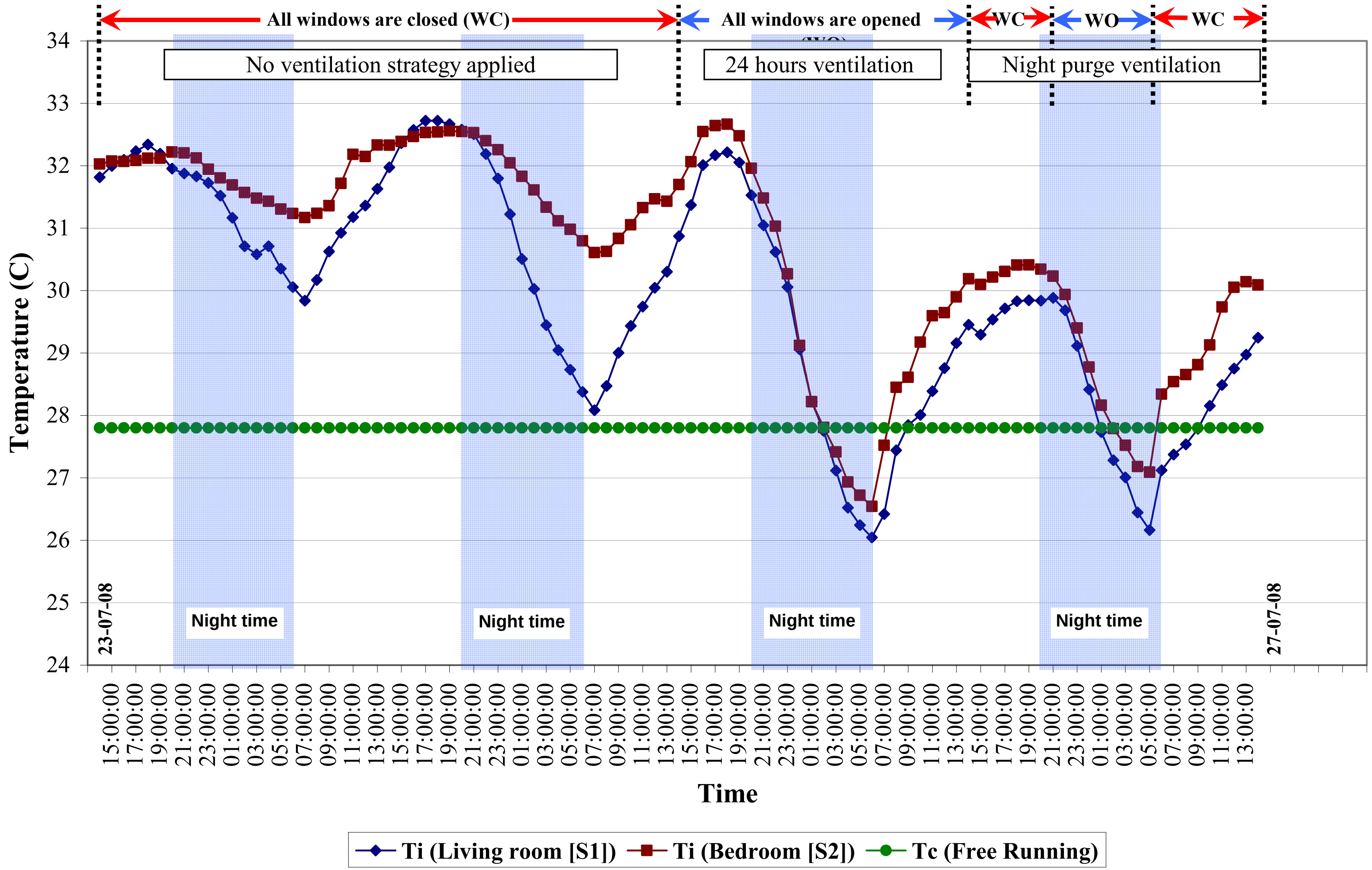


Figure 1-21: Monitored temperature against calculated free running adaptive comfort temperature

In general, the outcomes of the pilot study showed that there is a clear problem in the walk-up public housing blocks within the desert climatic design region in terms of achieving thermal comfort for their occupants.

Working generally on improving thermal comfort inside walk-up housing blocks in Egypt's deserts is a very wide subject as numerous factors and strategies have to be studied. Therefore, the research chose to deal with this problem by working on passive means and specifically, the most effective passive strategy in achieving thermal comfort within such context. As advised by the passive strategies analysis (*see section1.5.1*), the most effective passive cooling strategies in the research context are, in order, night purge ventilation with exposed thermal mass, indirect evaporative cooling, natural ventilation and direct evaporative cooling. According to this, the research chose to focus on studying natural ventilation passive cooling strategies. Bearing in mind the relationship between the air movement and both direct and indirect evaporative cooling strategies, one can argue that achieving well designed air movement for natural ventilation purposes in buildings can positively enhance the effectiveness of evaporative cooling strategies as well.

The performance of natural ventilation strategies along with its cooling effect inside *Al-Mokhtara* prototype built in the *New Al-Minya city* were further investigated by Gado and Osman[22]. This was studied by employing the same dwelling used in the pilot study. Although, the great potential of using natural ventilation strategies in achieving thermal comfort via cooling, the results of this study showed a very poor performance and cooling effect of natural ventilation strategies in the case study. They referred these negative results to improper design of the thermal mass along with insufficient exposure to the airflow. Hence, the air movement quality inside the dwelling was further investigated using *FloVent*[1] computational fluid dynamics (*CFD*) software. The *CFD* analysis was performed in two cases; the first case allowed cross ventilation through opening the rooms' doors and the second case allowed only single side ventilation through closing the rooms' doors. This analysis confirmed the poor air movement and circulation within the dwelling especially in the second case.

Note 1:
FloVent is Computational Fluid Dynamics (CFD) software that predicts 3D airflow, heat transfer, contamination distribution and comfort indices in and around buildings of all types and sizes.
http://www.mentor.com/products/mechanical/products/flovent

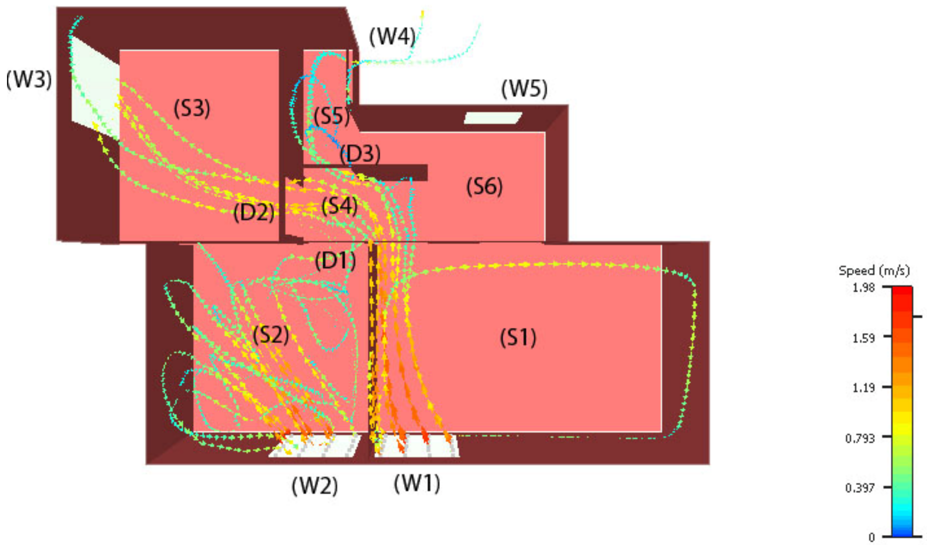


Figure 1-22: Airflow pattern in the cross ventilation case, after Gado and Osman[22]

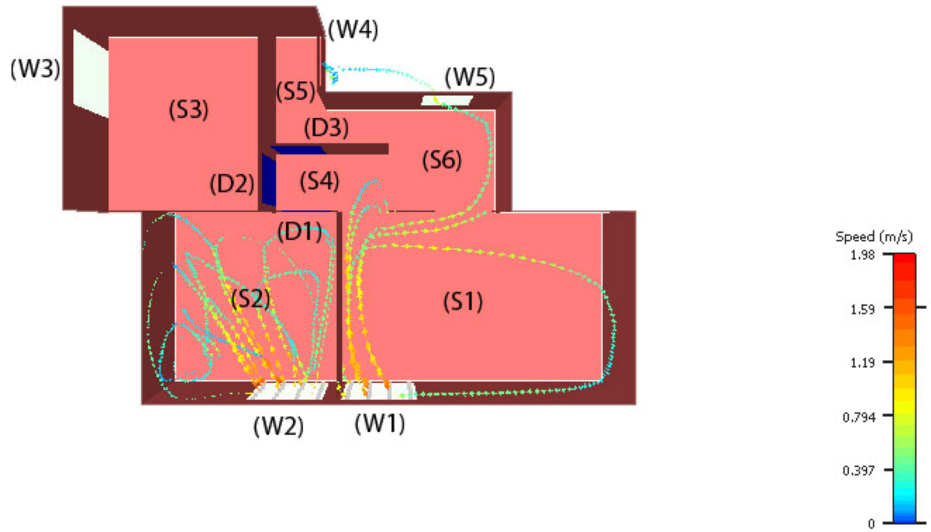


Figure 1-23: Airflow pattern in the single side ventilation case, after Gado and Osman[22]

In addition, it proved the researchers' hypotheses of insufficient exposure of the thermal mass to the airflow. Figure 1-22 and Figure 1-23 show the airflow pattern in both studied ventilation cases.

From the above discussion, one main problem can be identified inside walk-up public housing blocks within the Egyptian desert climatic design region with regard to natural ventilation strategies. *This problem is the reduced capabilities of natural ventilation passive cooling strategies in achieving thermal comfort, as theoretical potentials showed, due to the poor airflow in dwellings as well as the poor exposure of their thermal mass to the airflow*. This problem has been considered as the primary research problem of this work.

1.6. Previous work

The reviews of the previous work that investigated climatic responsive design and in particular airflow for natural ventilation purposes in Egyptian context were found to be very limited.

Some of these studies were shallow, in terms of climatic design, and their results needed to be verified due to the lack of accuracy sometimes and the lack of reliable methodologies sometimes. Bashandy [23] studied the climatic, socio-cultural and physical factors that contributed in creating the current local urban and architectural patterns of Upper Egypt cities with reference to the Nubians' architecture. She analysed the main aspects of the Nubian traditional architecture and urban morphology. She found that each identified design aspect is associated with a creation factor that responded to either local climatic, socio-cultural or physical context. The approach of designing by response to climate and local social identity was strongly recommended in her research. In this work, no particular case study was analysed and the researcher relied on theoretical analysis of her main observed aspects through basic scientific fundamentals. No validation for the research results was conducted.

Mohamed and Hassan [15] investigated the adaptability between environmental factors and the dwellings' design in contemporary Egyptian public housing blocks. In this study, the public housing prototypes that were built in *Cairo* and *Asuit* cities were analysed. They analysed the prototypes' design in terms of the sites' climatic conditions and the social requirements of local occupants. The investigation concluded that none of the investigated prototypes is responsive either to the climatic conditions or to the people's social requirements. Again, no objective evaluation of the prototypes' performance was done to verify the study's results.

Fagal [24], looked into the thermal effectiveness of applying traditional urban form configurations to the Egyptian deserts' new developments. He investigated the thermal performance of partially shaded lanes in *Qasr Al-Farafra* in *Al-Farafra Oasis*. He monitored the temperature, humidity and airspeed at 14 different points across *Qasr Al-Farafra*. 12 points of which were located in a shaded lane and 2 points at an open square. The analysis of results showed that although the airspeed inside the lane is less than the points measured in the square by 80% over the measurement period, the air temperatures across the lane were lower than the temperatures of the square by 1.5^{o}C to 3^{o}C on average. The study emphasised the significant role played by the *sa'bat* (*parts from the houses which bridge over the street*) in shading and improving the external air movement. He then studied the effectiveness of this technique when applied to a contemporary housing project at *Toshka* using *FloVent*[1] computer fluid dynamic simulation software. He claimed that simulation results suggested a similar pattern when the same technique was applied in *Toshka*. The problem with this work is the lack of rigour and depth of analysis. The methodology as applied is not clear and in many cases inappropriate especially in the monitoring methodology. For example, a conclusion was drawn that *sa'bat* played a significant role in driving the air movement by the effect of thermal buoyancy with reference to one of the measurment's points. This conclusion can not be drawn using only measurements taken at 1.50 m as used by the author. In addition, the measurement points were installed at the lane edges only, while the conclusions showed the performance in the depth of the lane. Also, no information were introduced about whether the measurements were taken at all monitoring points in the same time in order to introduce fair contrast between results or not. It was only mentioned that many readings were taken at the same point and averaged to avoid fluctuation in measured variables. The number of readings at each point was up to the experience of the equipment user. In general, no sufficient data were presented to justify the conclusions suggested by this work.

Note 1:
FloVent is Computational Fluid Dynamics (CFD) software that predicts 3D airflow, heat transfer, contamination distribution and comfort indices in and around buildings of all types and sizes.
http://www.mentor.com/products/mechanical/products/flovent

Attia [25] looked into studied the effect of landscape elements inside Old *Cairo* houses that used the courtyards' building forms. He studied the impact of vegetation, use of water, and walls on enhancing the thermal comfort inside the house of *Al-Suhaymi* as a case study from Egypt. He also conducted the same study in other two case studies; *Al-Hambra* and the *Generalife* villa in Granada, Spain. The design characteristics of the three case studies' courtyards were analysed, the shading pattern of them was studied and some temperature and humidity measurements were taken. He concluded that "*landscape design principles inherent to the traditional courtyard buildings can make a valuable contribution to contemporary design*" [25] The temperature and humidity measurements introduced clear evidence of the important role of the traditional courtyard as a passive technique. The researcher in this work extracted many positive cooling features from the traditional courtyards' design elements. However, he did not demonstrate the ways by which the findings can be applied to the contemporary designs.

The notion that the traditional buildings and their urban forms in Egypt were responsive to both climatic and socio-cultural contexts dominated the minds of not only Egyptian researchers, but also international colleagues. Filippi [26] studied two traditional villages in *El-Dakhla* oasis; *El-Qasr* and *Balat*. He aimed to identify the main typological and environmental characteristics of both villages in order to provide conservation guide lines. He looked at the urban form, housing typology, building materials and construction techniques. His analysis confirmed the adaptation of both villages to the climatic and social requirements of their context. He concluded that the urban form responded to the locally sensitive climate. However, his work was very limited to his own observations' analysis and did not give enough information or assessment on how the urban form or building design had itself responded to the climate.

The same two villages' urban patterns were analysed by Balbo [27] in terms of their typological and morphological aspects. This work analysed the case studies versus the Islamic values of the Law *(Shariaa)* dictated by the Holy Koran (*Arabic: El-Qur'an*) and the teachings of Prophet

Mohamed peace be upon him (*Arabic: Sun'na*). Through this analysis an evidence of the significant role of Islamic values in forming those villages was presented. He also highlighted the adaptability of urban form to climatic context. However, this work was to a far extent limited to the social and moral drivers of the urban form and did not give enough attention to the environmental aspects of either external or internal spaces. In general, it was a theoretical analysis-based study.

Some other studies went more deeply in studying thermal comfort matters in the Egyptian context and introduced verified results through clearer methodologies. Regardless to the study's context, all these studies almost used the same methodology (*parametric analysis using computer simulation*) in improving thermal comfort inside their case studies.

Gado [16] studied the possibility of formulating effective passive design strategies and measures that could be used in different climatic design regions of Egypt to enhance the thermal comfort and energy efficiency. This work implemented setting up a climatic design methodology to be applied in the early design stages for buildings in Egypt. He argued that the main elements of the buildings' structure can be used as passive measures to achieve thermal comfort. One of the youth housing project prototypes was used as a case study. A parametric analysis was conducted using *Autodesk Ecotect*[1] and *HTB2*[2] software in order to quantify the effectiveness of the proposed passive measures in terms of thermal comfort and energy efficiency. Different configurations of external walls' mass, internal walls' mass, shading devices, roofs' insulation, glazing, windows' tightness, walls' colour and roofs colour were tested over the whole Egyptian

Note 1:
Autodesk Ecotect is comprehensive software tool for building performance analysis. It provides a wide range offunctions and simulations
http://ecotect.com/products/ecotect

Note 2:
HTB2 is software suite intended for the general purpose simulation of the energy and environmental performance of buildings
http://www.cardiff.ac.uk/archi/computermodelling.php

climatic design region. This work concluded that the use of insulated external walls with light external colours along with extensive shading devices in a tight building is the best combination of passive measures that may effectively work across all the Egyptian climatic design regions. It recommended giving greater consideration to the building microclimate characteristics. Although the in depth analysis done in this work, no enough intension was given to natural ventilation, except testing the effectiveness of reducing the ventilation rate.

El-Hefnawi [18] tried to optimise the environmental performance of one of youth project's prototype in *El-Obour city* in the desert to the east of Cairo. This optimisation was conducted through performing parametric analysis used *DEROB*[1] computer thermal simulation software. He quantified the effectiveness of different building materials, wall thickness, solar shading devices and night purge ventilation during the summer. The study recommended that the following configurations of the studied variables were most effective at reducing building temperature during the overheated period:

- Using high thermal mass for both external and internal walls along with external wall insulation;
- Restricting total window area to less than 40% of the space area;
- Using 6 mm reflective glass;
- Installing external shading devices on the western and southern facing façades; and
- Applying night purge ventilation passive cooling strategy.

In this work, the night purge ventilation effect was applied by increasing the ventilation rate (*ACH*) [2] inside the thermal simulation model during night time. The increase in the ventilation

Note 1:
DEROB is design tool used to explore the complex dynamic behaviour of buildings for different designs.
http://apps1.eere.energy.gov

Note 2:
Stands for Air Change per Hour (The measuring unit of the ventilation rate).

rate can definitely improve the internal air quality, but not necessarily so improving the thermal comfort by ventilation. It is worth mentioning here that for effective cooling effect of ventilation strategies, the quality of airflow circulation within the building's spaces and around the human body seems to be more important in cooling down the building fabric and human body than the volume of air induced inside the space. No further investigation was conducted to test the quality of the airflow within the case study.

Three other studies used similar parametric analysis and methodology to study different housing types across two different climatic design regions throughout Egypt. All of them aimed to optimise the thermal performance of the case studies using computer simulation. Mostafa [28] studied the thermal performance of semi-detached residential units in the new Egyptian desert cities. Asar [29] studied a summer house in *Alexandria* city located in the Mediterranean climatic design region of Egypt. Osman [30] investigated the thermal performance of an experimental low cost housing unit in the *El-Farafra* oasis project in the Egyptian western desert. All these studies concluded that the use of high thermal mass with light colours can have a significant effect in winter and summer. They also proved the positive effect of natural ventilation, in particular night purge ventilation, as a passive cooling strategy during summer. In the all three studies, the application of ventilation strategies were expressed as input figures. No attempts were done to make sure that the building fabric was well exposed to a good quality airflow which came from the quantity of air they induced into the spaces.

Based on the hypothesis of the public housing blocks are not climatically responsive, Moustafa

[17] evaluated the thermal performance and energy consumption of low and middle classes housing prototypes within *6th of October* city. Two different housing prototypes were employed in this work as case studies. The evaluation and optimization studies were conducted using *Autodesk Ecotect*[1] thermal simulation software. The evaluation study proved the uncomfortable conditions inside both case studies in all Egyptian climatic design regions. This was clear in summer time when a significant increase in cooling loads was observed. The optimization study was conducted through applying parametric analysis. The study considered the parameters of Building orientation, walls material, walls colour, roof construction, roof insulation, roof colour, windows/wall ratio, glass type, shading devices, ventilation strategies, ceiling height and heat gain through occupants and appliances. The results of parameter alternatives' simulation were judged in terms of energy consumption. The best case in each parameter test was then extracted. As in studies above, this work emphasized the important role of night purge ventilation in achieving thermal comfort and energy efficiency. The problem with this work is the unjustified input of the high ventilation rate of *30 ACH* in the case of night purge ventilation applied. Also, no further investigation was conducted to make sure that this figure can be qualitatively and quantitatively achieved.

Note 1:
Autodesk Ecotect is comprehensive software tool for building performance analysis. It provides a wide range offunctions and simulations
http://ecotect.com/products/ecotect

The most related study to this work that was conducted by Abdin in 1982 [31]. This study aimed mainly to set up a comprehensive bio-climatic approach for housing design in semi-deserts and hot climates within Egypt. Through the research, a great concern was given to the natural ventilation and airflow patterns in and around buildings. Four public housing prototypes built in Cairo were employed as case studies. Wind tunnel aerodynamics' tool was used to test the effect of several design factors on airflow regime inside and around the physical models of the case studies. Block proportions, grouping patterns, courtyards' proportions, inlet/outlet area, internal partitions and inlet/outlet relative positions were the design factors under investigation. The boundary conditions of the wind tunnel test was set up to provide 1 m/s speed uniform air flow with incident angle ranged between -45^{o} to 90^{o}. As a result of this study, a long list of guidelines for ventilation optimization was extracted and implemented in the comprehensive bio-climatic approach proposed by this work.

Many problems were identified with this work. Firstly, no field investigation was done to validate the results as the researcher relied on validating his results by comparing them with others work. Secondly, the boundary conditions (*1 m/s speed uniform air flow with incident angle ranged between -45^{o} to 90^{o}*) that provided during the experiments could not represent the situation in reality as no turbulent models were applied to the airflow. In addition, no most frequent local wind profile was used. Thirdly, the study did not introduce practical solutions for ventilation problems identified in the case studies instead of just stating guidelines. Finally and as a recent point of view, the studied housing prototypes are no longer being used by the government. Moreover, the wind tunnel tool is quit old tool and it has been recently replaced by easier computerised mathematical codes implemented in *CFD*[1] softwares.

Note 1:
Stands for Computational Fluid Dynamics.

From the above review of the available work done in Egypt, it could be argued that the majority of work dealt with achieving thermal comfort through applying several measures. Most of them recommended the use of ventilation strategies, especially night purge ventilation. None of them attempted to test the cooling capability of ventilation strategies in reality. Moreover, none of them investigated the quality of airflow at any of their case studies. This gap in the body of knowledge was identified and is being pursued in this research.

1.7. The research main aim and objectives

The main aim of this research is to investigate the possibility of enhancing the use of natural ventilation as a passive cooling strategy in walk-up public housing blocks in the Egyptian desert climatic region.

In order to achieve the main aim of the research, it will try to fulfil the following objectives:

1- Quantitavely and qualitatively evaluating the natural ventilation performance of the walk-up public housing blocks in *New Al-Minya city*;
2- Formulating design measures that could enhance the natural ventilation performance of the walk-up public housing blocks in *New Al-Minya city*; and
3- Quantifying the effect of different design measures that could possibly enhance the natural ventilation performance of the walk-up public housing blocks in *New Al-Minya city*.

1.8. Methodology overview

The general methodology employed in this work in order to fulfil the research objectives and achieve its main aim comprises three main parts. Namely, they are in order; the research outline and scientific background, the evaluation study and the natural ventilation enhancement study. Many research techniques and research methods are included in each part. This methodology employs a combination of two different methodologies in the field; the methodology by Gado and Mohamed [32] and the methodology by Allard [33].

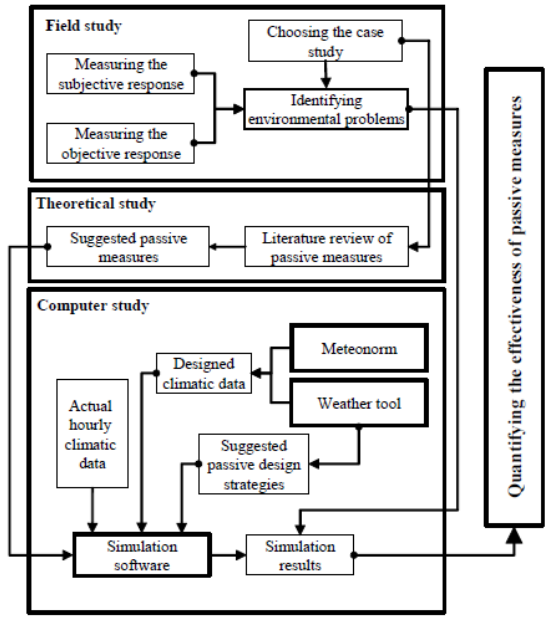


Figure 1-24: The methodology advised by Gado and Mohamed [32]

Gado and Mohamed [32] devised a methodology that employs computer simulation tools in quantifying the impact of passive design measures on existing buildings. They based their methodology on the basic steps of architectural design, which are; identifying the target, analyzing the context, formulating the initial design and then evaluating alternative solutions. In their methodology the target identification was advised to be done using field study. The context analysis along with the initial design formulation can be done through theoretical study. Then finally, the initial design can be tested by using computer based study (Figure 1-24). This methodology was created, in particular, to be applied to any relevant research projects to the environmental design of buildings.

Allard [33] proposed an outline methodology for the diagnostic studies. This methodology was designed in particular for natural ventilation studies. It was designed to be applied when the aim of the study is one of the following:

a) To obtain a basic understanding of building performance;
b) To understand why a building does not perform as expected; and
c) To check the agreement between predicted and real performance.

This diagnostic methodology relied on two research strategies; quantitatively monitoring the building under investigation and qualitatively collecting enquiries from its occupants and facility managers (Figure 1-25).

Figure 1-26 illustrates the research general methodology and the overview of each part in it is discussed below.

First part: The research outline and scientific background:

This part of the general methodology mainly represents a theoretical study. The scientific background of natural ventilation, its relation to thermal comfort as well as the physics of air movement are explained using the review of the related literature. Also, a wide review is conducted in this part in order to classify the architectural design measures and their parameters that affect natural ventilation performance. The outcomes from this part will then feed into the other parts of the methodology as they will form the basics through which the results of any analysis will be conducted and interpreted.

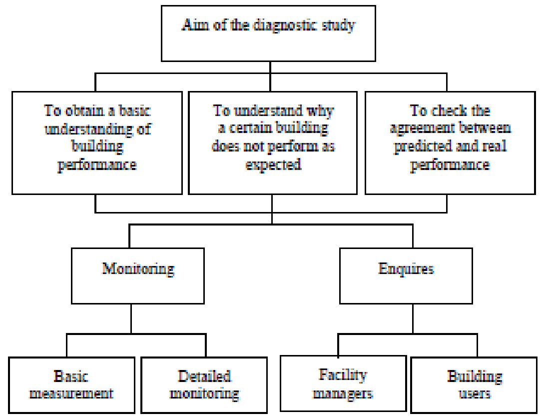


Figure 1-25: The overall methodology for natural ventilation diagnostic studies, after Allard [33]

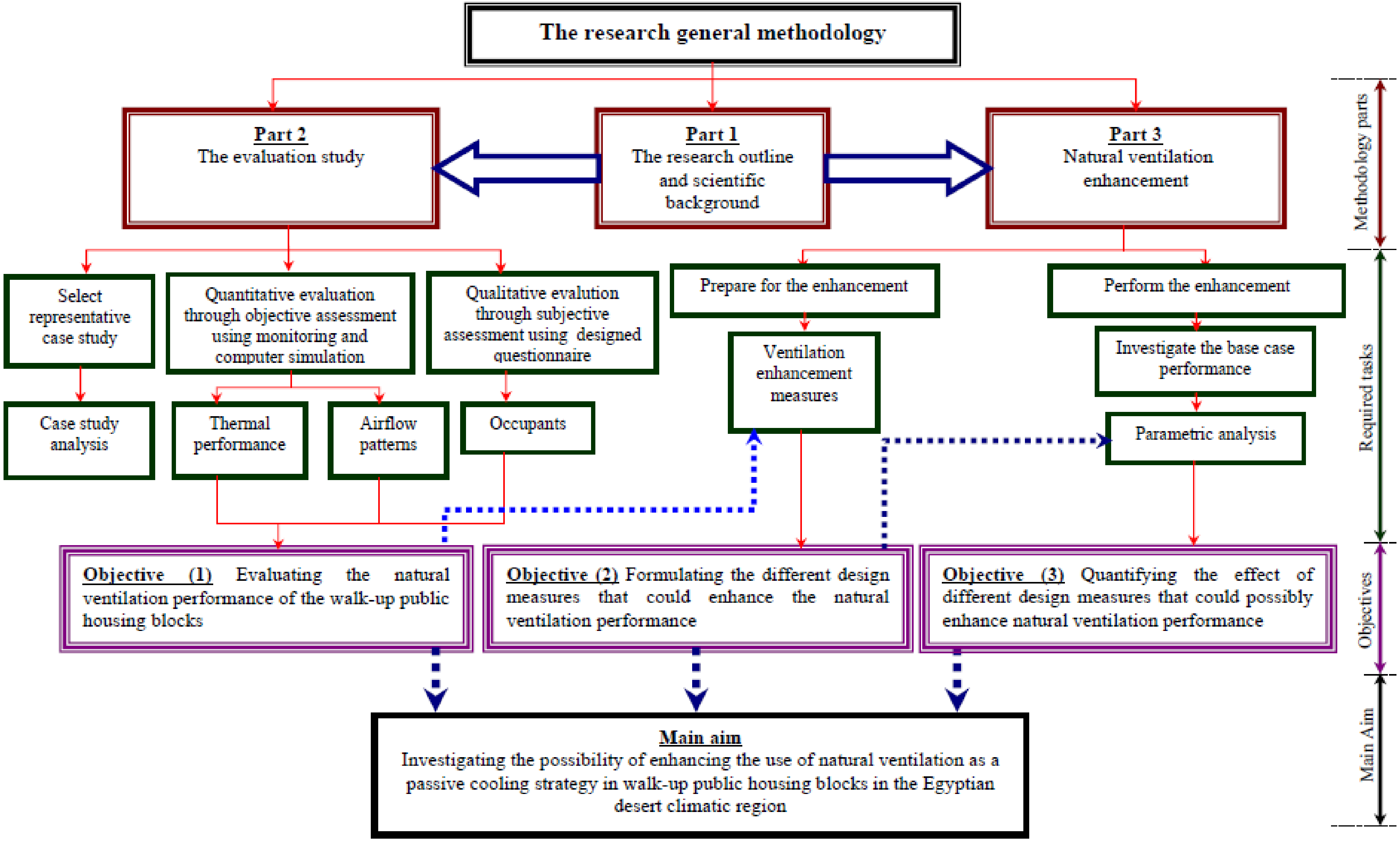


Figure 1-26: The research general methodology

Second part: The evaluation study:

This part is mainly a diagnostic study and aims to investigate the natural ventilation performance in walk-up public housing blocks within the Egyptian desert climatic design region. A case study from *New Al-Minya* city is employed in this study. The natural ventilation design features and drivers in the case study are then analyzed. The natural ventilation in the case study is evaluated quantitatively through objective assessment and qualitatively through subjective assessment. The objective assessment includes a thermal performance assessment of the case study, when applying natural ventilation strategies as well as an assessment of the airflow patterns in and around the case study. The thermal effect of the different natural ventilation strategies is investigated through monitoring the internal temperature inside the case study. While, the airflow patterns in and around the case study is evaluated using *FloVent*[1] computational fluid dynamics (*CFD*) software.

The subjective assessment aims to measure the occupants' response towards using natural ventilation as a passive cooling strategy. This is conducted by designing a questionnaire that measures; the occupants use for natural ventilation drivers, their behaviour in using natural ventilation, their evaluation for their dwellings' thermal performance, their use of mechanical ventilation as well as their awareness with the required improvement of natural ventilation in their dwellings. By conducting this part of the methodology, the first objective of the research (*Evaluating the natural ventilation performance of the walk-up public housing blocks)* will be fulfilled. The outcome of this part is considered in the enhancement process in part 3, so determining the problems need to be treated and the way of treating them.

Note 1:
FloVent is Computational Fluid Dynamics (CFD) software that predicts 3D airflow, heat transfer, contamination distribution and comfort indices in and around buildings of all types and sizes.
http://www.mentor.com/products/mechanical/products/flovent

Third part: Natural ventilation enhancement:

This part of the general methodology mainly aims to enhance the airflow in and around the case study for ventilation purposes. This part includes two main tasks. The first task is a preparatory task and aims to formulate the ventilation design measures that could possibly enhance the airflow in the case study in order to be tested in the parametric analysis hereafter. These measures will be formulated through extracting natural ventilation measures from the literature review that is conducted in the theoretical part and dealt with the design measures. In addition, the measures that fulfil the occupants' desires and those which are forced by the research context nature will be implemented. At the end of this task, the second objective of the research *(Formulating the different design measures that could possibly enhance the natural ventilation performance of the walk-up public housing blocks)* will be fulfilled.

The second task is to perform the enhancement itself. The natural ventilation in the case study, as designed, is enhanced through a parametric analysis. The effectiveness of the application of the formulated measures on the airflow performance in the case study is then quantified, compared with the base case performance and the optimum solution will then be accordingly obtained. At the end of this task, the third objective of the research *(Quantifying the effect of different design measures that could possibly enhance the natural ventilation performance of the walk-up public housing blocks)* will be fulfilled. This was only an overview of the research general methodology. The detailed methodology of each part of the general methodology will be explained in its context later in the thesis.

Chapter 2:
The science and strategic design of natural ventilation

2.1. Chapter two introduction

This chapter presents the related science to natural ventilation and airflow. In it, the interlink between natural ventilation and thermal comfort, in terms of impacts and limitations, is identified. In addition, the related physics to natural ventilation and the associated airflow are summarised. Finally, the strategic and technical levels of designing for natural ventilation are explained. In general, this chapter aims to build up a scientific background on which the discussion and interpretation of results ' analysis later in this work will be based.

2.2. Ventilation

The origin of the term "*ventilation*" is the Latin word "*ventus*", which means air movement [34]. Ventilation is defined as "*the process of supplying or removing air by natural or mechanical means to or from a space, usually through air exchange with the out of doors*"[34]. Natural ventilation in most cases satisfies the occupants' requirements as it can provide calm, healthy, comfortable and energy efficient environment in contrast with mechanical ventilation [33]. The term "*natural ventilation*" here is used to indicate intentionally designed systems by which the quality and quantity of air movement, that is naturally induced, is controlled and employed to achieve either thermal comfort or internal air quality. However when using natural ventilation, great attention should be given to pollution and noise effects[35] as well as a holistic view of the whole building's material, usage and its adaptation to the local climate is also required [36].

Apart from providing fresh air for internal air quality (*IAQ*), it is well known that natural ventilation could be very effective in passively maintaining acceptable internal thermal comfort [19, 33, 37-39]. Natural ventilation is known as the major passive cooling technique that works within all climatic regions of the world [35, 40]. However, its significant effect was found to be within the hot dry and the hot humid climates of the world, where its cooling effect is strongly needed [19, 37, 38]. It was emphasised also that well designed natural ventilation systems can significantly reduce the energy consumption required for summer cooling [41].

2.3. Natural ventilation and thermal comfort

Thermal comfort is defined as "*that condition of mind that expresses satisfaction with the thermal environment*" [42]. In other words, it is "*that conditions in which a person would prefer neither wormer nor cooler surroundings"* [40]. The sensation of thermal comfort can be affected by many factors. These factors can be categorised under three main categories; a) The environmental or physical factors [37, 40, 43] such as; air temperature, mean radiant temperature, humidity and air velocity, b) Personal or human factors [6, 37, 40, 43] such as; human activity level and clothing level, c) Organic or contributing factors [6, 37, 40, 42] such as; age, gender, food, drink, body shape, subcutaneous fat, human adaptation, occupants acclimatisation, climate variations, of occupants, colour of internal surfaces and lighting system. Between these factors, the environmental and personal factors were reported to be the most effective factors [40, 42]. While the contributing factors were reported by most researchers to provide a slight or sometimes neglected effect in relation to thermal comfort

[44]. As the wind is a major design factor for architects [45], air velocity is considered one of the most significant environmental variables that greatly impact thermal comfort [40]. Therefore, good indoor air movement can provide sufficient air velocity to maintain an acceptable level of thermal comfort when temperature and humidity fail so to do [40]. This air movement can be internally provided by ventilation.

Natural ventilation works generally within the convection mode of heat transfer, in which the air with low temperature flows over a higher temperature surface and carries away heat, reducing by this the surface’s temperature [40]. This concept applies on both; human body and building fabric, which targeted by the strategic design level of natural ventilation. The air movement is found to be an important factor that is incorporated in most of thermal indices' calculations such as; Predicted Mean Vote index (*PMV),* Predicted Percent Dissatisfied index (*PPD*)*,* Thermal SENSation index (*TSENS*)*,* DISComfort index (*DISC*)*,* and Standard effective Temperature (*SET*) [46].

2.4. Physics of moving air

It is necessary to acquire an understanding of the physical properties of the moving air itself. In this part, some physics associated with moving air will be addressed such as; airspeed and air flow patterns.

2.4.1. Airspeed:

The main source of air movement is the wind. Hence, the term "*Airspeed*" here is used to refer to the wind speed. The airspeed is the major factor to influence the air pressure on building surfaces which in turn enhances or undermines the wind-driven air movement through and outside the buildings. Since, the wind-driven ventilation systems cannot be effective unless the wind speed is greater than (*2.5 m/s*) [45]. This huge effect is due to the exponential proportionality between the wind force and the wind speed square [37]. This relation can be shown in Bernoullie's equation (Eq: 2-1):

$$P_w = 0.5\, \rho\, C_p V_z^2 \quad [Pa] \qquad \text{(Eq: 2-1)}$$

It was found that natural airspeed lies in the range between (*0 m/s*) and (*25 m/s*) [37].The different effects of various airspeed on human sensation and comfort were presented in *"Beaufort scale "* (Table 2-1).

The airspeed is by nature not a time constant value over the atmospheric boundary layer. Therefore, it is always expressed in terms of the mean speed and frequency. It is found that the airspeed increases according to the elevation from the ground as a direct effect of the air's friction with terrain roughness [47]. In most wind engineering applications, the height from earth surfaces at which the wind speed reaches its maximum value indicates the thickness of atmospheric boundary layer *"ABL"*. This height depends on the properties of the earth surface

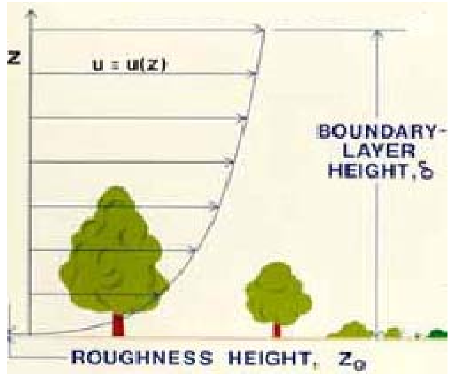


Figure 2-1: Mean speed *"u"* profile as a function of height *"z"*, after Wei and Desmond [48]

Where:
P_w = The surface pressure due to wind
ρ = The air density
C_p = The wind pressure coefficient at a given position on the building façade
V_z = The mean wind velocity at height (z)

Figure 2-2: Diagrammatic wind speed profiles above urban, rural, and sea surface, after University of California [49]

over which the air passes and varies from around *300 m* over the opened smooth surface to *500m* over the areas with rough surfaces such as urban areas (Figure 2-1 and Figure 2-2). In addition to the height and the surface roughness, the temperature also sophisticatedly affects the airspeed and turbulence within the *"ABL"*. Therefore, the profile of the mean airspeed

Table 2-1: Beaufort scale for outdoor air velocities and its effect on human sensation and comfort, after Randall [50] and Blocken, B. and J. Carmelie [51]

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

over the earth and within the *"ABL"* is a dependant on the above variables which are found difficult to be presented mathematically except by the empirical power law [48]:

$$u / u_\delta = (z / \delta)^\alpha \qquad \text{(Eq: 2-2)}$$

Where:
u = The mean free stream velocity
u_δ = The mean velocity at $z = \boldsymbol{\delta}$
z = The height from the earth surface
α = coefficient depends on surface roughness, Reynolds number, and the roughness length.

Normally, the wind speed is measured at 10 m height above the ground level at an ideal meteorological station with an aerodynamic roughness length ($z0 = 0.03\ m$) and denoted as a reference wind speed [51]. Many references [47, 52, 53] expressed the mean airspeed at specific height, as a function of the reference wind speed, in another form of the power law as follows:

$$\upsilon_z = \upsilon_m\, k\, z^a \qquad \text{(Eq: 2-3)}$$

Where:
υ_z = The airspeed at the building height (m/s)
υ_m = The wind speed at weather station (reference wind speed)
z = The building height
k, a = Factors depends on surface roughness and terrain

The values of the factors *"K"* and *"a"* for different terrain conditions are given in Table 2-2. Another more complex form of this equation was developed to be expressed as [47]:

$$v / v` = \alpha\, (H/10)^\gamma \;/\; [\alpha`\, (H`/10)^{\gamma`}] \qquad \text{(Eq: 2-4)}$$

Where:
v = The airspeed at the building height (H)
$v`$ = The measured wind speed at weather station (reference wind speed)
H = The building height
$H`$ = The height of speed reference speed measurements
α, γ = Terrain parameters of the building location
$\alpha`$, $\gamma`$ = Terrain parameters of the weather station location

The values of the parameters *"α"* and *"γ"* for different terrain conditions are given in Table 2-3.

Table 2-2: Terrain coefficients for equation (Eq:2-10), after CIBSE [52] and BS [53]

Terrain	***K***	***a***
Open flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

Table 2-3: Terrain parameters for equation (Eq:2-11), after Awbi [47]

Terrain	α	γ
Ocean or other body of water with at least 5 km of unrestricted expanse	0.10	1.30
Flat terrain with some isolated obstacles, e.g. buildings or trees well separated from each other	0.15	1.00
Rural area with low buildings, trees, etc	0.20	0.85
Urban, industrial or forest areas	0.25	0.67
Centre of large city	0.35	0.47

2.4.2. Airflow patterns and turbulence models

Naturally, the airflow patterns are extremely complex to be accurately described or analysed due to their gusty and turbulent nature [37, 47, 54]. Although, the natural sophisticated behaviour of air motion, its patterns can be classified into two major forms; laminar flow and turbulent flow [37].

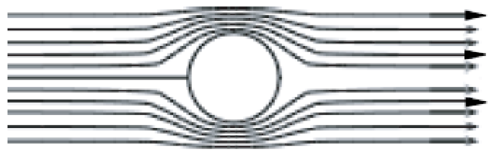


Figure 2-3: Laminar airflow around an object, after Alberto[56]

Laminar flow, in fluid dynamic's applications, is uncommon and only happens when the fluid has a high viscosity and flows into a tiny section [54]. Air as fluid is no exception. The laminar airflow (*also called "streamline flow"*) [37] mostly happens in nature near walls either inside or outside the space [55]. The laminar airflow (Figure 2-3) is characterized by [37, 56]:

a) The air moves in parallel layers with the same velocity and direction;

b) The air molecules move in a constant distance from the wall within its layer; and

c) No layer crosses over another layer's path.

The turbulent flow is the normal airflow in nature and inside architectural spaces [54, 55]. The air, in the turbulent flow, moves randomly in chaotic flow and its molecules cross over other molecules path forming as such, eddies and difference in speed [56]. See Figure 2-4. The air turbulent flow most likely happens in high speeds [37]. Despite the impossibility of precisely describing the turbulent flow [54], Tennekes and Lumley (*Quoted in [54]*) summarized the main characteristics of the turbulent flow as following:

a) *Irregularity or randomness*: The turbulent flow is physically random and irregular in motion, time, speed and space;

b) *Diffusivity*: The diffusivity nature of turbulent flow increases the flow combination, the momentum's rate, and the heat transfer;

c) *Three-dimensional*: The turbulent flow is rotational and has a high level of repeatable eddies;

d) *Dissipation*: Turbulent flow requires energy supplement to maintain its motion. This energy is mostly provided by shear or buoyancy phenomena; and

e) *A characteristic of flows*: The turbulence is the flow property, so each turbulent flow has its unique characteristics which cannot be applied on the other.

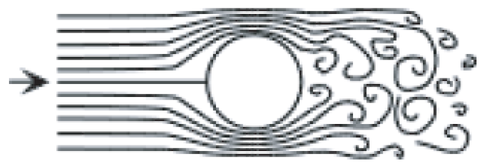


Figure 2-4: Turbulent airflow around an object, after Alberto[56]

An effect of turbulent airflow characteristics on human thermal sensation was recorded. It was found that the preferred speed of airflow used by subjects to gain the same level of thermal sensation in higher turbulent flow is lower than the one in the lower turbulent flow [57].

The determination of the airflow pattern is found to be reliant on a dimensionless ratio called "*Reynolds Number*" [56]. The *Reynolds Number* can be calculated in any architectural space that has dimensions of; length *L*, width *B*, and height *H* by using the equation [47]:

$$Re = D_h\, U_r / v \qquad \text{(Eq: 2-5)}$$

The laminar flow inside the space was found to happen, for example, when *Re* is less than *100* [47]. However, when the value of *Re* is, for example, more than *1000* the flow will be described as turbulent flow [56]. Also, it was found that the intensity of airflow turbulence is minimal in open rural areas (*10%*), while it increases in urban areas to reach (*30%*). A conclusion that the airflow has less speed associated with high turbulence in urban areas can be drawn here [19].

Many mathematical models have been developed to simulate the turbulent airflow, for example; *LES* [1], *DSM* [2], *ASM* [3], The *low Reynolds number models, RSM* [4], *DNS* [5], and standard *K-e* [6] model with its refinements *K-e EVM* [7] and *RNG K-e* [8] models [47]. Many pieces of research tried to investigate the accuracy of these models either by comparing their results with experimental data [58] or with numerical data generated from CFD

Where:
Re = Reynolds number
D_h = The hydraulic diameter of the space
= *2BH / (B+H)*
U_r = The equivalent room velocity
= flow rate (*Q*) / cross sectional area (*BH*)
v = The kinematics viscosity of air (m^2/s)

Note1:
Stands for Large Eddy Simulation model

Note2:
Stands for Differential Stress Model

Note3:
Stands for Algebraic Stress Model

Note4:
Stands for Reynolds Stress Model

Note5:
Stands for Direct Numerical Simulation method

Note6:
Stands for Kinetic Energy model

Note7:
Stands for K-e Eddy Viscosity Model

Note8:
Stands for ReNormalization Group k–e model

software [59]. So far, no single mathematical turbulence model has been found to be accurate in predicting airflow pattern within all real situations [47] nor even covers the full range of complexity of real airflow [35].

2.5. Natural drivers of natural ventilation

The air mainly moves, either outside or inside buildings, due to differences in air pressure. This pressure differences might be created naturally through the effect of wind forces and temperature difference or be forced artificially through using fans and pumps [60, 61]. Natural ventilation mainly relies on the natural drivers of pressure variation.

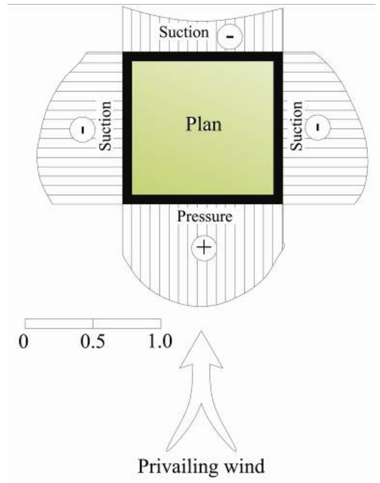


Figure 2-5: Schematic distribution of wind pressure around a building exposed to perpendicular wind flow, reproduced after Givoni[65]

The natural drivers of pressure differences work within two main known physical principles. Firstly, the air moves from higher/positive pressure regions to the regions of lower/negative pressures [62]. Secondly, the warm air is less dense than cool air so it rises and creates a difference in pressure which in turn induces air movement [62]. This phenomenon is called "*The thermal buoyancy*" [63] and is sometimes referred to as "*The stack effect*" or "*The chimney effect*" [45, 64]. These natural drivers may work separately or in combination in order to form the air flow patterns inside the buildings [55]. The natural drivers of air movement such as; wind forces, thermal buoyancy, and the combination between them are discussed in details below.

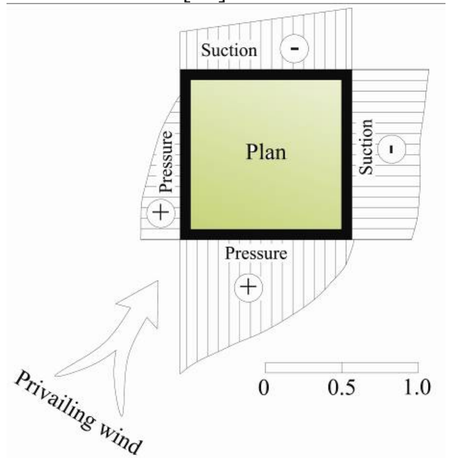


Figure 2-6: Schematic distribution of wind pressure around a building exposed to oblique wind flow, reproduced after Givoni[65]

2.5.1. Natural wind forces

Natural wind blows and creates various types and gradient of pressure on the different buildings' façades. Assuming the wind blows perpendicularly on one of the building's façades, a positive pressure "*pressure zone*" area is formed on that façade *"windward"*, while a negative pressure area "*suction zone*" is formed on the other side of the building's *"leeward side"* along with the building's side façades [19, 42, 43]. This pattern of pressure distribution differs, if the wind incident angle is changed [65]. See Figure 2-5 and Figure 2-6. This pressure distribution around a building in turn creates a negative pressure area inside the building that encourages air to move through the building and via its openings. The air moves through from the opening in the positive pressure façade to the opening in the negative pressure one [40, 64, 66] (See Figure 2-7). The magnitude of air movement through openings is a dependant factor on the difference in pressure between the outlets and inlets [42, 43, 47]. Many factors can affect the pressure difference and consequently affect the magnitude of wind driven air movement through buildings. From these factors; building geometry, wind velocity and direction, building location in relation to surroundings, and terrain context and geographical location of the building [47]. The dynamic wind pressure on any specific position on a building's surface (façade) can be calculated using the Bernoullie's equation (Eq: 2-1) [42, 43, 47, 64].

The pressure coefficient at a specific point on the building façade could be obtained by pressure measurements in wind tunnels, *CFD*[1] models or measurements on real scale building [42, 43, 47, 64]. For simple forms of buildings the values of C_p could be found in the tables of *CIBSE*[2] guide A[43] or in figures of *ASHRAE*[3] [42]. The mean wind

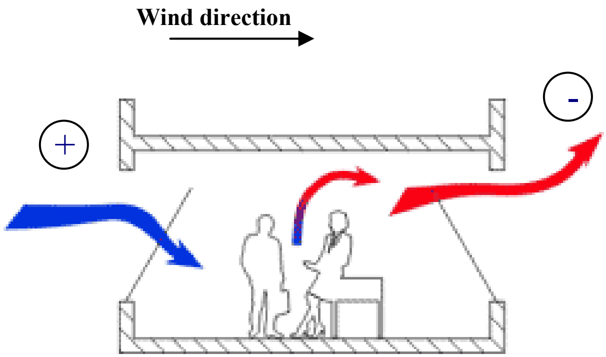


Figure 2-7: Wind driven airflow through openings due to pressure difference, reproduced after The dyer environmental controls limited[69]

Note1:
Stands for Computational Fluid Dynamics
Note2:
Stands for Chartered Institution of Building Services Engineers
Note3:
Stands for American Society of Heating, Refrigerating and Air-conditioning Engineers

velocity at height (z) could be calculated according to the building location and the given wind velocity measured at the weather station of that location. See section 2.4.1

With regard to the rate of the wind driven airflow through an opening in a building's façade, this depends on the drop of outdoor air pressure across the opening caused by the opening's design and any airflow obstructions within the ventilated space [19, 43, 67]. The rate of wind driven airflow across any opening in the building façade can be calculated by using the empirical power law [43]:

$$Q = C_d A (2 \Delta p / \rho)^{0.5} \qquad \text{(Eq: 2-6)}$$

Where:
Q = The volumetric airflow through the opening
C_d = The discharge coefficient = 0.61 for sharp-edged opening.
A = The area of the opening
Δp = The pressure difference across the opening
ρ = The air density

2.5.2. Thermal buoyancy "Stack effect"

The airflow due to thermal buoyancy occurs as a result of the pressure difference that is created by temperature difference between either outside and inside the buildings or between the internal parts of the building itself [64]. This airflow occurs mainly in the vertical direction through gaps or weak resistance points within the building such as stairwells, elevators, atriums, and shafts [67].

In winter, when the indoor temperature is higher than the outdoor one, the warm air inside the building flows upward (*low density*) and creates a positive pressure area on top as well as a negative pressure area at the lower part of the building. The warm air in the top positive pressure area is exhausted through the openings at the top of the building.

Meanwhile, the negative pressure area at the bottom of the building sucks external air inside the buildings through the lower building's envelope openings. In summer, when the indoor temperature is lower than the outdoor one, the flow reverses [43]. See Figure 2-8. When there is no effect of wind force and the thermal buoyancy is working separately, the level at which both indoor and outdoor pressure are equated and the difference in temperature becomes zero is called "*The neutral pressure level (NPL)*" [47, 64]. The pressure difference created by the stack effect (Figure 2-9) could be calculated by the equation [43]:

$$\Delta p = \rho_0 \, g \, 273 \, (h_2 - h_1) \, [1/(t_o + 273) - 1/(t_i + 273)] \qquad \text{(Eq: 2-7)}$$

Where:

Δp = The pressure diference (Pa)

ρ_0 = The density of the air at 0° C (kg/m^3)

g = The acceleration due to gravity (9.81 m/s^2)

h_1 = Opening 1 height above the ground level (m)

h_2 = Opening 2 height above the ground level (m)

t_o = The outdoor temperature (°C)

t_i = The indoor temperature (°C)

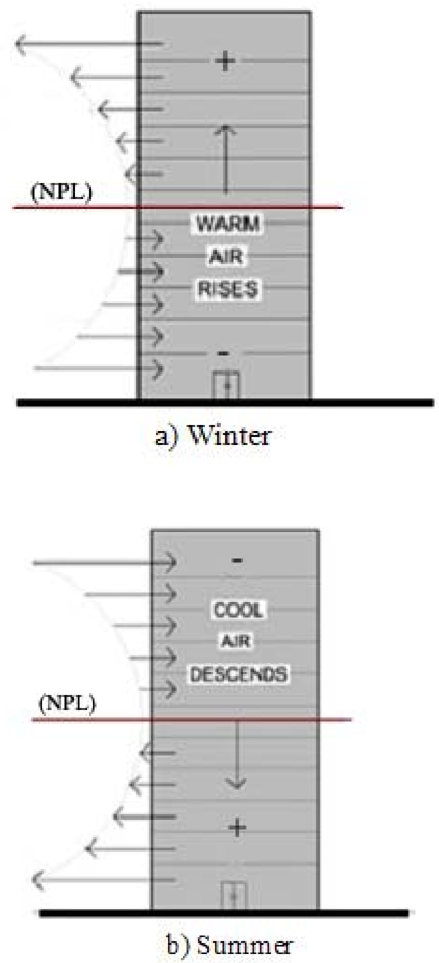


Figure 2-8: The patterns of airflow between indoor and outdoor due to stack effect during winter (a) and summer (b), reproduced after Morse et al, [70]

The gradient of pressure created by a stack effect in a building is directly proportional to the vertical height of the volume of heated or cooled air's enclosure [67]. It was found that the stack effect has greater effect in tall rooms and high-rise buildings than in short rooms and low or medium height buildings [67]. It was found also that using the stack effect to induce air in ventilation systems has greater potential in temperate climates rather than in hot and humid climates. The warm outdoor temperature and high humidity undermine its capabilities in hot and humid climates [65, 68].

The airflow pattern due to stack effect in between the building's parts performs differently. It is governed by the type of building's internal partitions and the degree of air tightness between the building's stories [47].

Figure 2-10 illustrates the airflow patterns due to the stack effect in the different forms of buildings.

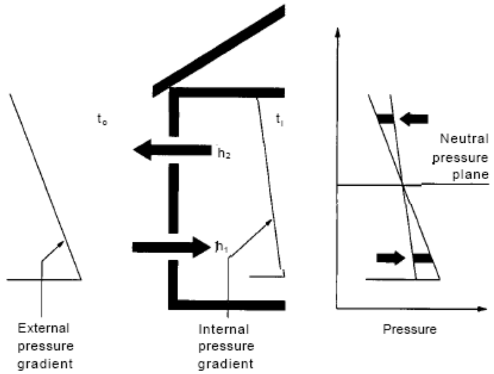
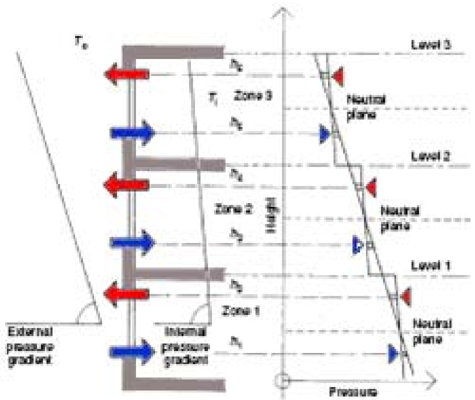
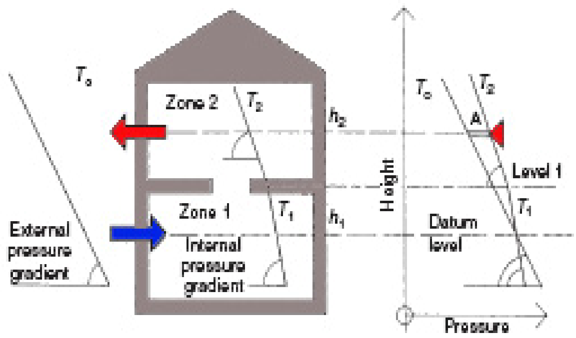


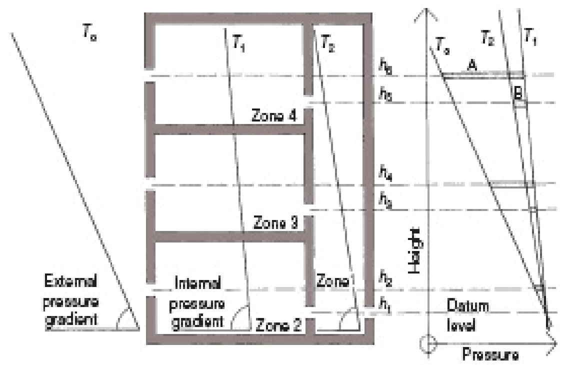
Figure 2-9: The indoor vertical pressure ingredient due to stack effect, after CIBSE[43]



a) Building with unconnected vertical zones



b) Building with interconnected vertical zones



c) Building with interconnected horizontal zones

Figure 2-10: airflow patterns due to stack effect in different forms of buildings, reproduced after Awbi[47]

2.5.3. Combined wind and thermal buoyancy forces

In most cases, the airflow through any building is a result of a combination of both wind pressure and stack effect [65]. The overall direction and rate of airflow within the building and through its openings is the algebraic summation of the effect of both drivers along with any other ventilation devices installed [47]. The overall airflow could be enhanced, if both stack and wind pressure drivers work in the same direction, i.e. have the same sign (-/+). If they work irreconcilably, i.e. have different signs (-/+), the airflow will decline and might stop completely as a result of their equality [47, 65]. The maximum increase in the airflow due to the combination, providing they work in the same direction, was found to be no more that 40% higher than the greater force alone [65].

Many calculation methods were developed by Walker and Wilson [71] (*quoted in Awbi [47]*) in order to estimate the airflow rate due to the combination effect of both wind and thermal airflow drivers. "They recommended the use of the pressure addition method because of its simplicity and reliability in predicting the combined effect of wind and stack" [47]. the pressure addition method's equation is as follows:

$$Q_t = [Q_w^2 + Q_s^2]^{1/2} \qquad \text{(Eq: 2-8)}$$

Where:
Q_t = The overall ventilation rate
Q_w = The ventilation rate due to wind pressure (can be calculated using Eq 2-6)
Q_s = The ventilation rate due to stack pressure (can be calculated using Eq 2-6)

Figure 2-11 and Figure 2-12 illustrate the pressure gradient and airflow patterns for each airflow driver and their combination.

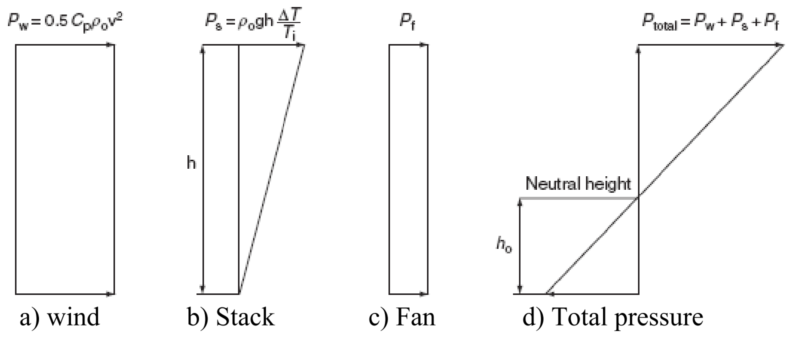


Figure 2-11: Pressure gradient in a building due to wind pressure, stack pressure, fan pressure, and their combination, after Awbi [47]

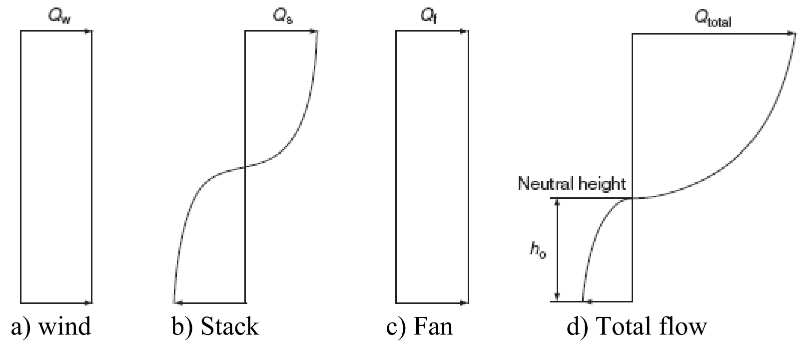


Figure 2-12: Airflow patterns in a building due to wind pressure, stack pressure, fan pressure, and their combination, after Awbi [47]

2.6. Designing for natural ventilation on strategic-level

Two main natural ventilation strategies were found, in warm and hot climates, by which it can promote thermal comfort [19, 34, 36, 38]. These strategies should be considered when designing for natural ventilation on strategic-level. The first strategy is called "*Comfort ventilation or daytime ventilation*". In this strategy, a direct physiological cooling effect is delivered through increasing airspeed around the human body, providing by this mean heat loss and higher evaporation rate, and so thus makes occupants feel cooler. The second strategy is called "*Nocturnal ventilative cooling, Night purge ventilation, or Structure ventilation*". In it, an indirect cooling effect is delivered through allowing the night cool air to cool down the thermal mass of the building, providing accordingly cooler temperature indoors than outdoors during the next daytime. These two strategies are reported to be valid not only for indoor spaces, but also for outdoor spaces with different considerations in the design [38, 39]. The next sections discuss these two ventilation strategies in details.

2.6.1. Comfort ventilation

Comfort ventilation is one of the simple adaptive behaviours[1], by which human beings adapt themselves to the surrounding environment and the prevailing climatic conditions. The building occupants can do that, in order to provide air movement, by using the possible controls available to them. These controls could be one or a combination of opening windows, opening doors, and switching on fans. A field study by Raja et al. [72], which was conducted on occupants of office buildings from UK during summer, found that using window controls is the most common adaptive behaviour done by occupants in order to provide air movement for cooling purposes using this strategy. The use of window control was started in indoor temperature of ($20^{o}C$) and reached its peak (*100%*) in ($27^{o}C$). Also, it was found that the use of fans started at the same indoor temperatures ($20^{o}C$) and reached its peak (*50%*) when the indoor temperature reached near 30^{o} C. The study went further and compared the results of this study by the result of another study conducted in Pakistan. The comparison asserted the validity of using the same controls, when the same boundary conditions applied, in both hot and cold climates. However, the pattern of use could be different.

Note 1:
The adaptive behaviour can be defined as "a combination between changing the surrounding conditions to achieve thermal comfort and changing the comfort temperature to cope with the prevailing conditions" [74], quoted in [75].

The comfort ventilation is dealing directly with the human body. It is based on the theory that high airspeed around the human body accelerates the skin's evaporation rate improving accordingly the heat dissipation from the human body [40, 65]. This in turn shifts up the comfort upper level providing by such direct physiological cooling effect and decreases human discomfort due to skin wetness and high humidity level [19, 38].

In comfort ventilation strategy, two different impacts of the air velocity on the human body were determined [65, 73]; a) it determines the heat exchange of the body that happens by convection and b) it influences the evaporative capacity of the air, thus, the sweating cooling efficiency. The direction on which each impact works along with the boundary conditions determines the cooling efficiency of the provided airspeed and thus the effectiveness of comfort ventilation strategy. Many boundary conditions were found to have great impact on the effectiveness of comfort ventilation such as; humidity level, activity level, clothing and external temperature [65]. Because of the variation and non-homogeneous distribution of the air velocity within the space, ventilation for comfort purposes should be always defined in terms of air velocity rather than change rate or supply [19, 65]. The optimum air velocity that fulfils different boundary conditions and considers the above two impacts of air velocity on human body can be calculated using the equation of the index thermal stress (I.T.S) Assuming *S*=0 [65]. The coefficients incorporated in this equation are given in Table 2-4.

$$S = [M - 0.2(M - 100) \pm \alpha V^{0.3} (t_a - 35) \pm I_N K_{pc} K_{cl} (1 - a (V^{0.2} - 0.88))] e^{0.6 (E/Emax - 0.12)} \quad \text{(Eq: 2-9)}$$

Where:
S = required sweat rate, in equivalent Kcal/h
M = metabolic rate, Kcal/h
α = coefficient depending on clothing
V = air velocity, m/s
t_a = air temperature, C
I_N = normal solar intensity, Kcal/h
K_{pc} = coefficient depending on posture and terrain
K_{cl} = coefficient depending on clothing
a = coefficient depending on clothing
e = the base of the natural logarithms
E= required evaporation cooling, Kcal/h = $(M-W) \pm C \pm R = M - 0.2(M - 100) \pm \alpha V^{0.3} (t_a - 35) + I_N K_{pc} K_{cl} (1 - a (V^{0.2} - 0.88))$
Emax= maximum evaporative capacity of the air = $pV^{0.3}$ *(42-VPa) Kcal/h*
Where:
P= coefficient depending on clothing
V = air velocity
42 = vapour pressure of the skin at 35^o C, mmHg
VPa = vapour pressure of the air mmHg

It was found that every (*0.15m/s*) increase in air velocity can compensate (1^oC) rise in air temperature in moderate humidity (*less than 70% RH*) [40]. This is not an absolute rule as it is limited to the maximum acceptable airspeed of the exposed occupants. The human sensation and related comfort responses for different outdoor air velocities were recorded and summarised in *"Beaufort scale*" [37, 50, 51] as illustrated in Table 2-1.

Table 2-4: The values of I.T.S. coefficients for different clothing levels and postures, after Givoni [65]

Clothing	**Coefficient**				**Posture**	**Terrain**	K_{pc}
	A	K_{cl}	*a*	*P*	Sitting with back to sun	Desert	0.386
Semi-nude: bathing suit and hat	15.8	1.0	0.35	31.6		Forest	0.379
Light summer clothing: under-wear, short sleeved cotton shirt, long cotton trousers, hat	13.0	0.5	0.52	20.5	Standing with back to sun	Desert	0.306
Military overall over shorts	11.6	0.4	0.52	13.0		Forest	0.266

For the acceptable indoor air velocity, *ASHRAE*[1] guide [76] has put an air velocity of (*0.8 m/s*) as a maximum allowable airspeed indoors. However, this speed was considered by *ASHRAE* in air conditioned office buildings specifically to avoid disturbance of paper in the workplaces, caused by higher speeds. Toftum [46] found that in naturally ventilated buildings and at high temperatures (*30^{o}C*), high air velocities up to 1.6 m/s are acceptable to the exposed occupants. Also, Givoni [38] emphasised the acceptability of an indoor air velocity range of (*1-2 m/s*) between the occupants of naturally ventilated residential buildings.

Note1:
Stands for American Society of Heating, Refrigerating and Air-conditioning Engineers

Givoni [19] found that the maximum cooling effectiveness of increasing air velocity around the human body can be achieved at internal temperatures up to (*33^{o}C*). However, no significant effect on heat sensation along with significant effect in reducing discomfort due to skin wetness was observed at internal temperature between (*33-37^{o}C*). In temperatures above (*37^{o}C)*, increasing air velocity negatively affects thermal sensation, but it might be required for reducing excessive skin wetness [19].

Givoni [19, 38] configured the outdoor climatic boundary conditions in which the comfort ventilation is desirable and has a significant effect in achieving thermal comfort. Depending on the assumption that the indoor airspeed is (*1.5-2 m/s*) and without neglecting the effect of humidity level and people acclimatisation, he proposed these climatic boundary conditions. These outdoor climatic conditions were reported since the maximum air temperature does not exceed the range of about (*28-32^{o}C*) and the diurnal difference is less than about (*10^{o}C*). These conditions were found to be the typical climatic aspects found in the warm humid climates of the world. Figure 2-13 illustrates the boundaries of outdoor temperature and humidity within which comfort ventilation has a significant effect on thermal comfort in both developed and hot developing countries. The figure assumes indoor airspeed of (*2 m/s*).

In hot dry climates, daytime temperature exceeding (*35^{o}C*) increases the heat gain by convection and the dry air accelerates the evaporation rate from the human body in still air conditions. Therefore, in such climates, comfort ventilation should be banned during daytime as it is unnecessary for evaporative cooling and is not preferable for convective heat exchange [34, 65].

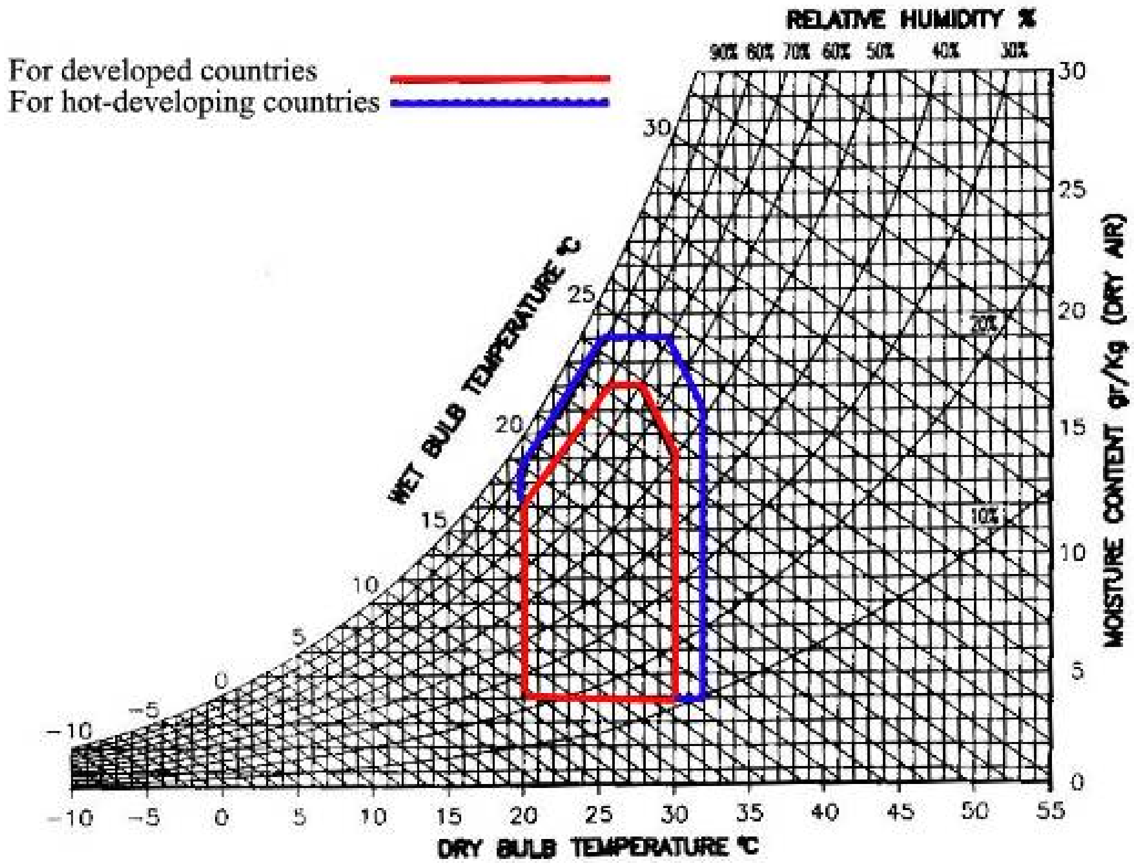


Figure 2-13: The boundaries of outdoor temperature and humidity within which comfort ventilation has a significant effect on thermal comfort in both developed and developing countries [19, 38]

Where comfort ventilation is applicable, there are some indications by which one can judge the efficiency of comfort ventilation strategy in a building. For example, effective comfort ventilation can be achieved when the indoor airspeed on the occupants' level (*1m above floor*) reaches the percentage of (*35-50%*) of the outdoor wind speed [19]. Also, in a space that is naturally ventilated during daytime and in a building with high mass, a reduction of ($2\text{-}3^{o}C$) in the maximum internal air temperature in comparison with the outdoor air temperature is expected [19].

The comfort ventilation can easily be enhanced by appropriate building design that provides a continuous direct high speed air flow at the occupants' level throughout the building [38, 40]. Hence, where sufficient wind speed is available, large shaded windows along with low storage thermal mass are required in such design [38]. Fans can be used to induce or expel internal air, where no sufficient wind speed is available or in the buildings' design that prevent the use of cross ventilation [38].

2.6.2. Night purge ventilation

Night purge ventilation, can be defined, according to Roaf [36], as naturally flushing out the heat from the building, which accumulated during daytime, at night time in order to achieve significant reduction in the next daytime's cooling loads. Such effect is conditioned on keeping the building unventilated during daytime [40]. Unlike comfort ventilation, nocturnal ventilation has a strong correlation with the amount of thermal mass exposed to night cool air rather than to the human body [38, 40]. It works within the theory of heat exchange between the cool night air and the building mass by convection and radiation modes [38]. When the outdoor temperature is low at night, the cool air flows over the building thermal mass and cools it down by convection. The cooled mass acts as a heat sink during the next day hot period and absorbs the heat gained from outside temperature, keeping as a result the internal spaces at a lower temperature than outside [33, 38, 40]. Therefore, the maximum effectiveness of night ventilation could be achieved in those buildings with high thermal mass that were exposed to high quality airflow. The high thermal mass of the building would not work in such a way without coming into contact with the ventilation airflow [36]. Also, night-ventilated low mass buildings will not be able to keep enough "*coolth storage*"[1] for effectively resisting the increase in the outdoor temperature's rate during the next day [38].

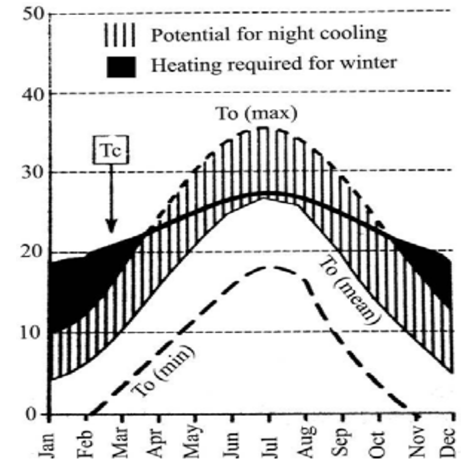
Note1:
The term "coolth storage" first used by Yellott refers to the heat storage capacity of a material as a function of its temperature and thermal response [34].

Thus, the effectiveness of night purge ventilation could be greatly enhanced by providing; good ventilation rate, high storage area exposed to flowing air as well as the heat capacity and thermal conductivity of the building material [40]. It is concluded also, that the colour, material and thickness of a building structure's element affect the benefit from night ventilation [65]. The climatic conditions such as; diurnal temperature range and the typical maximum temperatures are the main climatic factors that can considerably affect the effectiveness of night ventilation [38, 77, 78].

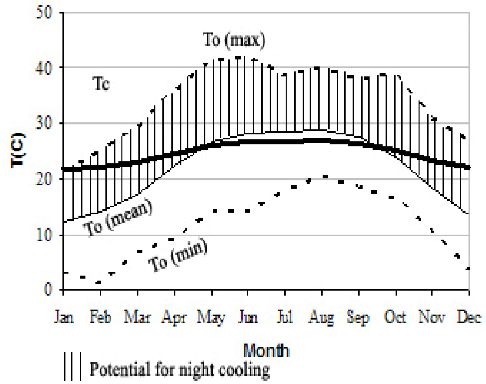
For evaluating night ventilation's performance in a building, some indicators were put mainly by Givoni. He established a rule of thumb based on assuming that building has high thermal capacity with modest heat gains. This rule states that the indoor maximum temperature could be less than the maximum outdoor temperature by nearly half the diurnal range (*35% to 45%*) in outdoor temperatures [19, 38]. Roaf in [36] added that by applying this rule, the internal temperatures seem to be equated to the mean outdoor temperature. She reported that the cooling efficiency of night purge ventilation for a given outdoor temperature could be extracted by using Nicol's graph [36]. The cooling capability of night ventilation for one of Indian climatic zone and for Al-Minya city (*The research context*) is hatched in Figure 2-14 (a) and (b) respectively.

Another significant indicator is that after applying night ventilation on a building, a reduction of (2^oC– 3^oC) in the average indoor temperature should be expected when comparing with another building that is not ventilated at night [38]. Givoni also, stated that buildings with high thermal mass and exposed to reasonable night airflow, can achieve reductions in their mass' temperature of up to (3^oC) closer to the outdoor minimum temperature [38].

Shaviv et. al, [78] found that the reduction in the indoor maximum temperature is a linear function in the diurnal temperature range and relies on the thermal mass along with the night air rate provided. They provided by such means a simple prediction tool for the combined effectiveness of thermal mass and night ventilation rate on the reduction of the maximum indoor temperature [78]. They provided three equations for three night ventilation rates (*H= 20ach, 5ach, and 2ach*) applied on a high thermal mass building. Theses equations are:



a) Nicol graph for an Indian climatic zone



b) Nicol graph for Al-Minya city

Figure 2-14: Cooling capabilities of night ventilation on Nicol's graph (an example from India and from the research context), reproduced after Roaf[36]

For night ventilation rate H = 20 ach

$$Td_{max} = 0.810 * T_{dr} - 1.627 \qquad \text{(Eq: 2-10)}$$

For night ventilation rate H = 5 ach

$$Td_{max} = 0.697 * T_{dr} - 1.722 \qquad \text{(Eq: 2-11)}$$

For night ventilation rate H = 2 ach

$$Td_{max} = 0.599 * T_{dr} - 1.436 \qquad \text{(Eq: 2-12)}$$

Where:
Td_{max} = The drop in the indoor maximum temperature
T_{dr} = outdoor diurnal range

Having said that these equations are based on thermal simulation for a building in a specific climatic context and they should be adjusted for every climatic context.

It was found that the maximum cooling efficiency could be achieved, where day temperature ranges between (*32^o C*) and (*36^{o}C*) with night temperatures around (*20^{o}C*) with a diurnal difference of above (*15^{o}C*) [19]. These boundary conditions are the typical climatic aspects of hot dry climates [19]. However, in very hot day temperatures (*over 36^{o}C*), night ventilation loses its cooling effectiveness during daytime even with the use of high thermal mass [19]. A study by Artmann [79] proved the high potential of cooling by night ventilation in many parts of Europe as well. This proves that in all climatic zones of the world, there are times in which any passive strategy, either for cooling or heating, could be applied. However, in hot seasons of moderate and cold climates, great attention has to be given to the period duration of ventilation needed for adequately cooling the structure in order to avoid overcooling and then needing heat for the following morning [80].

When night ventilation strategy is used in a building, great consideration has to be given to the occupants' awareness and capabilities for opening and closing windows at the required times as well as considering the security issues [38]. The issue of opening or closing windows' times was dealt with theoretically by investigating how to get it automated. La Roche and Milne [81] designed and proved the effectiveness of a smart windows' controller system that can open and close windows according to the outside and inside temperatures to maintain indoor comfort. However, such a system has not yet introduced in practice.

When night ventilation strategy is proposed by a designer, reducing the building openings size as well as providing other devices that can help in the pre-cooling of incoming air should be considered [34]. Aiding devices are ; evaporative screens, pools, wind towers, and ventilating tunnels such as were used in traditional architecture [34].

2.7. Designing for natural ventilation on techniques-level

The above-mentioned strategies and natural drivers for the airflow are implemented in the building design in form of techniques. These techniques give an indication on how air is induced into the building, and how it is expelled out of it [64]. There are two main natural ventilation techniques by which it can be delivered to the building; cross-ventilation and single-side ventilation. Where applicable, a stack effect could be integrated with these two techniques forming though such a complicated ventilation technique.

2.7.1. Cross-ventilation

Cross-ventilation is a dual-side control technique through face-to-face openings. Simply, the air enters from one opening (*in the windward wall*) and travels across the space to leave from another opening in the opposite side (in the leeward wall) [47]. See Figure 2-15. Cross ventilation can be considered as the most effective technique that can grant a consistence large airflow with deep air penetration across the ventilated space [47, 82]. The airflow in cross ventilation, in most cases, is a wind driven airflow, Unless a significant difference in height between the inlet and outlet openings is provided and thus thermal buoyancy starts to play a role [47].

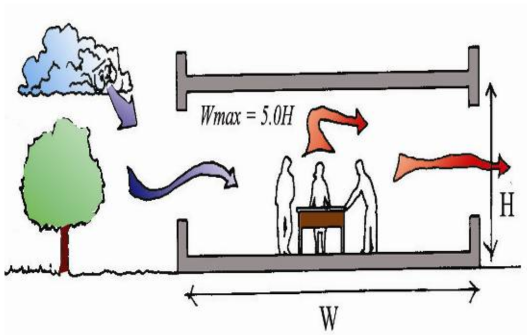


Figure 2-15: Cross ventilation technique, reproduced after Roaf [82] and CIBSE [84]

Cross ventilation is the most suitable technique for ventilating deep-plan buildings. By this technique, a space with depth of more than *2.5* times the space's height (*H*) and up to *5H* could be efficiently ventilated [47, 82]. The airflow can also pass across several rooms through open doors or overflow grills [64]. It is more desirable than single side ventilation in the places with large heat gain [47].

2.7.2. Single-side ventilation

Single side ventilation is a solo side control technique through one or more openings in the same wall. In other words, The air enters from one opening and leave from the same opening or from another opening in the same wall [47]. See Figure 2-16. The airflow in the single side ventilation is a wind driven airflow, unless a difference in height between the inlet and outlet

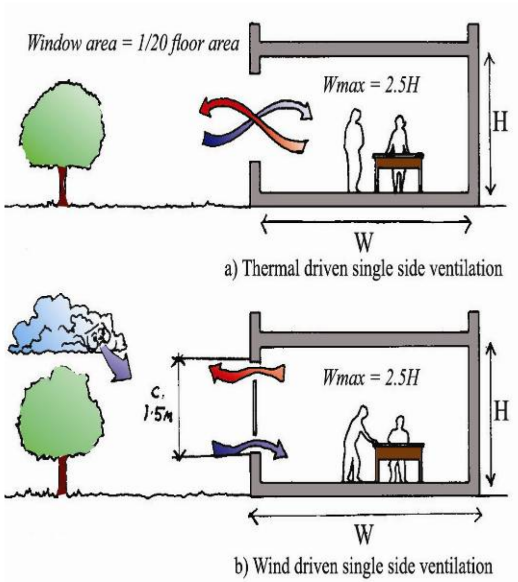


Figure 2-16: Single side ventilation technique with wind and thermal driven airflow, reproduced after Roaf [82] and CIBSE [84]

openings within the same wall is provided and thus thermal buoyancy starts to play a significant role [47]. The contribution from thermal buoyancy relies on the indoor/outdoor temperature difference, the vertical distance between inlet and outlet, and the actual area of the openings. The capability of the thermal buoyancy, in enhancing the airflow within the space, is directly proportional to the vertical distance between the openings, and the indoor/outdoor temperature difference [64].

The effectiveness of single side ventilation technique is shallow and can be only effective within a distance of *2.5 H* (*space height*) maximum from the inlet/outlet wall [47, 82]. It was found that this technique is more suitable for moderate climates [47] and not effective in hot climates [82]. It was recommended by *BRE*[1] that the more suitable space for single side ventilation is that space with a window area 1/20 floor area with depth of maximum 2.5 times the ceiling height [83]. Quoted in [47].

Chapter 3:
Design measures for natural ventilation: macro, intermediate and micro levels

3.1. Chapter three introduction

This chapter discusses the design measures and their parameters affecting air movement in and around the buildings. This in turn affects the performance of natural ventilation strategies explained in the last chapter. These design measures along with the studies examined the effectiveness of their parameters were not found grouped or categorised in the available literature. Each study classified only what it used from these measures and parameters. In this chapter of the research, the design measures are comprehensively classified and categorised. In addition, the effect of their parameters on natural ventilation that identified by other researchers is critically reviewed.

To an organized display of these measures, the research devised a new classification of these design measures. This classification expresses these measures in order, starting from the largest scale down to the internal design scale. The measures are grouped under three levels; the macro-level, the intermediate-level and the micro-level. The design measures and their parameters are reviewed in details within this chapter under those three levels.

Figure 3-1 illustrates the proposed classification of the design measures affecting natural ventilation performance.

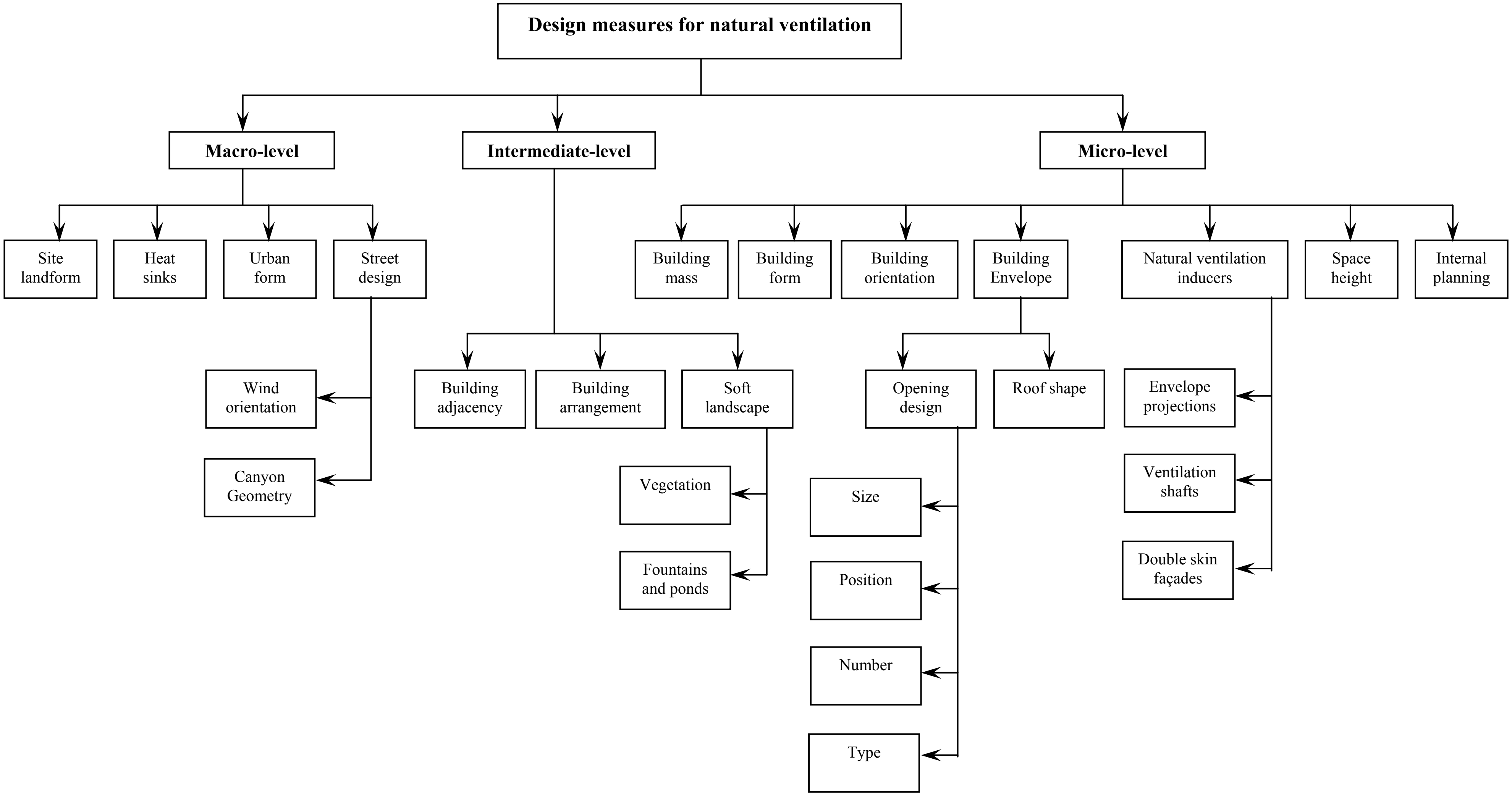


Figure 3-1: The proposed classification of design measures affecting natural ventilation

3.2. Macro-level design measures

The given site parameters and how to respond to them when designing for natural ventilation along with the design measures of urban form and street design are all included in the macro-level. They are discussed in details below.

3.2.1. Site landform

The site landform can significantly affect the airflow profile over the site. To some extent, the designer can employ its potentials and limitations in serving his proposal for natural ventilation design.

The site landform could be flat, sloping or undulating (*mounds, etc*.). Different local airflow is developed over the site in each case. In flat sites, the prevailing conditions are most likely the same over the entire site with little variation can be identified. However, slopes and depressions could create significant variations in the airflow and air temperatures across the site [36]. In general, on slopes, the temperature decreases by (0.8^o *C*) every (*100 m*) increase in the height [85]. However, the situation could be different according to the form of terrain and the time of the day. Due to the different exposure to the solar radiation between the day and the night times, the airflow could be reversed in mountainous regions in particular [45]. During the daytime, the air, in the valley, is heated up and then drown up the hill, where the low pressure area is formed (Figure 3-2). This flow is called (a*nabatic flow*) [86]. During night time, the cool air tends to fall down the hill under the effect of its high density and settle

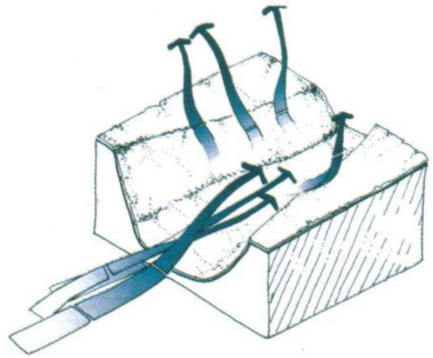


Figure 3-2: Airflow over the valley at daytime (*anabatic flow*), after Battle McCarthy Consulting Engineers [45]

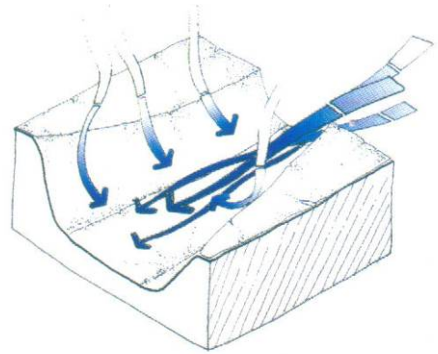


Figure 3-3: Airflow over the valley at night time (*katabatic flow*), after Battle McCarthy Consulting Engineers [45]

into the depression creating a cold reservoir (Figure 3-3 and Figure 3-4) [36, 45, 87]. This flow is called (*katabatic flow*) [86]. The local airflow result from this natural phenomenon is driven mainly by thermal buoyancy and can be stronger in narrow valleys [87].

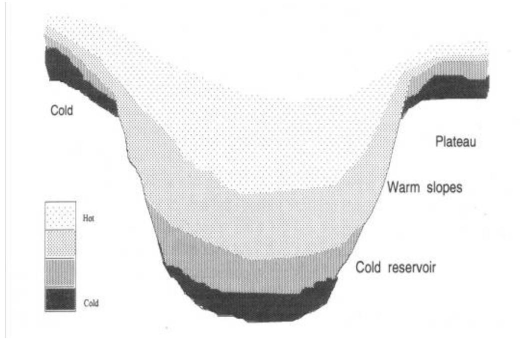


Figure 3-4: Temperature stratification on a mountain slope, after Asimakopolous, D. and M. Santamouris [87]

For the wind driven airflow, the slopes that face the windward direction experience much higher wind speed than those that face the leeward direction [19]. Also, the highest airspeed could be found at the crest of the slope [36]. The wind driven airflow pattern was found to follow the hill shape that obstructs its way [87]. A schematic illustration of the effect of topography on local wind exposure was presented by Carmona [88] and quoted from [19]. See Figure 3-5.

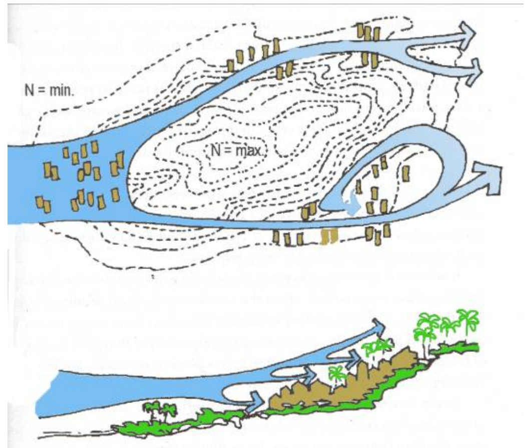


Figure 3-5: Schematic illustration of the effect of topography on local wind exposure, reproduced after Carmona [88] in [19]

This local flow over such a landform can be used by the designer to locate buildings on the hill. However, choosing the location of the building on a site with a sloped landform depends on the proposal that the designer would like to achieve, and it is controlled by the nature of the climate. According to Allard [33], when considering only the suitability of the building location for providing the optimum natural ventilation, the designer has to consider the following factors in his selection:

- The best exploitation of the airflow pattern due to landform;
- The best combination between summer and winter airflow and their impact on comfort in both seasons;
- Avoid the unwanted wind shelters and the uncomfortable high wind speed; and
- Avoid an airflow, which carries dust and pollutants.

According to the above factors and while considering only the natural ventilation, Allard [33] emphasised that the best location of a building on a slope is at the middle of the slope's side that faces the windward direction along the contour lines. He justified this selection by the significant potential of this location in providing cross ventilation and the avoidance of colder winds downhill as well as the high wind velocity at the hill's crest.

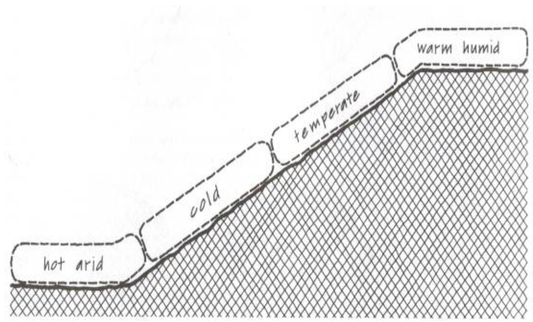


Figure 3-6: The most desirable building location on a slope based on the nature of the climate, after Brown and Dekay [85]

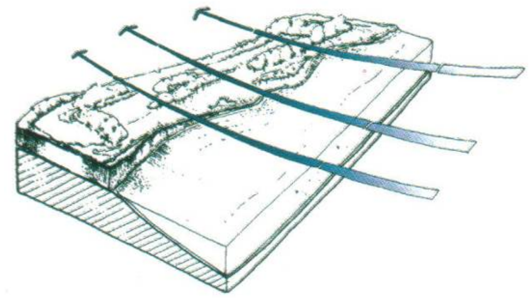
However, when looking into the bigger image, many other factors have to be considered in the selection of a location on hill landforms in order to produce a successful building in its context. Therefore, when selecting the building location on a slope, the designer has to look into the whole factors involved in achieving a climatic design proposal. Brown and Dekay [85] introduced a primary location of a building on a slope based on the design requirements of each different climatic context and provided building orientation advice in each case (Figure 3-6).

In hot-arid climates, the best location is at the bottom of the slope oriented towards the East in order to get the maximum exposure to the cold katabatic flow during night along with providing a minimal exposure to the afternoon sun. In hot-humid climates, the best location is at the crest of the slope oriented towards East in order to maximize the exposure to the wind and minimize the exposure to afternoon sun. In the cold climates, the best location is low on a south facing slope (*North facing in south hemisphere*) in order to maximize the exposure to solar radiation, provide wind protection and avoid a cold reservoir at the bottom of the valley. In temperate climates, the best location is at the middle to upper part of the slope in order to provide good exposure to sun and wind as well as provide protection from the high wind speeds at the crest.

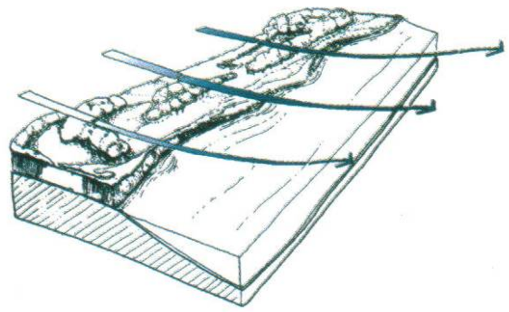
3.2.2. Heat sinks

The availability of heat sinks such as; large bodies of water (*sea, river and lake*) and/or forests, near the building site play a role on the macro-level. These heat sinks could create local airflow patterns over the site, which in turn affect natural ventilation performance in the surrounding buildings.

Building on the sites near the large water bodies is more suitable for hot-dry climates as water bodies produce a cool breeze that result from what is called (*land and sea breezes phenomenon*) [36, 89]. In this phenomenon, the similar but reverse airflow patterns between day and night times occur near water bodies (Figure 3-7) [87]. During the day, the air over the land surface is hotter than the air over the water body surface, which in turn creates a higher pressure area over water than that is over land. Due to the difference in pressure, a cool local airflow current (*sea breeze*) blows from over the water towards the land (Figure 3-7a) [87]. In the case of very large water bodies, this sea breeze could flow in speeds of 2-5 m/s and penetrate the land as far as 100 Km with an effective thickness of 1-2 Km above the earth level [89]. In addition, it could achieve a reduction of about (*8.3^o C*) in air temperature over the land surface [87]. The situation inverses at night producing airflow from the land side towards the sea (*land breeze*) (Figure 3-7 b) [87]. The land breeze is weaker than the sea breeze due to the smaller difference between the air temperature above water and land



a) The sea breeze during day time



b) The land breeze during night time

Figure 3-7: Local airflow and convection current results from land and sea breezes phenomenon, after Battle McCarthy Consulting Engineers [45] surfaces at night [87]. Its speed could reach 1-2 m/s, but is smaller in the horizontal and vertical effective range than that of the sea breeze [89].

Locations near large bodies of water may be preferable if cooling breezes can be directed into the building [67]. Also, the building should be designed with the longitudinal axis parallel to the water body's bank to maximize the benefit from cross ventilation through its short depth [33].

3.2.3. Urban form

In fact, the measures of urban from and the street design are working in conjunction with each other in order to provide either protection from wind or maximum exposure according to the design proposal. The urban form has a significant role in serving the climatic design generally and designing for ventilation specifically, as it greatly control the access of the sun and wind to be used in buildings [85]. From the ventilation point of view, the urban form could be designed to maximize the air movement through the city level, and thus allow wind access to more buildings for optimum ventilation [65, 85]. Solar orientation should be greatly considered in their design, especially in hot climates, where providing solar shading is given priority over ventilation.

Streets layout and their configurations determine the urban form of the settlement or its districts and neighbourhoods. Four main urban forms could be identified from the historical background in building cities in order to be adapted to a specific climates' requirements [90].

Those are:

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

a) The compact urban form site

b) The clustered urban form site

c) The disperse (western dotted) urban form site

Figure 3-8: The three Cairo sites that were taken by Fahmy and Sharples as representative case studies for the different urban forms, after Fahmy and Sharples [91]

Fahmy and Sharples [91] studied the airflow and thermal comfort performance of the three forms; compact form, clustered form and disperse form. They took three representative sites in Cairo as case studies (Figure 3-8). All the buildings in all sites were medium height that varied between 4 and 5 storeys height. Their study revealed the suitability of the clustered form for both ventilation and general comfort requirements as it provides enough wind speed and solar access to the site. They advised that the use of the clustered pattern with a different orientation, different aspect ratio as well as using vegetation to provide shading could be the best option for achieving passive cooling in such context. On the other hand, in the compact form, the wind was found to have almost no access to the site, which in turn prevents the heat dissipation from the streets at night as well as providing bad environmental conditions.

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

These results confirmed the concerns of Jenks et al [92] regarding the compact form. They reported that the compact layout could provide a reasonable degree of sun shading, however, it also substantially restricts ventilation [93]. Fathy [94] also advised the use of a compact form where protection from sand storms is required, providing it is designed with winding streets and with closed vistas.

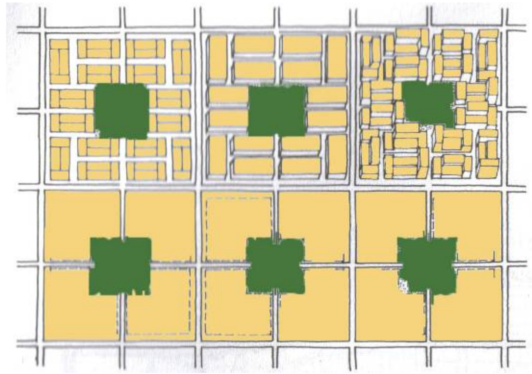


Figure 3-9: The clustered form organized around green areas , reproduced after Brown and Dekay [85]

Brown and Dekay [85] advised that, for cooling purposes, the integration of green areas in urban form could greatly enhance the cooling effectiveness of the air. In addition, in supporting the clustered form, they asserted that more smaller open spaces distributed evenly in clusters around a neighbourhood will have greater cooling efficiency than large parks (Figure 3-9). This confirms the role of open spaces between buildings as air pressure regulators. As for the disperse form, it was reported to give the optimum exposure of buildings to the wind and thus, maximum ventilation potential [95]. However, it could be used, where the ventilation is given priority over sun shading, for example in humid climates [90, 96].

3.2.4. Street design

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

3.2.4.1.Street wind orientation

The performance of each urban form, in relation to natural ventilation, greatly depends on the orientation of the streets' grid and the buildings that line them on both sides.

Street orientation could be parallel, oblique or normal to the wind direction. When the major streets in a site are oriented parallel to the prevailing wind, the highest velocity could be obtained in the streets and the adjacent open spaces, while poor ventilation potential could be found in the buildings on its sides [36, 97]. In this case, the primary factors determining the airflow velocities in the streets are; the street width and the frontal area of the building façade that faces the wind [85]. These factors determine the *Blockage ratio* (R_b) that can be calculated as follows [98] quoted in [85]:

$$R_b = (W \times H) / (W + L)^2 \qquad \text{(Eq: 3-1)}$$

Where:
R_b = The blockage ratio;
W = The width of the building façade that faces the wind;
H = The height of the building façade that faces the wind; and
L = The street breadth

For the explanation of the variables used in this equation, refer to Figure 3-10. According to Wu [98], the wind speed in the streets of a group of buildings, whose major streets are oriented parallel to the prevailing wind, is a function of the group's blockage ratio. By calculating the blockage ratio for a given buildings group, the wind speed within its streets could be expected, as a percentage of the unobstructed wind speed, using Figure 3-11.

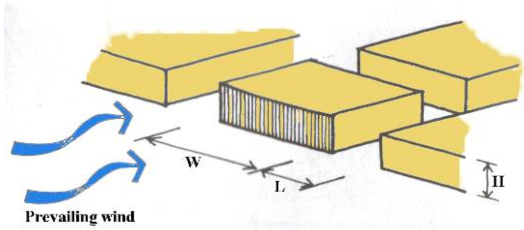


Figure 3-10: The variables used to calculate the blockage ratio, reproduced after Brown and Dekay [85]

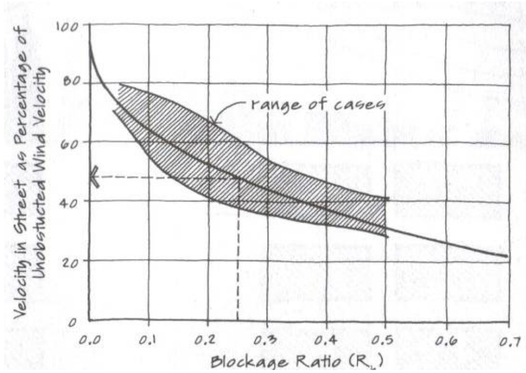


Figure 3-11: Predicting the wind velocity in the streets by the knowledge of the blockage ratio, after Brown and Dekay [85]

Orienting the street grid and buildings obliquely at an angle in relation to the wind direction provides good homogenous wind patterns through streets and better ventilation potential for buildings [36]. Generally speaking, the optimal street orientation for ventilation purposes, which is advised by Givoni [99] and confirmed by Brown and Dekay [85] and Ng [100], was found to be oblique to wind direction by approximately 20 – 30^{o} with the narrowest buildings façades facing the wind (Figure 3-12). This in turn enhances the potential of using natural ventilation, and cross ventilation in particular. According to Givoni [19], buildings that have oblique orientation that ranges between 30^{o} to 60^{o} to the wind direction have greater potential for using natural ventilation. This oblique orientation creates two (+) pressure sides of the building and two (-) pressure sides (Figure 3-12), which in turn maximize the potential of using cross ventilation within the building [85].

In the case of orienting the major streets of a given site normal to the prevailing wind direction, most of the wind is skimming over the buildings and providing by such, low velocity turbulent air movement in the streets [97]. The airflow pattern and the velocity profile in such a case are significantly controlled by the street canyon configurations.

3.2.4.2.Street canyon configurations

Street canyon can be defined as "*the space between buildings lining up along both sides of a street, from street surface to rooftop level*" [101]. The geometrical configurations of the street canyon can significantly affect the airflow pattern within the street, especially, when it is oriented normal to the wind direction [102]. This in turn can affect the potential for using natural ventilation inside buildings on both sides of the street. Street canyon geometry is also one of the main measures that can have a great impact on air temperature distribution within the street [103]. This in turn could affect pedestrian thermal comfort.

Street canyon geometry can be described using three variables; height of buildings on both sides (*H*), street width (*W*), and street length (*L*) [89]. The airflow pattern within the street can be defined using the ratios of *H/W* and *L/H* [89]. According to Vardoulakis et al [104] and Ahmed et al [105], six types of street canyons in terms of *H/W* and *L/H* ratios can be defined. These are as follows:

- Regular canyon, when (*H/W =1*);
- Shallow canyon, when (*H/W<0.5*);
- Deep canyon, when (*H/W>2*);
- Short canyon, when (*L/H = 3*);
- Medium canyon, when (*L/H=5*); and
- Long canyon, when (*L/H=7*).

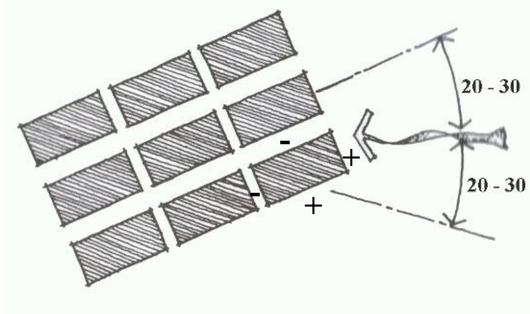


Figure 3-12: The generic optimum street orientation for natural ventilation purposes, after Brown and Dekay [85]

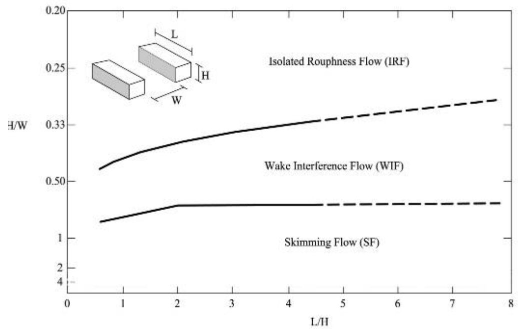


Figure 3-13: Identifying the airflow regimes in the street canyon based on the correlation between H/W and L/H, after Oke [106]

Oke [106] identified three air flow regimes based on the correlation between the two ratios H/W and L/H (Figure 3-13) in the case of the wind being almost perpendicular to the street axis. Those three regimes as seen in Figure 3-14 are:

- Isolated roughness flow (*IRF*);
- Wake interference flow (*WIF*); and
- Skimming flow (*SF*).

When the span of the street canyon is wide enough to prevent the interaction between the downwind flow of the first row of buildings, and the upwind flow of the second row of buildings, as shown in Figure 3-14a, isolated roughness flow occurs ($H/W < 0.3$) [107]. As the street becomes narrower, the interaction between the two air currents starts to happen and the wake interference flow starts to occur at ($0.3 < H/W < 0.65$) [106] (Figure 3-14b). As the canyon span becomes even narrower as in Figure 3-14c, the air flux does not enter the street and this induces a circulatory vortex in the canyon and skimming flow occurs. According to Taylor [108], this pattern of flow was first noted by Albrecht in 1933 [109]. In the case of deep canyons (Figure 3-14d), the vortex occurs at the top of the canyon [101]. This vortex starts to be deformed to two vortex when *H/W* reaches 1.5 [110]. In the case of a deep canyon, the air does not reach the street level, if the airspeed less than 2 m/s. However, it starts to have some effect, when the wind speed exceeds 5 m/s [111] (quoted from [108]).Tahbaz and Djalilian [95] suggested H/W ratio of 0.5 to 0.44 for the maximum benefits from summer breezes in ventilation purposes, providing that the windward façade's length does not exceed twice the building height.

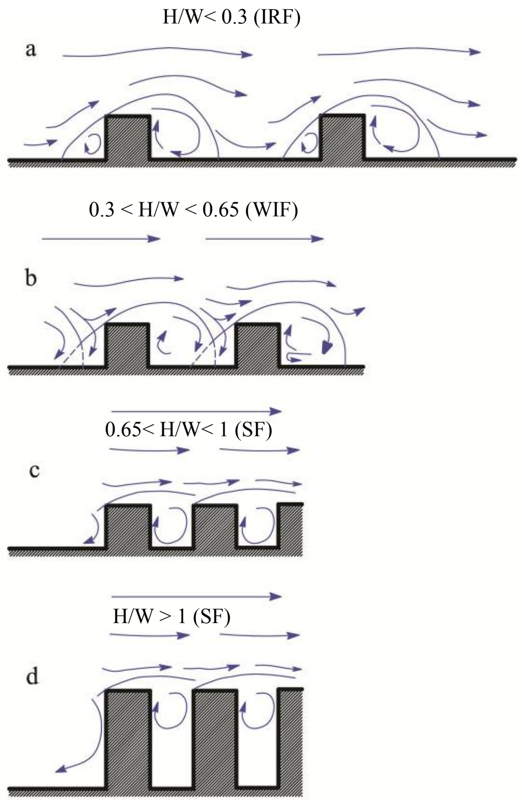


Figure 3-14: The airflow patterns in the street canyon based on the H/W ratio in case of the wind being almost perpendicular on the street axis, reproduced after Littlefair et al. [89] and Letzel [101]

Recently, the problem of poor ventilation in the deep street canyon bottom has been overcome using a novel pedestrian ventilation system developed by Mirzaei and Haghighat [112]. This system depends on providing airflow to the lower part of the canyon through a designed vertical ventilation shaft in the canyon's building mass. The ventilation shaft draws the air from the building roof level and delivers it to the lower part of the canyon through ducts in the street floor and buildings walls (Figure 3-15). In addition, the system can be reversed, when needed, by the use of active controlling systems (*Fans*) [112].

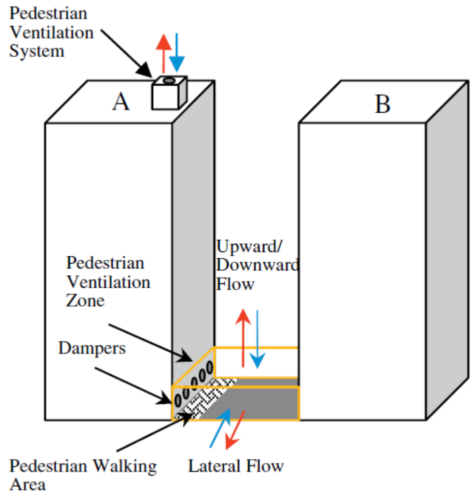


Figure 3-15: The innovative pedestrian ventilation system (PVS) for overcoming poor ventilation problem in the deep canyons, after Mirzaei and Haghighat [112].

In general, the optimum characteristics of street layout that can promote airflow and enhance the potential of providing natural ventilation to its buildings were described by Givoni [99]. He suggested that a street which has a wide span and is neither parallel nor normal to the wind direction is the optimum in terms of enhancing the natural ventilation potentials of both the street level and the buildings on both sides. However, greater attention has to be given to the nature of the climate and the other climatic considerations as advised by Asimakopolous and Santamouris [87]. Brown and Dekay [85], also, suggested some generic solutions for streets layout in each climate that provide access to or protection from the wind where required. See Figure 3-16.

3.3. Intermediate-level design measures

The building adjacency, soft landscape and building arrangement are the design measures discussed in the intermediate-level.

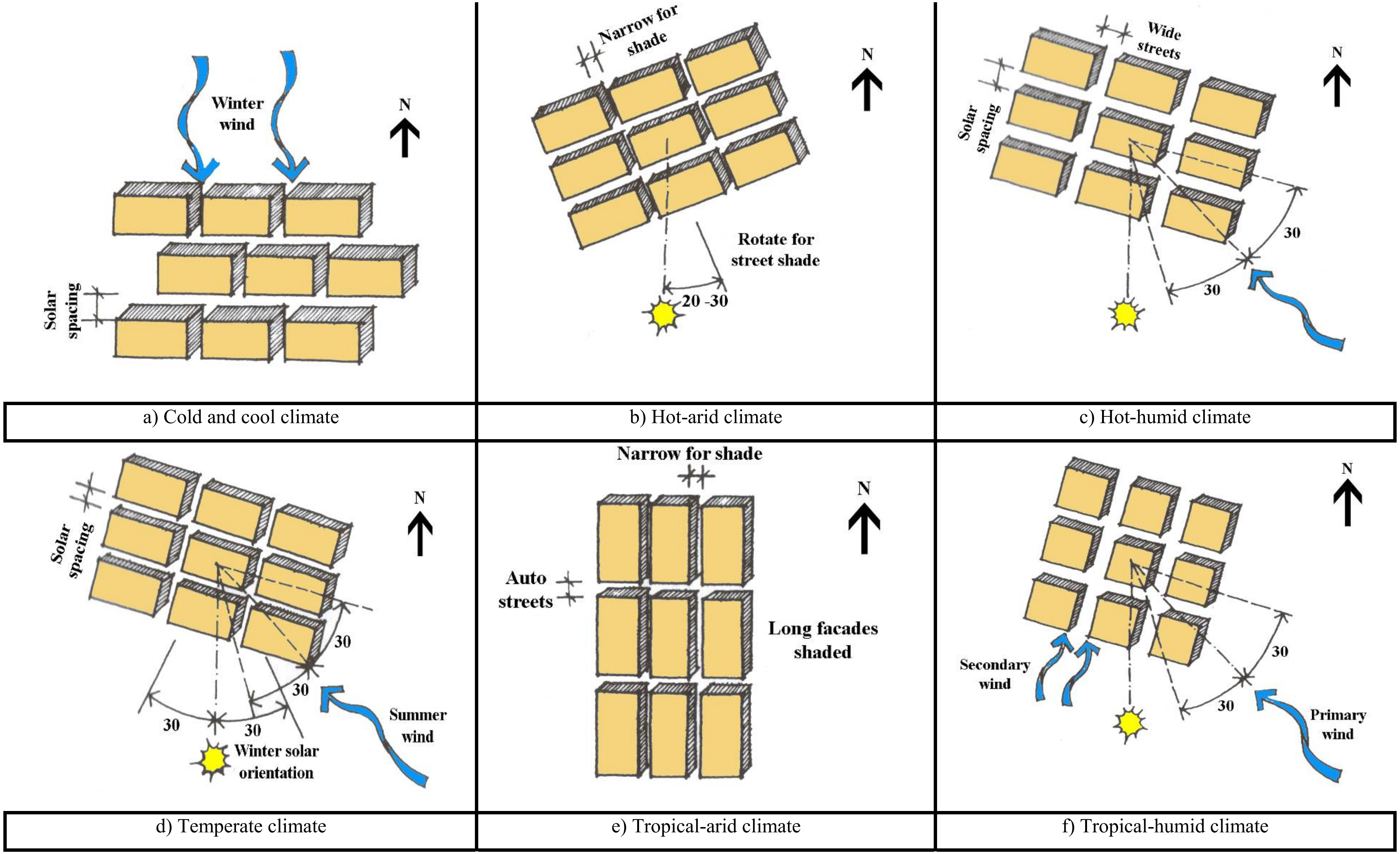


Figure 3-16: Generic design solutions for streets layout in each climate, reproduced after Brown and Dekay [85]

3.3.1. Building adjacency

Building adjacency status is one of the most effective measures in natural ventilation performance, as it is possible to significantly facilitate or hinder the potential of using natural ventilation. For example, to obtain the optimum natural ventilation performance within a residential building, each dwelling's design should facilitate the possibility of providing openings in both; windward and leeward sides [38]. In terms of adjacency status, residential buildings could be categorized in four different types; detached, semi-detached, rows lining single-loaded corridors and rows lining double-loaded corridors [113].

The poorest natural ventilation performance was found to be in the buildings rows that line streets from both sides (double-loaded corridors) or some parts of them[113]. This poor performance is declared to be even worse, if the staircases of the buildings serve more than 2 units / floor [113]. On the contrary, the row of buildings that line the street from one side only was judged to offer a high possibility of providing cross ventilation, and thus, well ventilation performance [113].

The detached and semi-detached residential buildings were found to have a high exposed envelope-to-floor ratio that increases heat exchange with surroundings, while provides high potential of using passive cooling strategies such as ventilation [113]. The optimum case, in terms of natural ventilation performance, was found to be the detached buildings that offer the possibility of locating an opening in its walls all around [38]. Bady et. al. emphasised the importance of providing gaps between the adjacent buildings, where ventilation is required, as the gaps introduce more wind to an urban domain and improve the ventilation potential [114]. Although the recommendation of using the detached buildings where high potential of using natural ventilation is required, this could not be consider an absolute as the arrangement of buildings and their orientation significantly affect this scenario.

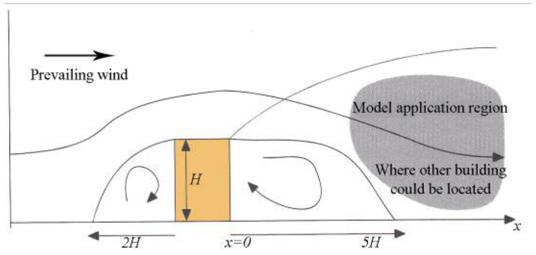


Figure 3-17: Flow structure around a single building, after Allard [33]

3.3.2. Building arrangement

Buildings arrangement in a site, in relation to natural ventilation, could vary between locating a building, a small group of buildings or large compound of buildings. When locating a building within an urban site, great attention has to be given to the distance between the building and other buildings in the site. In order to provide maximum wind exposure to a building, it has to be located at a distance from other buildings that is larger than their wake depth [33]. The wake depth of a single obstacle could reach five times its height (Figure 3-17) [33]. In the case of this not being possible, the designer can locate the building upwind with its longitudinal axis normal to the wind direction. However, in most cases, the designer has to decide on positioning the building in the site, especially when the summer wind direction is different from the winter one. In such a case, the building has to be located to pick up summer streams and sheltered from winter winds (Figure 3-18) [33].

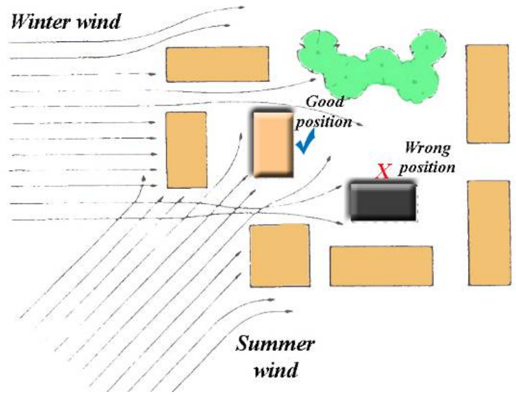


Figure 3-18: Example of good and bad location of a building on an urban site with respect to the wind, reproduced after Allard [33]

In order to determine the best position of two buildings in relation to each other, Klemm et al [115] analyzed the effect of several arrangements of two buildings with dimensions of (*depth=16 m, width=32 m, height=32 m*) on the urban wind speed. A total of *96* cases, which included different distances and displacements of (*Sx and Sy=16, 32 and 48m*) (Figure 3-19) between the buildings as well as different orientation in relation to the north, were all investigated. The optimal case was given automatically using the computer program *CAMOS* by applying the criteria of achieving the maximum area of wind speeds of (*0.4 to 4 m/s and 3 to 6 m/s*) and the minimum area of (*0 to 0.4 m/s*) around the buildings. The optimum desirable layout was the case in which the two buildings were so aligned (*Sy =0*), the distance between them (*Sx = 46 m*) and oblique by 103^{o} to the north direction (*i.e. the street oblique 13^{o} to the most frequent wind at this site that is coming from the west*). Also, it was advised by Allard [33] to avoid locating buildings together to form narrow passageways with too close corners (Figure 3-20). These configurations could, in turn, create a critical gusty wind flow area due to the *Venturi effect*[1], which is reported to be uncomfortable to the pedestrians [33]. Blocken et. al. studied these configurations in case of buildings normal to each other [116] and parallel to each other [117]. Both studies confirmed that the increase in wind speed through the passageway (*Venturi effect*) is limited to the pedestrians level as the speed decreases with the height increase.

In the scale of a small group of buildings, the arrangement of the buildings on the site can introduce unlimited possible arrangements. Asfour [118] investigated the effect of 6 hypothetical different arrangement configurations for a group of buildings (Figure 3-21) associated with three different wind orientation on the potential of natural ventilation throughout the site. He took the difference in pressure across the site, which was created by

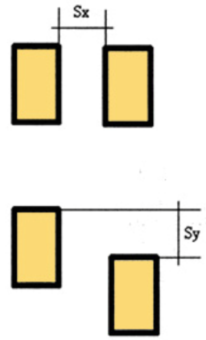


Figure 3-19: Building arrangements in Klemm et al study, after Klemm et al [115]

Note 1:
According to Bernoulli's theorem, when the cross-section of the fluid inlet is different from that of the outlet, great pressure difference and higher fluid speeds across the domain of the fluid flow are created. This is what known as the Venturi effect [136].

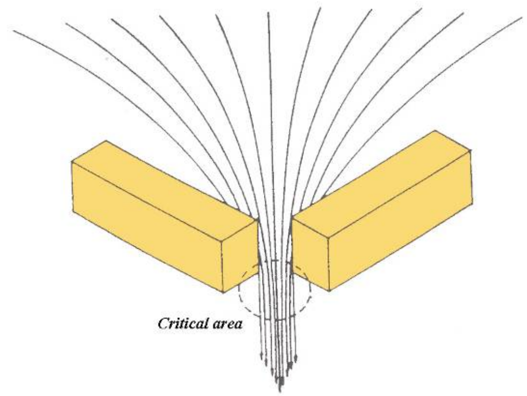


Figure 3-20: Building arrangement that creates critical discomfort area for pedestrian (*Venturi effect*), after Allard [33]

each case, as the judgement criterion. He found the best natural ventilation potential was achieved in the (*configuration 2*) with wind angle (*0^o*) and the worst case was (*configuration 6*) with wind angle (*45^o*). In general, the results of his work concluded that the best ventilation potential could be provided by arranging the buildings around a central space (*clustered pattern*) that opened to the prevailing wind direction.

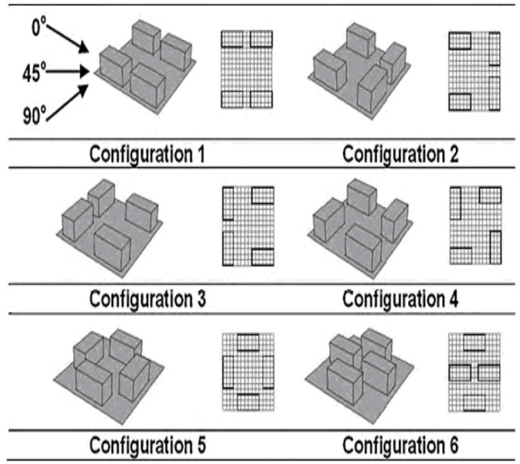


Figure 3-21: Different small group of building arrangements studied by Asfour, after Asfour [118]

Jensen and Franck 1963 [119] (quoted from [85]) studied the wind shelter patterns created by different arrangements of a small buildings group in relation to variations in incidental wind direction. They studied the different arrangements of buildings around L-shape, U-shape, and closed-shape clusters (Figure 3-22, Figure 3-23 and Figure 3-24). These figures can be used as a preliminary instrument helping in building arrangement according to the proposed admittance or blockage of wind access to the site and its buildings.

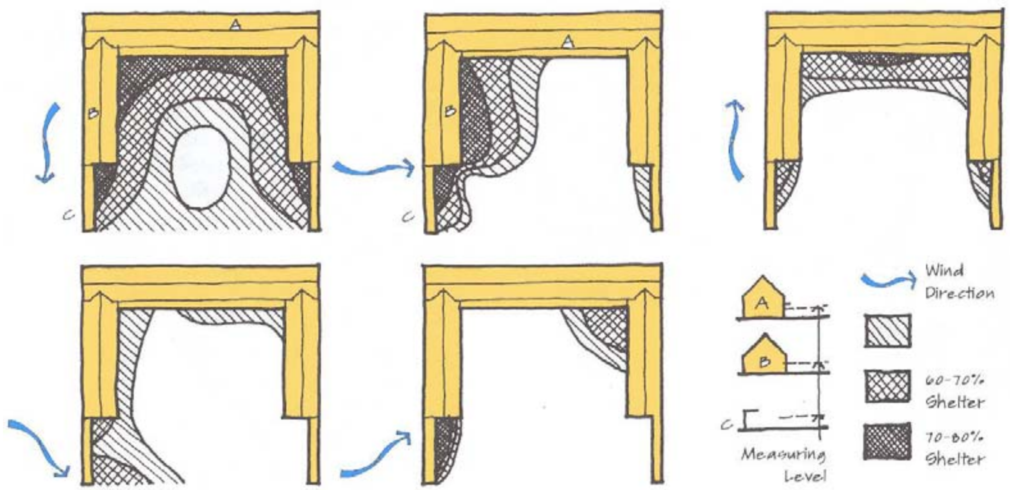


Figure 3-22: Wind shelter patterns in U-shape building arrangement, after Brown and Dekay [85]

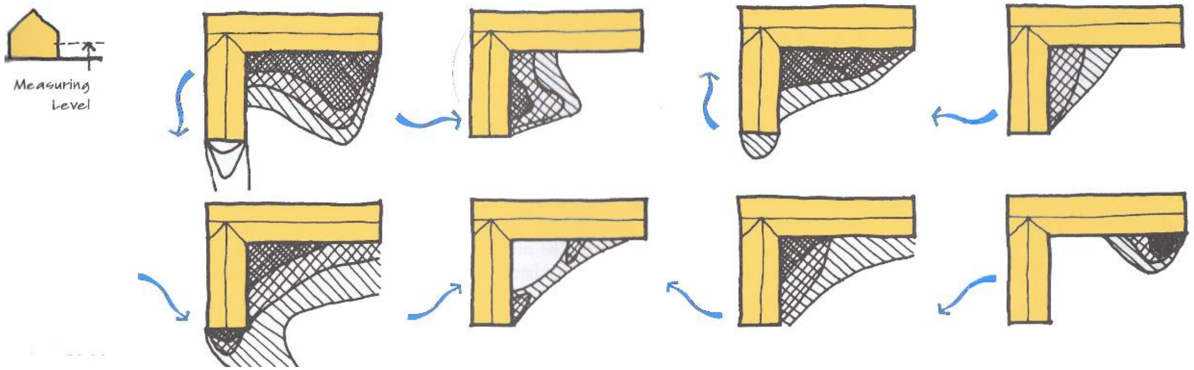


Figure 3-23: Wind shelter patterns in L-shape building arrangement, after Brown and Dekay [85]

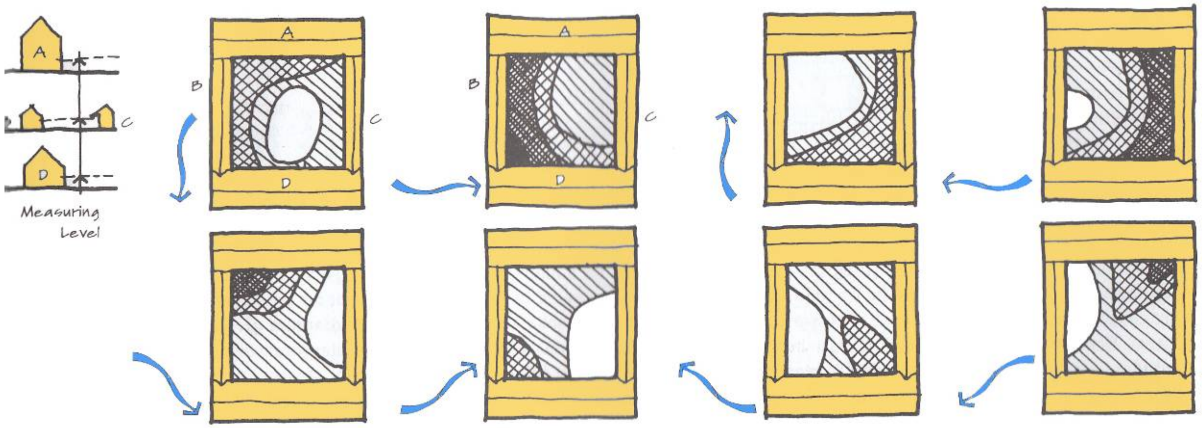


Figure 3-24: Wind shelter patterns in closed-shape building arrangement, after Brown and Dekay [85]

When arranging a compound with several buildings, the rule is to avoid a wake interference flow regime and arrange the buildings in relation to each other to allow good exposure to wind for each building [33]. Three main different arrangements were studied and compared by several researchers in terms of their suitability for providing good natural ventilation potentials. These arrangements are; arrays with clearly defined long streets, diagonal arrangement and staggered arrangement [33, 89, 90, 100, 120, 121] (Figure 3-25). The airflow in different building arrangements seems to greatly depend on the wind direction. As for the buildings arranged in regular, clearly defined long streets as running through it, this could be opened to the airflow in some directions, while it seems to be closed in others [89].

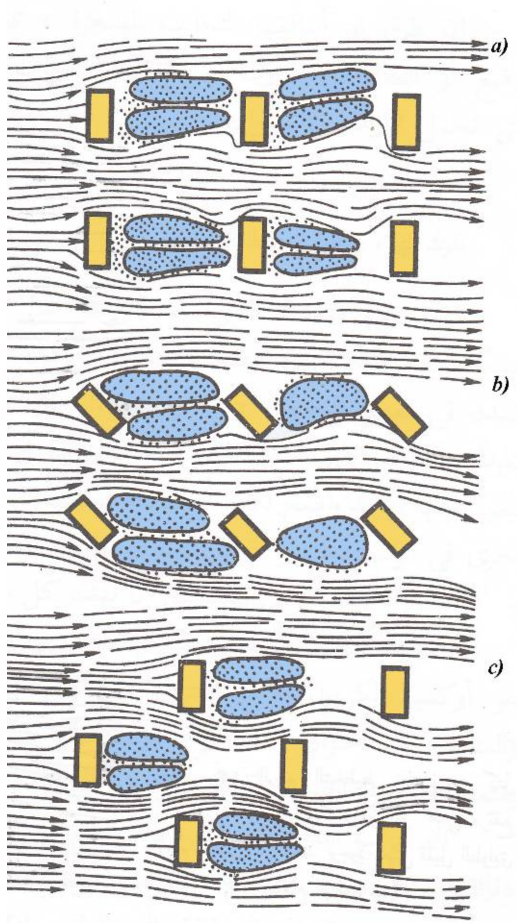


Figure 3-25: Air movement profile in different building arrangements. a) Aligned rows, b) diagonal arrangements, c) staggered arrangement , reproduced after Rimsha [120]

As a result of previous work in the USA (quoted in [120]), it is proved that the well ventilated buildings are those which are exposed to the wind before other buildings in the site. By studying the three different buildings arrangements (*Aligned rows, diagonal arrangement, and staggered arrangement*), it was found that in the staggered arrangement option, the distance between buildings increases, which in turn allows the airflow to recover before arriving at the next building (Figure 3-25) [120]. In addition, the use of the staggered arrangement was recommended by Zhang et al [121], Allard [33] and Ng [100] in order to get the best natural ventilation potential. However, Zhang et al [121] were conditional on providing the association of the staggered arrangement with 45^o orientation to the wind direction (Figure 3-25b). Allard [33], also, reported that a similar performance as in staggered arrangement could be obtained from the normal arrays arrangement, when oriented obliquely to the wind direction (Figure 3-26).

A different opinion was produced by Golany [90]. He claimed that the normal arrays arrangement lined up with wind direction, increases the wind penetration of the site and cause a swift urban ventilation conditions. On the other hand, he reported that the staggered arrangement blocks the wind penetration of the site. Also, the staggered arrangement was advised to be avoided by Beranek [122] and Bottema [123] (quoted from [51]) for the severe wind environment around buildings that are created by the huge pressure difference caused by such arrangement with some orientations. Quite separately, the researcher here believes that the blockage or allowance of wind penetration on site, in the staggered arrangement, is dependable on the distance between buildings, building volume and shape, which have not been mentioned by any of the researchers' studies.

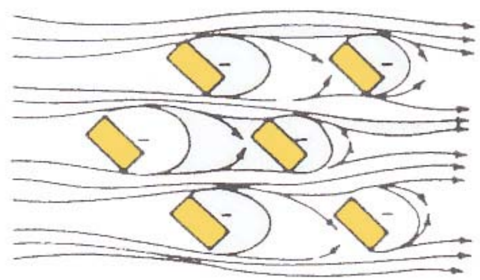


Figure 3-26: Air movement profile in normal array arrangement when oblique to the wind direction , after Allard [33]

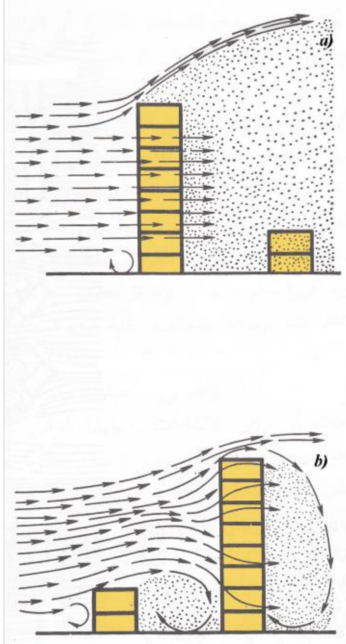


Figure 3-27: Air movement profile in different arrangement of buildings according to their heights, a) the tallest building first (wall effect), b) the shortest first (recommended arrangement) , after Rimsha [120]

Furthermore, many researchers [87, 120, 124] recommended, for best natural ventilation performance in and around buildings, considering varying the building heights around the site rather than building them in the same height. They also advised making some gradient of the buildings' height that allows the shortest one to be exposed to the wind first and the highest to be exposed to wind last in order to avoid the wall effect blockage (Figure 3-27).

3.3.3. Soft landscape elements

Landscaping was reported to have an important role in controlling the air movement and air quality around buildings for optimum natural ventilation [33]. The combined and appropriate use of its soft elements such as, vegetation and water surfaces (*heat sinks*) in the building layout was found to work as significant microclimate modifiers [125]. The details of the impact of vegetation profile and the availability of fountains and ponds (*heat sinks*) in the building layout are explained below.

3.3.3.1.Vegetation

The vegetation profile has a significant role in modifying the air properties, quality and direction for the best natural ventilation potentials. The effects of vegetation profile in the building site on the air can be summarized as follows:

- Provides Air conditioning [33, 36, 89, 90, 126-130];
- Improves air quality through removing dust and carbon dioxide [33, 90, 130, 131];
- Reduces noise [33, 90];
- Increases and decreases the airspeed [33, 34, 36, 89]; and
- Directs the airflow [33, 34, 36, 87, 89, 128, 132].

The vegetation, especially trees, has a good impact on air conditioning, as it is very effective in producing sun shade and reducing heat gain in hot climates [36]. In addition, a significant cooling to the air is provided by the trees' leaves through the evaporation (*evaporation inspiration*) that increases the air humidity [89, 128, 130]. The preference of this humidification effect depends on the prevailing humidity and temperature conditions [89]. It is proved that better comfort conditions are provided, when the site contains areas of grass and green walls in the sidewalks [129]. It is also proved that vegetation in the site plays a significant role in reducing the heat island intensity in urban areas, especially with its maximum evaporative cooling effect at night time [126]. Moreover, it was found that the building layout that is covered by large trees rather than small trees or grass has the largest average drop in temperature during hot day time, which in turn increases the potential of using natural ventilation during these hot hours [127].

The presence of vegetation in the site greatly helps in improving the air quality by removing dust particles, absorbing carbon dioxide and producing oxygen into the air [33, 90]. Although, the accurate determination of the airflow patterns and the particle transportation through the trees' canopies is difficult as yet [133], their role in filtering the air is clearly defined [130]. Lancaster and Baas [131] proved that sand flux decreases exponentially with vegetation cover. Apart from that, as an extra feature, fragrant species can be also used to perfume the air flowing through their site's buildings [128].

According to Allard [33] and Golany [90], the vegetation in urban areas helps in reducing the noise that is transmitted by the air into buildings' spaces. The proper design of the trees around a building could serve as traffic noise barriers by deflecting the sound waves away from the buildings [134].

Trees and hedges can be used in accelerating the airflow or decreasing its speed according to its position in relation to the building or a group of buildings [33, 34, 36]. On the one hand, the airflow can be accelerated by planting trees in a way that forms narrow passages, which in turn funnels the air through narrower area (*venturi effect*) (Figure 3-28) [36]. The less the

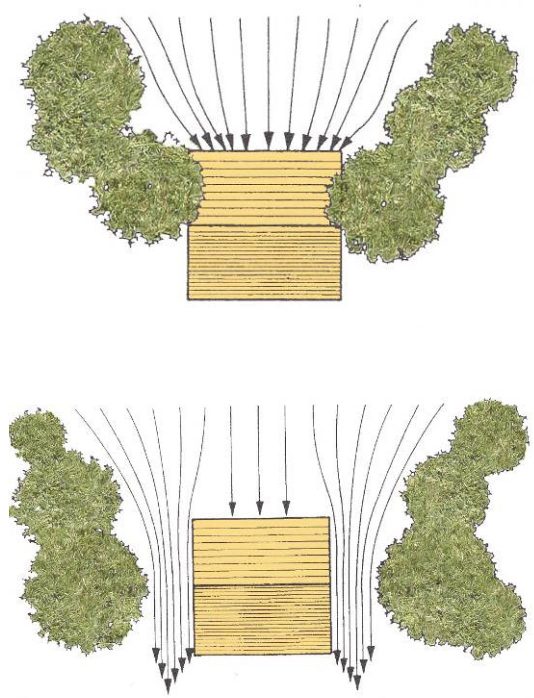


Figure 3-28: Accelerating the airflow by funnelling it through narrow passages toward the building and around it , reproduced after Allard [33]

space between the trees funnelling the air, the more the increase in the airflow speed that could reach 25% higher than normal wind speed [33].

On the other hand, the vegetation profile around a building can possibly reduce the airspeed or even cause it to pool rather than flow by forming air dams that produce equivalent pressure to the upwind one and in the reverse direction (Figure 3-29) [34].

The trees and hedges work as pressure regulators, so they can change the air direction to induce it toward a building or deflect it away [36]. In general, the trees and hedges create pressure difference between the upward side and the leeward side of their canopies, with the lower pressure at the leeward side. In the case of hedges, the lower pressure area on their leeward side changes the air path downwards. However, in trees the lower pressure area behind their canopy shifts the air path upwards (Figure 3-30) [36]. The effect of the vegetation profile on redirecting the air movement can be used in design to serve several purposes, when needed, such as; providing sheltering from the wind (*wind breakers*), deflecting the air away from buildings, preventing air spillage, and directing the air to enter buildings.

Although, the use of vegetation as wind shelter belts has a long history in agriculture and forestry, its use in protecting buildings nowadays is very limited [89]. Since the solid wind breakers are known to reduce the local wind speed and increase the air turbulence, and hence, the local gusty effect. Permeable wind breakers seem to be more efficient as they decrease the local wind speed without developing wind guests around [89]. According to Bache and

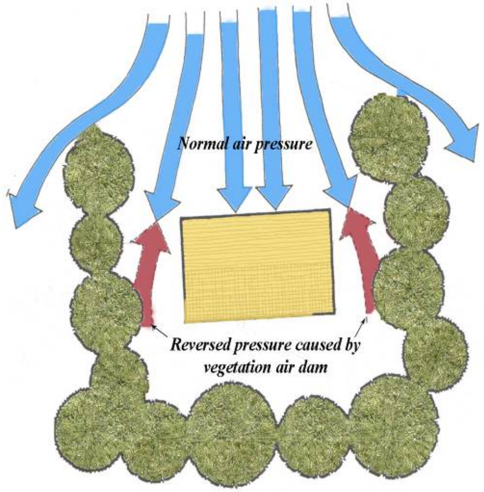


Figure 3-29: Making the air pool rather than flow by the effect of air dam and vegetation profile , reproduced after Watson and Labs [34]

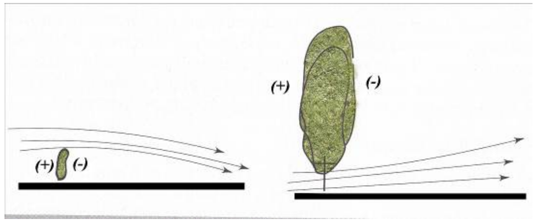


Figure 3-30: Vegetation causes pressure difference which shifts the air path, reproduced after Krishan et al [36]

MacAskill [132], the optimum permeability for wind breakers is generally about (*40-50%*). Allard [33] advised permeability of (*35%*) for the optimum performance. According to (*WMO*) [135] (quoted from [89]) , the sheltering effect of a group of wind breaker trees could reach 10 to 15 times the height of the trees that compose the protection belt (Figure 3-31). However, Bache and MacAskill[132] suggested that the optimum protection could be found in a distance of twice the trees' height from the protection belt. Also, Allard [33] determined the optimum protection area to be at a distance from 1.5 to 5 times the shelter belt's height.

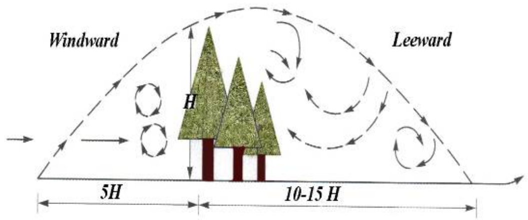


Figure 3-31: Basic flow characteristics of shelter belt, reproduced after WMO [135] and Littlefair et al [89]

The location of planting outside the building and its profile can possibly deflect the air away from the building (Figure 3-32), direct it to go through it or prevent wind from spilling around the building sides (Figure 3-33) [87]. In order to induce the air inside a building, dense hedges could be used as pressure regulator elements around it. It works in the same way as solid wing walls (Figure 3-34). In this case, the appearance and the cost of the hedges will be better than the solid wing walls, but of course with less efficiency [33]. In the case of planting individual trees or hedges around the building, their distance and position in relation to the openings should be carefully designed. Big trees with large canopies force the air stream to wash upwards as a result of the negative pressure area in its leeward side. This flow direction could result in the flow going through the building's window or being deflected away from it depending on the distance between the tree and the building. If the tree is just outside the window, it will produce a ceiling wash flow inside the building (Figure 3-35). If it is at a distance from it, it can deflect most of the air stream so to miss the building (Figure 3-35) [34]. In the case of hedges, these produce a negative pressure area on their leeward side that

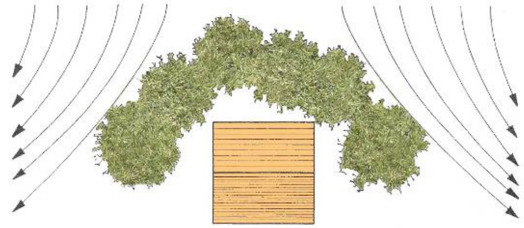


Figure 3-32: Planting location near the building deflecting the airflow away from it, reproduced after Allard [33]

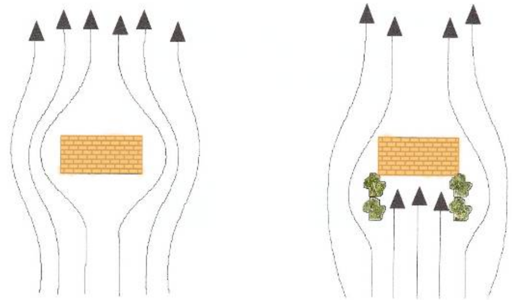


Figure 3-33: Planting location from the building preventing the airflow spilling around it edges, reproduced after Asimakopolous and Santamouris[87]

could reach 6.0 m [34]. This suction area forces a downwash flow that could be directed to penetrate building's lower levels (Figure 3-36). Although it was reported that the grassy areas give maximum ventilation conditions [89], the trees and hedges could be used efficiently to enhance ventilation conditions and airflow, as illustrated above. The use of a vegetation profile for enhancing ventilation conditions is not limited to the building layout level. It can be used efficiently at neighbourhood level or even city level [89].

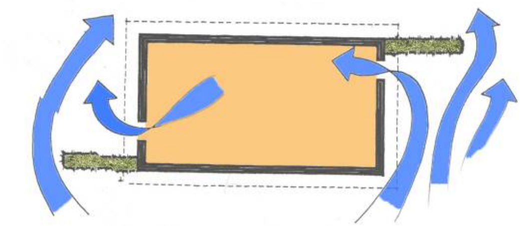


Figure 3-34: Using hedges as wing walls to induce the air into a building, reproduced after Watson and Labs [34]

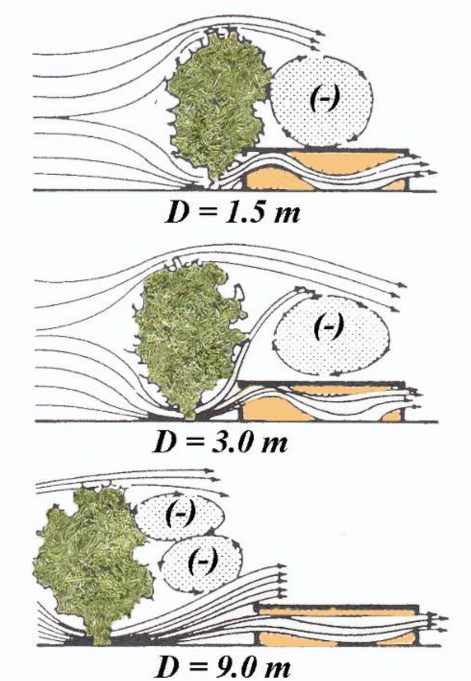


Figure 3-35: The effect of a tree on the airflow direction at different distances from the building, reproduced after Allard [33]

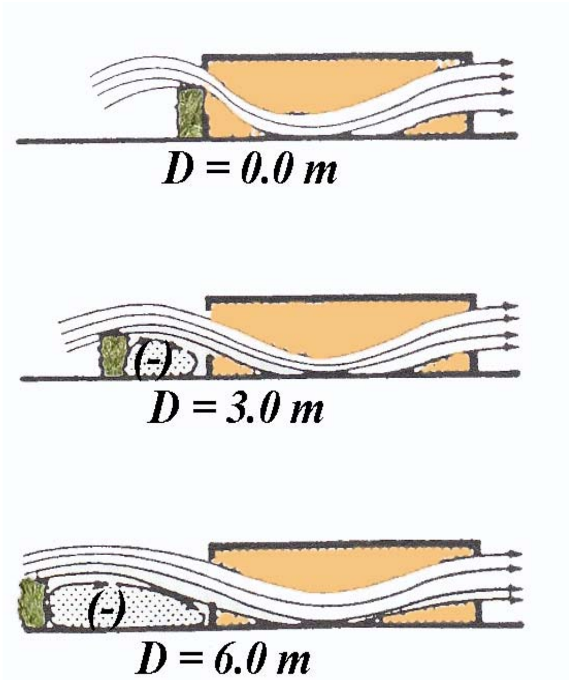


Figure 3-36: The effect of hedges on the airflow direction at different distances from the building, reproduced after Allard [33]

3.3.3.2.Fountains and ponds

The availability of fountains and ponds as water surface in buildings' sites has the ability to modify the microclimate and air properties so to be suitable in cooling by natural ventilation. Because of the high thermal mass of the water, it can cool down the air by either evaporation or conduction through its direct contact with the flowing air [87, 90]. The availability of water surfaces in outdoor or indoor spaces can provide a desired sense of coolness, especially, in medium and low humidity climates [128]. This sense of coolness is due to the lower temperature of the water surface and its low reflectivity [137]. The coolness effect of the water surfaces could be easily enhanced by increasing the water-air contact area (*evaporative surface of water*) through fountains and sprays with very fine droplets [89, 97, 128].

This effect of water surfaces in cooling the air by evaporation is the best fit in hot dry climates where low humidity exists [85]. This in turn provides the ability of using the cooled air for natural ventilation in hot daytime, when it is advised to be avoided. However, great attention should be given to locating the water surface for cooling the air in humid climates, as its cooling effect is hindered by the weather humidity. Also, in hot-dry climates, these water surfaces should be drained off during the cool season [36].

3.4. Micro-level design measures

In this level of design, the role and configuration of seven design measures in controlling natural ventilation performance will be clarified. These design measures include; building mass, building form, building orientation, building envelope, natural ventilation inducers, space height and internal planning.

3.4.1. Building mass

Building mass configurations (*volume, area, dimensions and aspect ratio*) also play an important role in controlling airflow and thus natural ventilation potentials. Different aerodynamic effects could be created by the same built volume [138] (quoted from [139]). It is possible to design the same volume by either a small number of large volumes or a large number of small volumes. Different arrangements of these volumes could introduce different airflow patterns.

One of the effective parameters in buildings' configurations that markedly affect airflow and natural ventilation is the area density (A_b *[Buildings area]*/A_s *[Site area]*). It was found that the airspeed is considerably decreased, when the area density increases [89, 140]. This reduction could reach 80% to 90% in high area density regions and the air then tends to flow upwards over the buildings' roofs [89].

In terms of building dimension, there is a rule of thumb which states that the cross-section of a building that faces the wind should be kept at functional minimum for allowing the use of cross-ventilation [33]. However, Heiselberg [141] added that a relatively narrow plan depth could be having a positive effect on both single-side ventilation and cross-ventilation. Although, it is known that the building height has a greater effect in airspeed than the building width, it was found that the greatest effect of building width appears at area density of 20% [89]. According to this, it was advised that better ventilation conditions could be provided when relatively wide and low buildings are built at a site with low to medium area density [89].

For the best ventilation performance, the building aspect ratio (Length/Width) should be kept low to avoid large reduction in pressure at the middle of the windward façade with a suction effect at edges [33]. The complete aspect ratio term (*Total area of building envelope / site area*) was used by Gimmond and Oke [142] (quoted form [139]) to describe the total exposed area to the air taking into account both the vertical and horizontal profile of a group of buildings or a city. No study has been found to introduce quantitative data about the airflow performance in or around different buildings' aspect ratios.

3.4.2. Building form and shape

The building form is one of the important measures that could affect the air movement in and around the building. It can also allow or reject the application of different natural ventilation strategies derived either by wind or thermal buoyancy forces. Although building forms can widely vary and are over complicated, three basic general forms are defined and extensively studied by scholars. They are; the atrium building form, the courtyard building form and the modern pavilion block building form.

The atrium and courtyard forms are historically related to each other. The origin of the atrium and courtyards goes back to the Greeks and Romans, when they traditionally organised the building spaces around uncovered space in order to allow access for daylight and air. This uncovered space was later covered to form the known atrium building, and it was also extended by Arabs to form the known courtyard [143]. Both atrium and courtyard forms were declared to raise the potential of using wind and stack driven natural ventilation within their buildings [143].

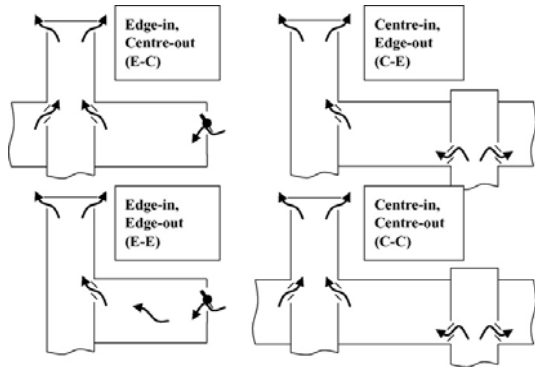


Figure 3-37: Schematic diagram of different forms of airflow in atrium buildings, after Lomas [144]

Although the atrium building form was reported to be the most suitable form for applying the stack ventilation technique [141], it was also found that it works with the wind driven ventilation [143]. In this building form, especially during summer and when there is no wind, the airflow is mainly driven by the stack forces and the atrium acts as a chimney to expel the warm air from its rooftop openings [143]. Throughout the year, when there is wind outside, the wind contributes in enhancing the airflow by creating a difference in the pressure between the outside façade and the inner façade of the atrium [143].

Lomas [144] identified four different conceptual schematic ways, in which the air flows within an atrium buildings. These ways, as seen in Figure 3-37, are:

- The air enters from the edge of the building and exits from an atrium in the centre of the building (*Edge-in/Centre-out [E-C]*);
- The air enters from courtyard in the centre of the building and exits from an atrium at

the edge of the building (*Centre-in/Edge-out [C-E]*);

- The air enters from the edge of the building and exits from an atrium at the opposite edge of the building (*Edge-in/Edge-out [E-E]*); and
- The air enters from courtyard in the centre of the building and exits from an adjacent atrium at the centre of the building (*Centre-in/Centre-out [C-C]*).

These conceptual designs indicate no limitation in the building depth that is designed in the atrium form [141].

Sharples and Bensalem [143] studied the performance of the atrium building form in relation to natural ventilation and airflow. They highlighted the fact that most of the atrium's roofs perform in the same way, especially when at 45^{o} oblique to the wind direction. They also identified two main problems associated with the use of atrium roofs as stack ventilation devices. They are:

- The weak positive pressure inside the atrium needs very large roof openings and surface area in order to make the most from it; and
- The negative pressure on the leeward side of the building counteracts the negative pressure in the roof weakening by such the suction effect of the roof.

In order to overcome these problems, they advised the use of roof shapes that could create a vortex at the roof's edges as well as make use of the venturi effect, and thus accelerate the airflow.

Another problem with using the atrium building form to ventilate tall buildings was highlighted by Etheridge and Ford [145]. They raised concerns about the huge pressure difference created between the bottom and the roof of the atrium in the tall buildings and also the difference in temperature due to thermal buoyancy. In such a case, the building seems to behave as one space with a very warm top. They asserted that dividing the tall building into small segments separated by an open space (Figure 3-38) can overcome this problem as the design proposal will achieve the ventilation requirements for each individual segment. This solution could be hindered by the change of the aerodynamic effect around each segment outlet as the wind direction changes. Daniels et al [146] adopted a novel approach to overcome this problem by considering the axi-symmetric venture. An example of that approach is the Commerzbank designed by Norman Foster in Frankfurt, Germany (Figure 3-39) [145].

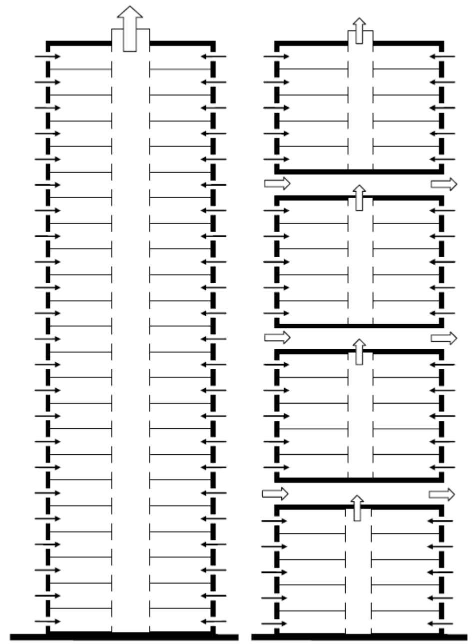


Figure 3-38: Segmentation of tall atrium buildings, after Etheridge and Ford [145]

The courtyard building form was extensively used by traditional Arabs as a microclimatic modifier. Its development was a result of a complicated historical process that accumulates unconscious adaptation to climate [147]. In the courtyard building, all the building spaces are distributed around an internal open space with all the spaces' large openings directed towards it [147]. The other ventilation devices, such as wind catchers "*Arabic: Malkaf*", can also be used in courtyard buildings (Figure 3-40). The courtyards were designed in a confined form, by which the courtyard gained the capability to create its own thermal environment [89]. It acts as a transitional space that has the ability of enhancing the building's microclimate and its internal airflow[148]. The significant difference of the temperature in the courtyard from that of outside [89], the limited fluctuation of indoor conditions [147], and the altered ventilation potential [108], are examples of these abilities. These impacts of the inner courtyard on microclimatic conditions make it a pragmatic air conditioning solution suitable for hot climates, especially when designed in a narrow depth plan [149]. When taking into account the combination of the courtyard's environmental effects and the building footprint, Ratti et al [150] confirmed that the courtyard form makes the best use of land in hot and cool climates. They based their assumption on the energy efficient context created by the combination of some attributes of courtyards such as, the large surface area with thermal mass, the shallow plan form, the provision of day lighting, the narrow shaded spaces, the enhanced thermal environment and the clean private open space.

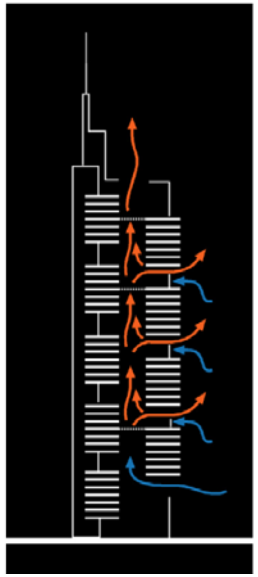


Figure 3-39: Sectional diagram of Commerzbank by Norman Foster illustrating the axi-symmetric venture approach, after Etheridge and Ford [145]

The thermal performance and airflow within the courtyard building form stimulated many researchers to look into it. These characteristics were found to greatly depend on the aspect ratio of the courtyard (*Hieght/width [H/W]*) [89, 108, 151] and its morphological configurations [152]. Littlefair [89] studied the airflow patterns and their thermal effect in different courtyards' aspect ratios. He asserted that the main parameter that controls the pattern of the airflow in the courtyard is (*H/W*) ratio as with different ratios the airflow access and circulation within the courtyard varies. For low aspect ratio (*wide courtyard H/W < 0.3*), a large a mount of outside air effectively enters the courtyard, skimming over it and does not circulate (Figure 3-41 a). In narrower cases (*0.3 < H/W <1*), less air could access the

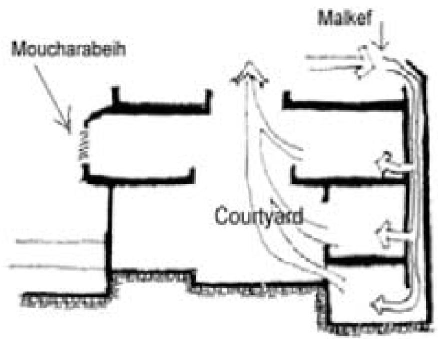
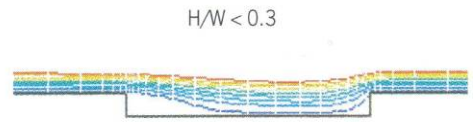


Figure 3-40: Sectional diagram of a courtyard building, after Mansouri et al [147]

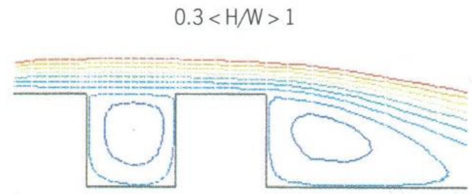
courtyard with vortex circulates into its enclosure (Figure 3-41 b). For high aspect ratios (*H/W>1*), the air access and circulation are extremely hindered and it does not reach the courtyard floor (Figure 3-41 c). He also found that the best thermal performance of the courtyard was observed when the aspect ratio of (0.3 < H/W <1) was provided. This was justified by the effect of the vortex circulation within the courtyard enclosure that helped in dissipating more heat from the courtyard.

Bittencourt and Peixoto [151] studied the effect of different combination between the aspect ratio of (*H/W = 0.5, 0.34, 0.17*), wind direction of (*90,45*) and the use of floor lifting (*pilotis*) on natural ventilation performance in an open low-rise courtyard building with. Results of this study showed that airspeed values have their maximum increase (*80%*) with wind direction of (*45^o*) and (*H/W=0.17*). An additional increase of (*25%*) in the speed was experienced when using floor lifting option. In terms of airflow pattern, they advised to give more attention to (*H/W*) ratio in designing courtyards for ventilation purposes, as they can produce undesirable effects such as, stagnation areas, air currents and turbulent zones. They, also, highlighted that the use of floor lifting (*pilotis*) may introduce solutions for these problems. The same floor lifting technique was advised by Tantasavasdi et al [153].

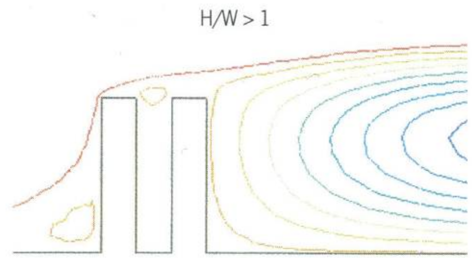
Taylor [108] highlighted a study that aimed to investigate the efficiency of cross ventilation in a standard courtyard (*H/W= 2*) of Jeddah housing in Saudi Arabia and another courtyard model with (*H/W = 0.25*). The study showed great improvement in cross-ventilation rate when (*H/W= 0.25*) was provided. Courtyards were, also, reported to have a good role in enhancing



a) Low aspect ratio courtyard



b) Medium aspect ratio courtyard



c) High aspect ratio courtyard

Figure 3-41: Streamlines within different aspect ratio courtyards, after Littlefair [89] the thermal buoyancy driven ventilation in different seasons and different times of the day [154]. At night, the cool air falls down to the courtyard forming an airflow within surrounding spaces and a heat sink within its enclosure that is stored to the next day. At daytime, the air starts to heat up by sun radiation and create upward airflow that reaches its maximum effect at afternoon time and helps to extract hot air from inside the spaces (Figure 3-42).

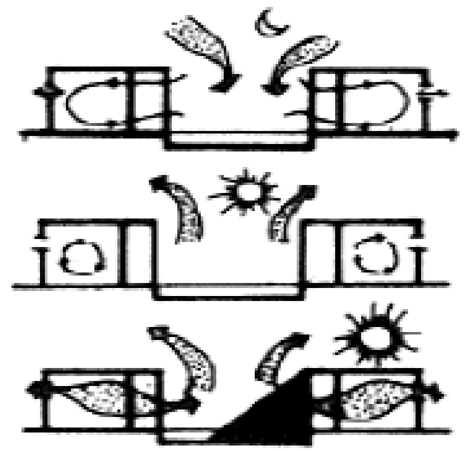


Figure 3-42: Thermal buoyancy driven airflow within the courtyard at different day times, night (top), midday (centre) and afternoon (bottom), after Edward et al [154]

The morphological configuration of the courtyards can be modified by adding cavities to their side mass. Based on the assumption that creating cavities in the courtyard walls could enhance the natural ventilation performance in the courtyard, Ok et al [152] studied the effect of 17 different cavities profile in courtyard mass (Figure 3-43) on the airflow within it using wind tunnels. The results were compared to a standard two stories height courtyard building with dimensions of (*14x14x6 m*) that provides net dimensions of the courtyard of (*6x6x6 m*). The results proved the truth of their assumption and showed a significant effect of the openings profile on the airspeed within the courtyard. The results also showed that the close courtyard (*base case*) has the lowest airflow velocity. They also found that providing two opposite cavities in the courtyard mass at upwind and downwind sides enhances the velocity in direct proportion to the opening size. A significant increase in the airspeed was found in this case, when the upwind cavity is larger than that of downwind. When the cavities were provided in lateral walls facing the wind, a higher velocity was achieved than the case when another cavity was added to the downwind side. The effectiveness of creating connections between the courtyard and outside context through the walls' cavities on improving natural ventilation was further advised by Tablada et al [75]. Brown and Dekay [85] introduced a guiding matrix for sizing the courtyard for ventilation purposes. This matrix provides the average airspeed (*as a percentage of free wind speed*) inside the courtyard and with different aspect ratios and different prevailing wind angle. See Figure 3-44.

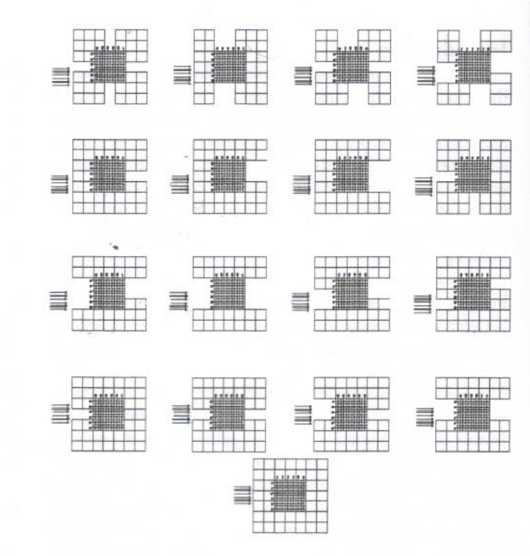
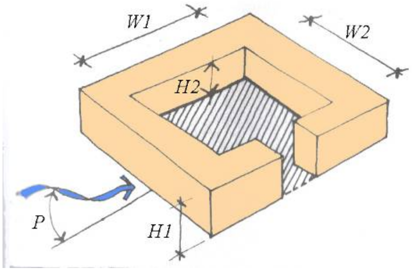


Figure 3-43: Different morphological cases of courtyard openings studied by Ok et al, after Ok et al [152]

General conclusions can be drawn from this figure, such as:

- Decreasing the aspect ratio (*H/W*) in along-wind direction has greater effect than decreasing it in cross-wind direction;
- Changing the wind direction seems to have only a slight effect on the average wind speed for the same along-wind aspect ratio;
- Changing the wind direction seems to have only a slight effect on the average wind speed for the same cross-wind aspect ratio;
- The maximum average wind speed percent, in most of the cases, was obtained when the wind incident angle was 45^{o}; and
- Further investigations are required to investigate other wind directions, as it is expected that the cavity in the courtyard wall will start to play a useful role when the wind is directed to it

As for the modern pavilion block building form, it reflects the contemporary form that is being recently used in tower buildings and has become popular following the modern movement [150]. This form could be high rise building (more than 10 stories), medium rise building (3-6 stories) or low rise building (1-2 stories) [141].



cross-wind courtyard aspect ratio (H_2/W_2)	Along-wind courtyard aspect ratio (H_1/W_1): $H_1/W_1 = 1.00$			$H_1/W_1 = 0.50$			$H_1/W_1 = 0.25$			$H_1/W_1 = 0.17$		
Incident wind angle (P)	0^o	22.5^o	45^o	0^o	22.5^o	45^o	0^o	22.5^o	45^o	0^o	22.5^o	45^o
$H_2/W_2 = 1.00$	20%	20%	20%	26%	27%	28%	37%	40%	43%	50%	61%	65%
$H_2/W_2 = 0.50$	24%	24%	24%	31%	32%	33%	46%	47%	51%	60%	72%	78%
$H_2/W_2 = 0.25$	32%	32%	32%	43%	43%	44%	61%	63%	68%	80%	97%	100%

Figure 3-44: Sizing courtyards for ventilation, reproduced after Brown and Dekay [85]

Limited studies were found that dealt with such building form in terms of natural ventilation. This is because of the huge varieties in design with no determined concept, unlike the atrium and courtyard forms. Most of the found studies are concerned with high rise buildings and their ventilation problems. Only a few of them gave guidelines on how to shape such building form for natural ventilation enhancement. The main objective of these guidelines is to design the building block in a more porous form was to allow access for ventilation. Hirano et al [155] studied the effect of making a building more porous on natural ventilation performance. They designed two models, each consist of six flats. The first model was designed as a compact block with 0% voids in its mass and the second was designed with 50% voids in its mass (Figure 3-45). They found that the natural ventilation performance in the porous model is far better than the compact one, as the air change rate in it was four times larger and the airspeed in front of its windows was 30% faster.

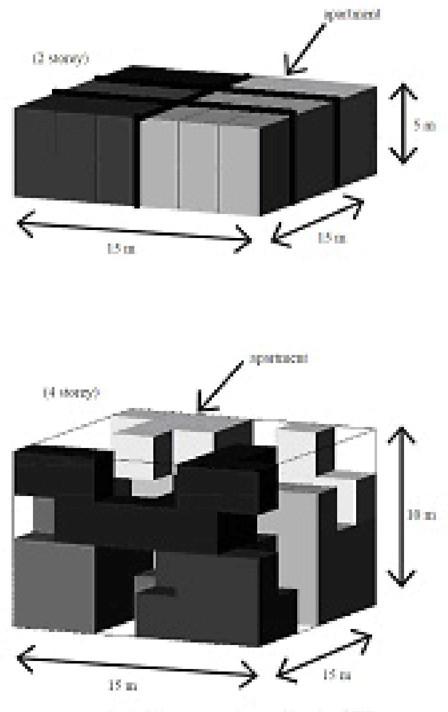


Figure 3-45: Designing the same building model in different porous mass, 0% voids (top) and 50% voids (bottom), after Hirano et al [155]

Ng [100], in dense urban areas, also advised not to use pavilion blocks with large solid podiums at the bottoms and so create air paths through the podiums, when natural ventilation is concerned (Figure 3-46). In addition, he advised to shape up and scale the podium in a way that facilitates airflow penetration to the pedestrian level around the block (Figure 3-47).

No studies were found to set the preference of and compare each of these three building forms in relation to natural ventilation. Only two studies were found, which in fact only compared the performance of natural ventilation in atrium and courtyard forms. Sharples and Bensalem

[143] investigated the performance of natural ventilation in courtyards and atrium buildings, when isolated or positioned within an urban development. The results indicated better performance for the open courtyard building, especially when it was perpendicular to the wind direction. Khan et al [148] made the same comparison, but in terms of energy efficiency against different climatic conditions. They asserted that open courtyards are more energy efficient in smaller building heights, while, atrium buildings performed better at greater building heights. On the other hand, Safarzadeh and Bahadori [156] introduced their opinion as against the courtyard form. They claimed that in the light of increasing land cost, courtyard building became very expensive to build. Moreover, a larger reduction in cooling and heating loads could be obtained from other forms, if their envelope is well treated.

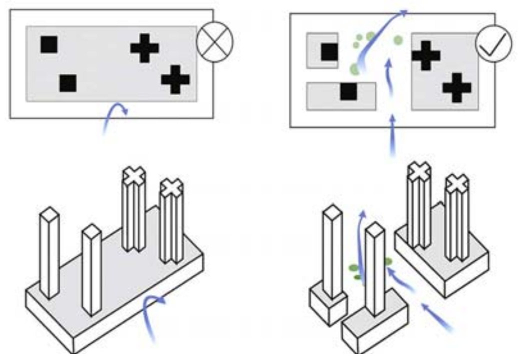


Figure 3-46: Creating air paths within podiums to allow air access, after Ng [100]

In terms of shape, where ventilation is required, any of the above building forms could be shaped and oriented to maximize its exposure to the summer breezes and thus optimise cooling by ventilation [34, 128, 157]. Building shapes could be designed in unlimited varieties. The studied performance for simple ordinary shapes and scholars' advices in shaping the buildings for maximum ventilation efficiency are detailed below.

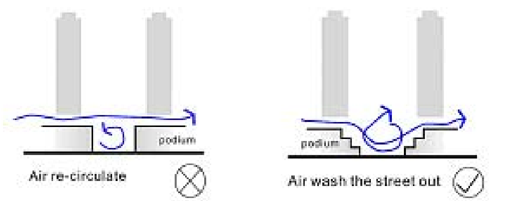


Figure 3-47: Shaping up and scaling the podiums to allow air access to pedestrians level, after Ng [100]

In general, the natural ventilation potential in ordinary simple rectangular shapes could be significantly enhanced by centring its long façade to face the direction of the summer wind or preferably direct it obliquely to the wind by 20-30o. When the predominant summer wind is known, the building shape should be designed to capture and funnel the airflow through its interior. In such a case, L shaped building could act as an effective air dam. When there is no known wind direction, the building should be shaped to allow ventilation through the most of its axis. Therefore, the square floor plan could be the most suitable shape providing that there are openings on both windward and leeward sides of it [34].

Evans [158] (quoted from [85]) introduced a series of wind tunnel experiments that aimed to investigate the wind flow pattern around different basic building shapes with different orientations. He tested the rectangular shape, U-shape, L-shape and T-shape (Figure 3-48). It was advised to use these basic patterns to set alternative basic designs to meet their ventilation requirements.

The irregular shapes of buildings can provide large surface area and better potential for natural ventilation [38]. For complex irregular building shapes, the difference in pressure that builds up on its facades could enhance the airflow within it. The proposal then is to design the shape of the building mass in a way that helps in enhancing the pressure difference around the building [34]. The large exposed surface area offered by irregular building shapes may not be required in some climates where to minimize the exposed surface area is the preference for some seasons or times of the day [38]. Givoni [38] introduced a possible way in shaping the building in order to fulfil both proposals; large surface area for ventilation and compact form for sun protection. He suggested shaping the building in an irregular way by adding some indented porches within its mass that are equipped with operable large shutters.

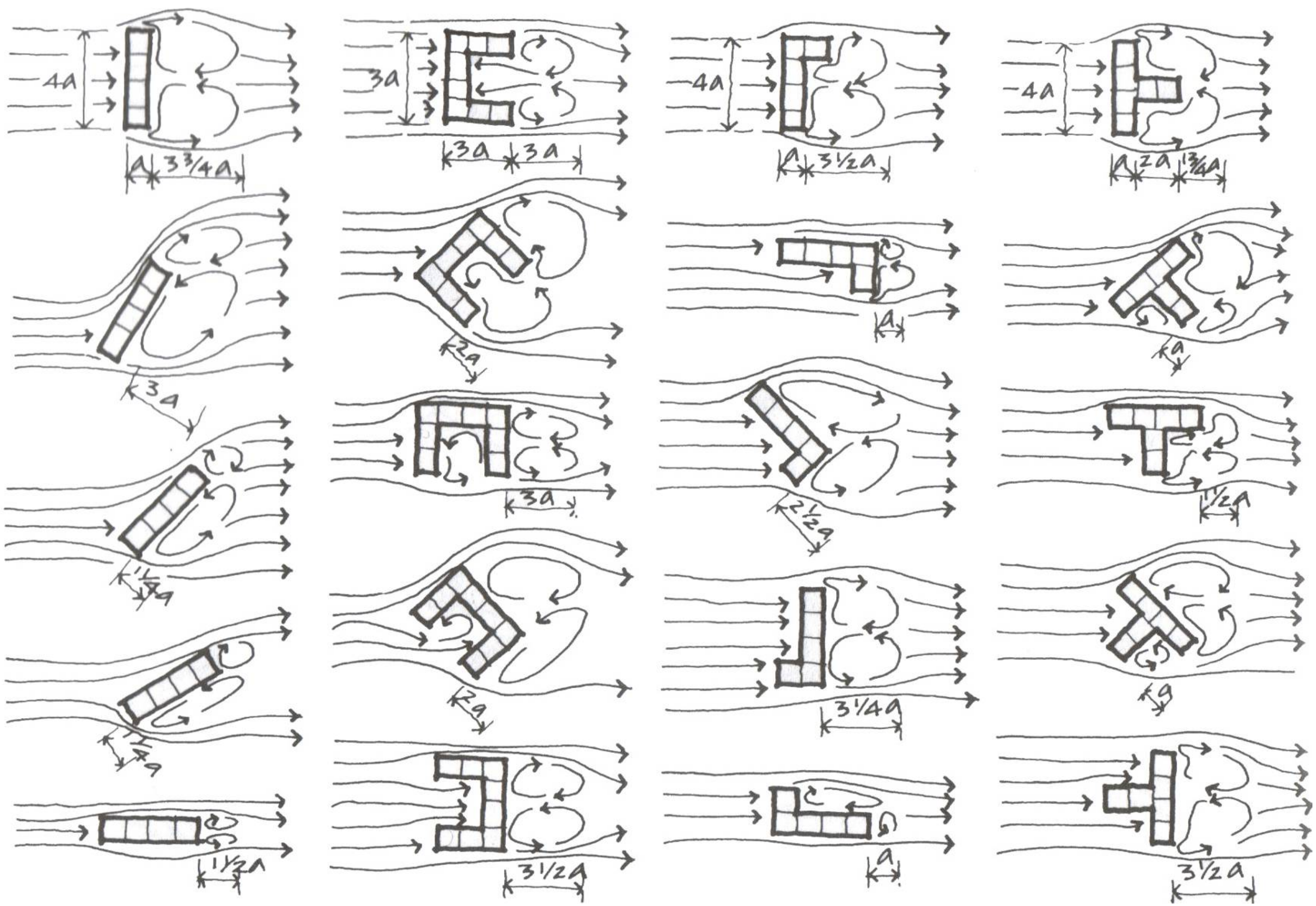


Figure 3-48: Air flow patterns around different basic building shapes with different orientation, after Brown and Dekay [85]

These shutters could be closed offering compact building shape or opened offering widespread irregular shape (Figure 3-49) [19, 38]. Allard advised on using corrugated building shape to make it irregular. He highlighted that the proper use of the corrugated building shape can impose a significant enhancement of natural ventilation, especially when the potential of properly orienting and laying out the building to enhance ventilation is restricted by the site conditions. This corrugated building shape could be designed using wall projections on the envelope or the building's spaces themselves (Figure 3-50) [33].

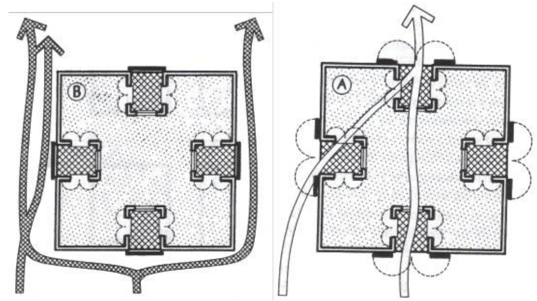


Figure 3-49: Givoni proposal of using controllable shutters to change the building shape and its exposed surface area, when required, after Givoni [19, 38]

Some guidelines about designing building shape to reduce sensitivity to the wind were introduced by Littlefair et al [89]. They can be summarized as follows:

- Avoid large flank walls facing the dominant wind; orientate long axis parallel to the dominant wind;
- Avoid flat roofed buildings and large cubical forms, choose stepped pyramid-shaped forms, use pitched rather than flat roof;
- Avoid buildings pierced at ground level;
- Use a podium to limit downdraughts at ground level; and
- Roughen building surface faces to provide resistance to the wind.

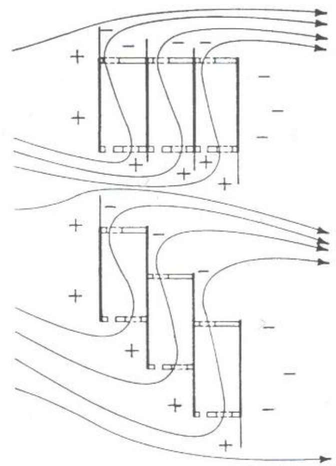


Figure 3-50: Building corrugated shape designed by wall projections or spaces arrangement, after Allard [33]

3.4.3. Building orientation

The building orientation with respect to wind direction significantly affects natural ventilation performance [65]. Since the building orientation is mostly associated with the street orientation, the optimum ventilation potential could be obtained in an oblique orientation as discussed earlier. When cross ventilation is provided, Givoni [38] reported that an oblique wind at angle 30-120^o to the external wall can provide the most effective cross ventilation. The optimum angle, which provides the best air circulation inside spaces, could be obtained by orienting the inlet 45^o to the prevailing wind. As, in this case, turbulence occurs for most of the air volume, so circulates around the room to reach the outlet and flows over walls and corners [65]. The angle of 45^o was, also, advised by Robinette [159] (quoted from [89]) in order to increase ventilation potential. The oblique angle is also preferred in the case of single side ventilation. Givoni [19, 38] justified that by the gradient in pressure that is created over the wall by the oblique wind. Therefore, when the wall has two windows, the pressure at the upwind window is higher than the downwind one. This in turn enhances the airflow to enter the room from the upwind window and leave it from the downwind one. Such a pressure gradient is not available when the wind is normal to the building wall and both windows have the same pressure.

3.4.4. Building envelope

The building envelope design measure includes two sub design measures. They are; the building opening design including (*size, position, number and type*) and the building roof shape.

3.4.4.1.Opening design (Size, position, number and type)

The effectiveness of natural ventilation strongly depends on the controllability and the properties of ventilation openings such as, size, position, number and type [160, 161]. Window and door openings are covered by the term "*building openings*" here. This is because they are considered as the primary ventilation devices in most normal size buildings due to their low-tech and manual operation [148].

The opening size controls both the ventilation rate and air velocity within interiors. The general rule to maximize the natural ventilation efficiency is to have openings as large as possible [34, 128]. Minimum size of building openings for ventilation purposes is normally defined by building regulations, while realistically there is no limit for the maximum size except the consideration for security, privacy, heat gains and personal comfort [128]. The effectiveness of window size on ventilation was found to be the highest when the space is cross-ventilated, while little effect was observed when the space is single-side ventilated [65, 162]. A slight increase in the internal air velocity associated with the increase of the window size was identified in a single-side ventilated room, only when the window was oblique to the wind direction. This was because of the gradient in pressure over the window area [65].

The openings size in most cases is expressed as an area percentage of the space area or, when cross-ventilation applied, as outlet area / inlet area ratio (A_o/A_i). In a study by Tantasavasdi et. al. [153] that aimed to produce guidelines for natural ventilation design within Thailand through quantifying the effect of several design parameters using CFD, it was advised that the air inlet area should be around 20% of the floor area in order to achieve acceptable comfort level by ventilation. Similar results were reported in another study by Tantasavasdi et. al.

[127], when they studied the effect of different openings areas as a percentage of serviced floor area (*5% to 30%)* in different ventilation scenarios (*cross-ventilation, tow-sides ventilation and single-side ventilation*) on average internal airspeed. They found that, in general, increasing the opening area improves the average indoor air velocity and percentage of time spent in comfortable conditions. The optimum opening area was found to be 20 % of the functional floor area in rectangular rooms. On the other hand, Aynsley [128] confirmed that the average airspeed through building openings could be 18% higher than wind speed, if the total openings' area ranges between 15% - 20% of façade area.

In terms of the outlet area / inlet area ratio (A_o/A_i), when cross-ventilation is applied, all studies agreed that making a difference between the inlet and outlet area considerably maximizes the air velocity throughout interiors. This happens as result of changing the flow cross section area between the outlet and inlet, and thus activates the "*Venturi effect*", which in turn secures maximum air velocity within the building [161, 163]. However, which should be larger than the other inlet or outlet was a debatable point between the researchers. On the one hand, most of these studies [19, 33, 34, 65, 128, 164] confirmed that maximum airspeed inside cross-ventilated spaces could be obtained when the air outlet is much larger than the air inlet. Givoni [19] reported that the maximum internal airspeed was obtained when ($A_o/A_i = 3$) with oblique wind direction 45^o. Also, the reasonable average airspeed with slightly high maximum internal speed was achieved, when wind was oblique and with ($A_o/A_i = 1.5$).

On the other hand, only Tantasavasdi et al [153] claimed that a larger inlet than outlet is preferable and he advised using a ratio of ($A_o/A_i = 0.5$). They argued that reversing the ratio ($A_o/A_i = 2$) significantly reduced that ventilation rate and created stagnation zones in the ventilated space (Figure 3-51). Givoni [19, 38], stated that the choice of which one should be larger is dependable on the usage of the ventilated space. He explained that the internal average air velocity is dependant on the size of the smaller opening, whether it is the outlet or the inlet with no difference. However, the maximum internal air velocity (*most likely near the inlet*) is dependant on the relative size of the inlet and outlet as it increases with the increase of (A_o/A_i) ratio. So the room that has a larger outlet than inlet can experience higher maximum air velocity near the inlet than the room with opposite conditions. However this velocity is only limited to the area near the inlet. This effect was judged to be preferable in bedrooms with beds near the window. In living rooms, where any spot within the level of 0.5 to 1.00 m above floor level may be occupied, large inlets are most suitable even with a small outlet.

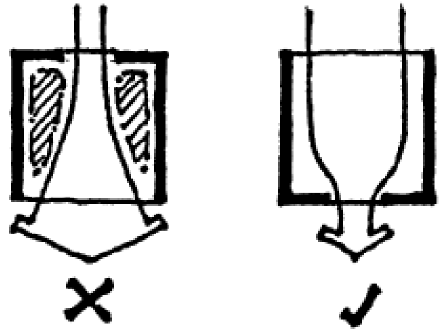


Figure 3-51: Stagnation zones created by larger outlets than inlets, after Tantasavasdi et al [153]

The window opening area could be controlled automatically by using sensors for measuring PMV comfort level and so operating the windows according to the expected occupants' needs [165]. Also, it can be automatically controlled through cells that monitor the surrounding temperature and open windows, when there is the possibility of having a positive effect on thermal comfort and achieving the required ventilation rate [166].

Opening position, either horizontally or vertically, has a great effect on not only the airspeed, but also airflow pattern in internal spaces [34]. In a study conducted in Japan [167] to evaluate the ventilation performance due to the variety in opening positions, it was found that the relative airspeed around occupants to the airspeed which blows from the inlets is greatly dependable on the opening positions. The general rule in locating openings on a building envelope, for best air distribution and velocity, is to force the air to change its direction within the room [34].

In order to locate openings horizontally for optimum ventilation, the air inlets and outlets should be located in the portion of façade that secures maximum pressure differential between them [34]. See Figure 3-52. The relative horizontal position of inlets and outlets can determine the quality of air distribution in the space and its ventilation effectiveness. Figure 3-53 shows some possible relative positions of inlets and outlets and their effect on the airflow pattern. When locating both opposite windows in the centre of the windward and leeward façades, the highest velocity air stream will pass through a narrow passage in the middle of the space (Figure 3-53 a). Although, this provides high speed airflow, it provides poor ventilation, in general, to the space [34]. When structure cooling by ventilation is proposed, The opening position should be close to the thermal exchange surfaces (*walls, ceilings or floors*) (Figure 3-53 b, d and e) [33]. When openings are installed in lateral walls near to each other, the low airspeed is provided and short circuit occurs [167] (Figure 3-53 c,f). Therefore, for best airflow distribution and higher average velocity, the position of openings on lateral walls should be as far apart as possible to avoid short circuits problem [127] (Figure 3-53 e).

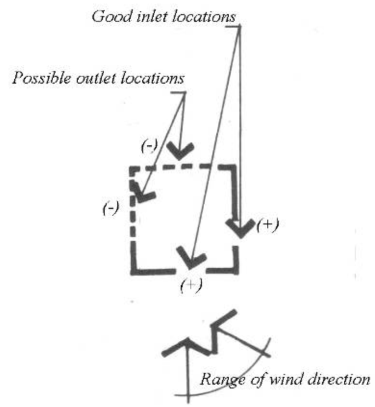


Figure 3-52: Possible inlets and outlets position to achieve maximum pressure differential between them, after Watson and Labs [34]

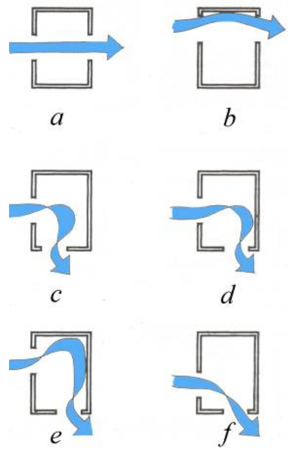


Figure 3-53: Possible relative horizontal inlets and outlets position and their effect on airflow pattern, after Watson and Labs [34]

The vertical location of openings serves both wind-driven ventilation and stack-driven ventilation. The main role of the vertical position of the openings, in wind-driven ventilation with cross-ventilation applied, is to direct the air current to the occupants' zone [44]. The vertical location and design of the inlet opening is more important than those of the outlet [36]. The height of the outlet has almost neglected effect in directing the airflow. If the inlet opening, for example, is at high level, the main air stream flows at the ceiling height and is not affected by the low position of the outlet (Figure 3-54 a). This condition provides very poor occupants' cooling by ventilation. When such effect is required, inlets should be placed at the occupants' height [33] (Figure 3-54 b). Low inlets in general, whatever the outlet height is, provide good airflow current at the occupants' level [44] (Figure 3-54 c). Placing an occupied zone just under the inlet sill could provide poor ventilation for those occupants, unless the drop in air velocity under the opening sill is avoided. This drop may be altered by changing the sill height [36]. In addition, if the airflow is required at occupants' level, placing the air inlet above sedentary occupants will provide poor ventilation in most of the occupation zone [19, 36, 38, 65]. For best effective ventilation, It was advised by Aynsley [128] to use a horizontal opening near floor level rather than vertical openings.

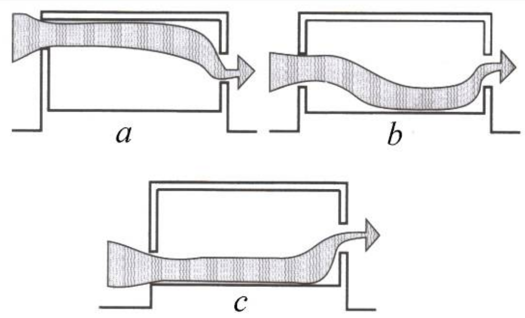


Figure 3-54: Possible relative vertical inlets and outlets position and their effect on airflow pattern, after Krishan et al [36]

When taking into consideration the stack effect, the outlets and inlets have to be located at different heights [168] and as far apart as possible from each other [141]. Having said that, in both wind-driven and stack-driven, the outlet should always be higher than the inlets in order to avoid conflict between both forces [33]. In the single-side ventilated space, It is also advised to design the window in a way that offers two openings in different heights (*the higher will act as outlet*) in order to induce more air movement within the space [128].

Number of openings in a ventilated space, providing at least one inlet and one outlet in different walls is the default option for good ventilation [127]. However, when this is not possible due to only one external wall being provided in the space, two openings as far apart as possible should be provided in the same wall and so direct it obliquely to the wind direction [33, 168]. The pressure gradient over the wall will force the upwind one to function as an inlet and the downwind one to function as an outlet.

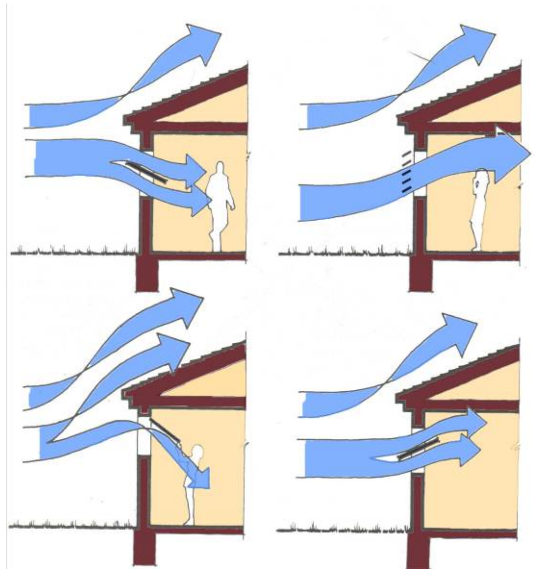
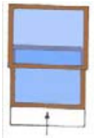
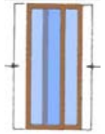
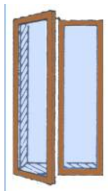
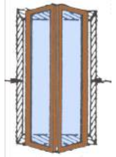


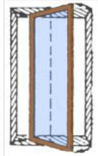
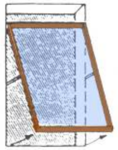
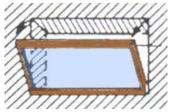
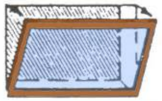
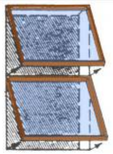
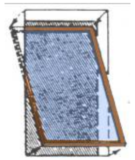
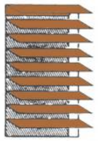
Figure 3-55: The role of different opening types in directing airflow and providing good or poor ventilation, reproduced after Watson and Labs [34]

Opening type has also a great role in directing the airflow and controlling its speed. The poor selection of the window type could result in very poor ventilation conditions within the ventilated space (Figure 3-55) [34]. Allard [33] classified the wall window types as one or a combination of three main types; simple opening, vertical-vane opening and horizontal-vane opening. Simple openings are any window type that opens by sliding in a single plane such as; single-hung, double-hung and horizontal sliding windows. Vertical-vane openings are any window type that opens by pivoting on a vertical axis such as; side-hinged casement (single-sash or double-sash), folding casement and vertical pivot windows. Horizontal-vane openings are any window type that opens by pivoting on a horizontal axis such as; projected sash, awning, basement, hopper, horizontal pivot and jalousie windows. The side-hinged casement double sash type of windows is commonly used in the Egyptian context.

Table 3-1 shows the different types of openings and their properties in relation to airflow and natural ventilation. This table was created by the author to summarize the data found in the available literature dealt with this subject.

Table 3-1: Different opening types and their properties in terms of airflow and ventilation, by the author using data from [19, 33, 34, 38, 65, 127, 128, 160, 161, 169]

Opening type	Window design		General effect on airflow	Specific effect on airflow	Effective area*	Achievable ventilation rate	Adjustability of opening size
Simple openings	Single-hung		This kind does not affect the airflow pattern or speed as the air stream through them stays horizontal and in its same initial direction. Slight effect could be observed near the window as the airflow squeezes through the opening. This is because there is no sashes' projection affects the airflow.	- No ability to steer the incoming flow; and - Can control the airflow rate according to its operated area	50% total area maximum	O[1]	P[1]
	Double-hung			- No ability to steer the incoming flow; and - Flexibility in selecting the height of the airflow;	50% total area maximum	O	P
	Horizontal sliding			- Can direct the airflow to a particular area of the interior; and - It allows less control over the airflow than the double hung one, as the variation in the airflow pattern direction is much greater in the horizontal plane than the vertical plane.	50% total area maximum	O	P
Vertical-vane openings	Side-hinged casement		This kind has a variety of impacts on both the airflow pattern and speed, especially across the horizontal airflow pattern. It is possible to control the airflow rate through them by adjusting their operated area. They are 60% more efficient as air inlets in buildings than other opening types.	- It is the most commonly used type of them. - Its performance is greatly affected by the type of the unit (*single hinged or double hinged casement, inswinging or outswinging*), the way of its opening and the operational positions of the sashes. - When casement window opens out-swinging, the sashes can act as a wing wall help to induce to or exhaust the air form the room according to which sash is opened in relation to the wind; - Less effective in controlling the airflow pattern and direction; and - High average speed could be obtained at setting level, when it is used	100% total area if needed	P	P
	Folding casement			NDA	100% total area if needed	NDA[2]	NDA

	Vertical pivot			- High average speed could be obtained at setting level, when using this type of windows, but less than side-hinged casement.	100% total area if needed	NDA	NDA
Horizontal-vane openings	Projected sash		This kind of openings has its greatest effect on directing the airflow in the vertical direction either downward or upward.	- It directs the airflow upwards.	Limited to the max. tilt angle	O	P
	Basement			-It directs the airflow upwards or downwards according to it installation direction; and - Should be opened at angle of 45^o upwards or downwards, for maximum ventilation at standing level or setting level respectively.	Limited to the max. tilt angle	NDA	NDA
	Hopper			-It directs the airflow upwards or downwards according to it installation direction.	Limited to the max. tilt angle	N[1]	N
	Awning			-It directs the airflow upwards or downwards according to it installation direction	Limited to the max. tilt angle	NDA	NDA
	Horizontal pivot			-It directs the airflow upwards or downwards according to its opening direction. - Has a flexibility to direct the airflow to any desire level. - Low average speed could be obtained at setting level, when compared with the side-hinged and vertical pivot windows.	Up to 100% total area if opened horizontal	P	P
	Jalousie			- can direct the airflow upwards and downwards according to the position of their sashes - Can be used in conjunction with sliding or double-hung windows to control the airflow path.	Depends on the louvers density	NDA	NDA

* The effective opening area is the area where the air can freely flow and enter the space [127] / 1 : (P) means good, (O) means medium, and (N) means poor. / 2 : NDA (No Data Available in the available literature.

3.4.4.2.Roof shape

The building roof shape could be flat, single-slope, double-slope (*Pitched*), dome or vault. In terms of external airflow, The shape of a building roof has a great effect on the size of the downwind eddy as well as the wind pressure distribution over the roof structure itself [33] (Figure 3-56). However, it was also reported to have a significant role in inducing internal airflow [143].

According to the parametrical study of air pressure distribution over three kinds of roofs (*flat roof, single-slope roof and double-slope roof*) conducted by Grosso et al [170] (quoted from [33]), it seems that the distribution of pressure over the surfaces of different roof shapes, and consequently their potential use in ventilation, is greatly dependant on the wind orientation. The resultant pressure distribution on the roof fabric from this study and the associated ventilation implications can be summarized as in Table 3-2 and Figure 3-58. It was also noted that the single-slope (*mono-pitch roof*) could give the opportunity for openings at the negative pressure area of it (*Clerestory*) (Figure 3-57), by which the hot air accumulated under the ceiling due to thermal buoyancy could be expelled [149]. This clerestory was found to be an effective mean for night ventilation rather day time ventilation, in non-domestic building due to the lesser control the occupants have in such opening [171] (quoted from [160]).

The effectiveness of the dome and vaulted roof in preventing the formation of hot air pockets under the ceiling and expelling it outwards was proved by Asfour and Gadi [172],

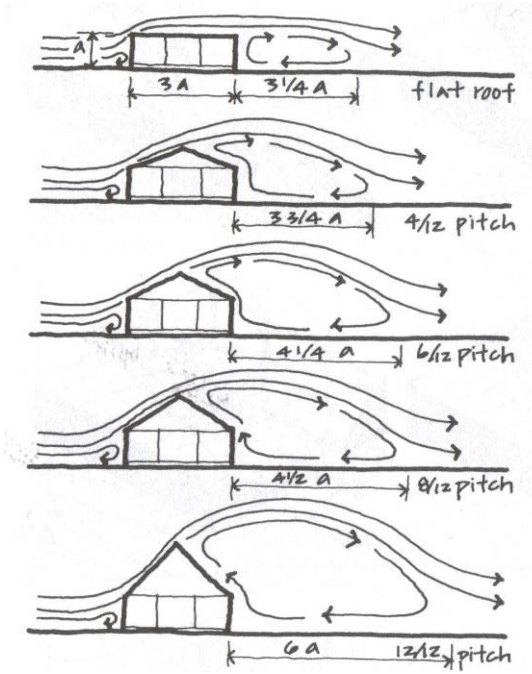


Figure 3-56: The effect of different roof shapes on downwind eddy size, after Brown and Dekay [85]

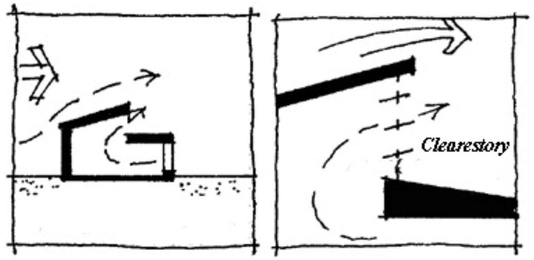


Figure 3-57: Clerestory in the single-slope roof to vent the hot air, after Prelgauskas [149]

Table 3-2: Wind pressure over different parts of different roof shapes and configuration along with their ventilation implications , by the author using the data from [170] quoted from [33]

Wind direction	Pressure type	Areas of the different roof shapes under this pressure type	Ventilation implications *
Regardless of wind direction	(-)	- All surface of flat roofs; - All surface of single slope roofs with pitch up to 15°; - All surface of single slope roof facing downwind; - Both slopes of double slope roof with pitch up to 21°; and - Leeward slope of a double slope roof with any pitch angle.	O
	(+)		I
Perpendicular to eaves line	(-)	- The area near the ridges of windward side of the double slope roofs, when the pitch exceeds 41°	O
	(+)	- Middle of slope of single slope roofs with pitch just above 15°; - The area near the ridge of single slope roofs with pitch of 25°; - All surface of single slope roofs with pitch about 30°; - Middle of slope of windward side of the double slope roof with pitch of just above 21°; - The area near the eaves of windward side of the double slope roof with pitch 33°; and - The area near the ridges of windward side of the double slope roof with pitch 33° - 41°.	I
30° oblique to the eaves line	(-)	- The area near the ridges of windward side of the double slope roof with pitch above 50°	O
	(+)	- Middle of slope of windward side of the double slope roof with pitch of just above 22°; - The area near the eaves of windward side of the double slope roof with pitch above 30°; and - The area near the ridges of windward side of the double slope roof with pitch 35° - 50°.	I
60° oblique to the eaves line	(-)	- The area near the ridges of windward side of the double slope roof with pitch above 50°.	O
	(+)	- The middle of slope and the area near the eaves of windward side of the double slope roof with pitch above 30°; and	I

*O: Openings in these parts can function as air outlets
I: Openings in these parts can function as air inlets

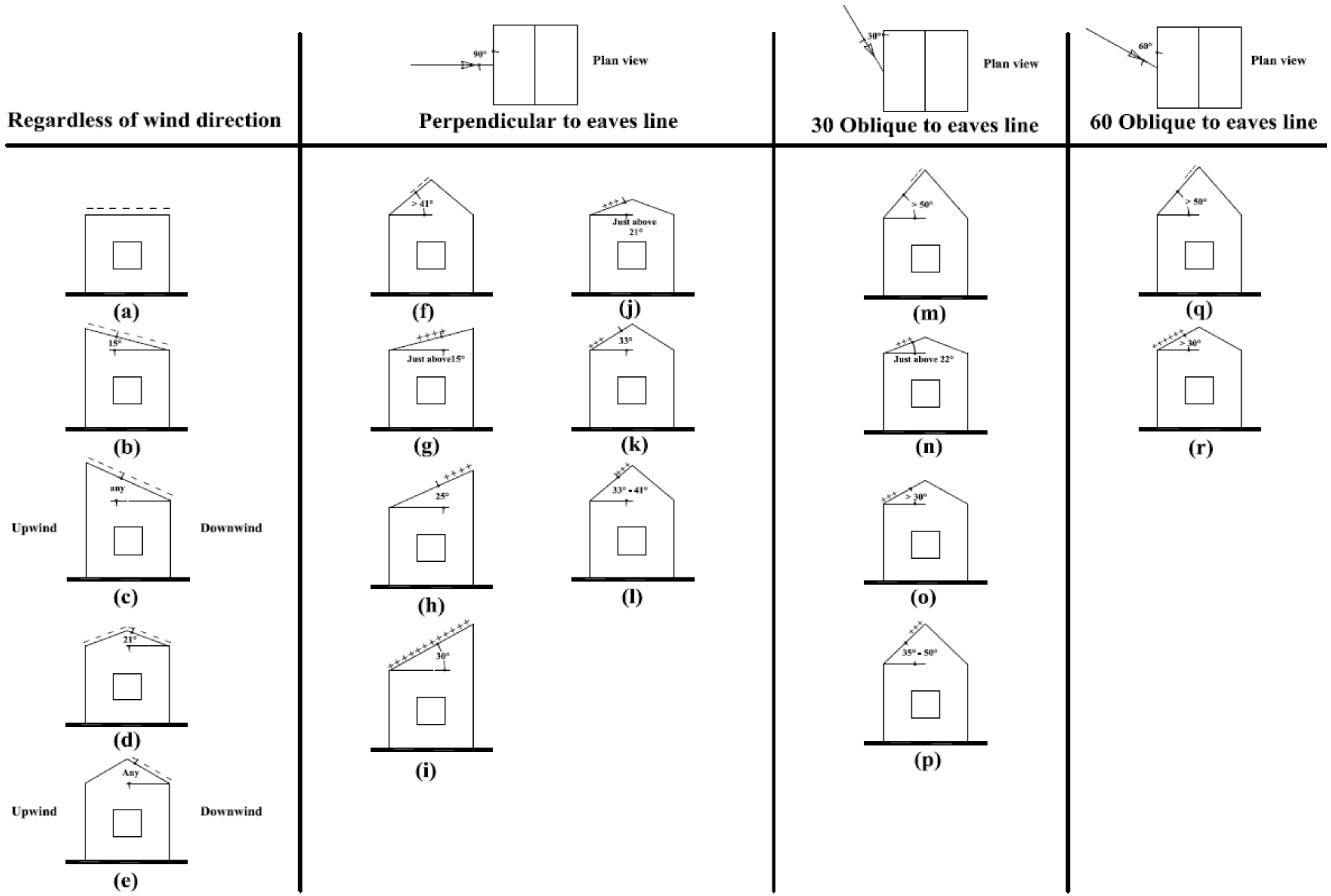


Figure 3-58: Wind pressure over different parts of different roof shapes , by the author using the data from [168] quoted from [33]

khan et al [148] and Gadi [173]. Asfour and Gadi [172] studied the ventilation effectiveness of dome and vaulted roofs in different building configurations and different orientations. They concluded that the vaulted roof over a rectangular building, with openings in its base and its short side facing wind, gave the maximum suction and ventilation rate. When the wind direction was perpendicular to the long side of the building, the dome roof presented better performance. However, both roof shapes were found to be having the same efficiency in extracting the air from the building, when they were exposed to 45^o oblique wind. Gadi [172] emphasized the effectiveness of dome roofs in extracting the air from a building, especially when openings added to its apex. This added opening functions as a suction cowl and accelerates airflow through it as a result of the formed negative pressure. Also, he added that the dome roof could enhance internal stack effect due to the difference in its surface temperature, as due to its domed shape 40% of its area is kept shaded.

3.4.5. Natural ventilation inducers

The effect of three natural ventilation inducers on its performance inside buildings is discussed in this section. They are building envelope projections, ventilation shafts and double skin façades.

3.4.5.1.Building envelope projections

Building envelope projections could be horizontal elements such as (*shading devices and overhangs*) or vertical elements such as (*wing walls*). Also, they can be installed in fixed or operable form. Both of them have great effect on directing the airflow and its speed inside the building even, under less than ideal conditions [34]. They operate through forming an air dam that blocks the air; regulates its pressure and deflects it to the desired space.

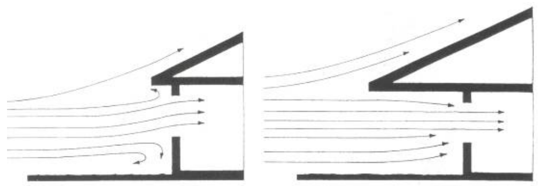


Figure 3-59: Effect of increasing the overhang size on the airflow through an opening, after Allard [33]

Horizontal projection, such as shading devices and overhangs, create pressure pockets under their surfaces, which in turn trap the air and funnel it into the interiors. In addition, their use combines the benefit from both; solar and air movement control. The increase of the overhang projection increases the positive pressure near openings under it, and thus, increases the airflow rate and velocity. Meanwhile, it provides more shade (Figure 3-59) [33]. Sometime the path of airflow could be more important than its velocity. Overhangs and shading devices can direct the air where it should be. For example, solid horizontal shading devices deflects air stream up to the ceiling, which is not desired by occupants. This effect can be modified by adding a gap between the building wall and the projection (Figure 3-60) [34].

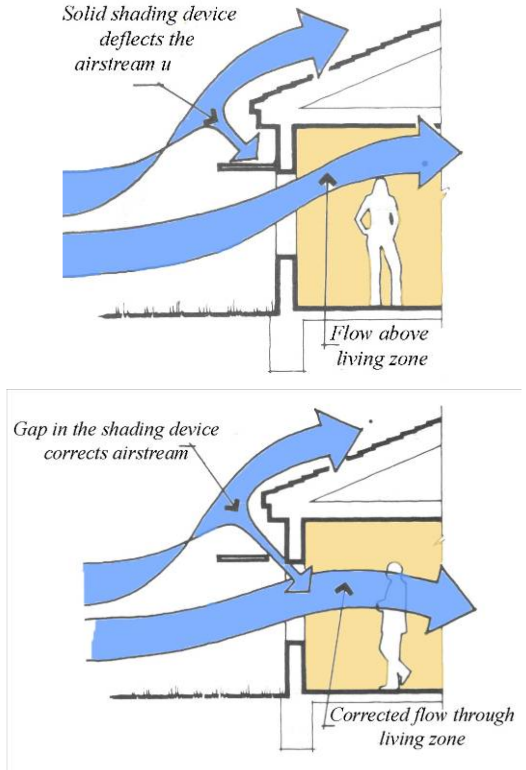


Figure 3-60: Correcting the airflow by adding a gap in the shading device, reproduced after Watson and Labs [34]

Vertical projections, such as wing walls, were first introduced by Givoni [174] as an architectural feature that could enhance poor ventilation performance in single-side ventilation cases [148]. These wing walls could be baffles, panels, hinged perpendicular shutters or solid structure wing walls. With a single-side ventilated space with only one opening parallel to the wind direction, these devices could trap the air, create high pressure zone and force it to enter the space. If they are added to downwind side of the opening (Figure 3-61) [34].

Wing walls can also be used to create artificial cross-ventilation in a single-side ventilated room and with its outside wall parallel to the wind direction by creating an artificial pressure and suction zones along this wall. This is through providing two windows in that wall and providing each window with a single vertical projection from the internal sides of each [34, 65, 148]. This in turn creates positive pressure zone in front of the upwind projection and negative pressure zone behind the downwind one, thus it induces cross-ventilation to happen (Figure 3-62) [148]. Architectural functional design features could be used to achieve the same effect. For example, balconies and openings could be designed in conjunction with each other to allow the use of their sides as wing walls (Figure 3-63) [65].

An experiment at the B.R.S in Haifa [174] demonstrated that the best ventilation conditions with higher average internal airspeed (*as a percentage of the wind speed*) can be obtained with a vertical projection depth of the same window's width or double its width, with a tiny difference between both cases. This was associated with oblique wind direction at 45^{o} (Figure 3-64)[19].

Mak et al [175] repeated the same experiments using a CFD simulation tool. They confirmed the same results as of Givoni with an average internal velocity of 40% when the wing wall was used and 15% without using wing walls. They realised that the relative size of a wing wall for a given window size reaches a value, above which the size of the wing wall provides no further improvement in performance. The only disadvantage that was reported of wing walls was the obstruction of sun light. This could be treated by using transparent material in its construction [148].

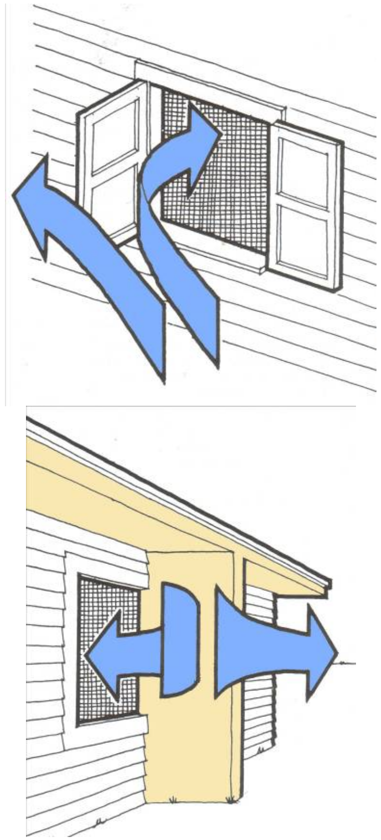


Figure 3-61: Using hinged perpendicular shutters and solid structure wing wall to induce air into a space, reproduced after Watson and Labs [34]

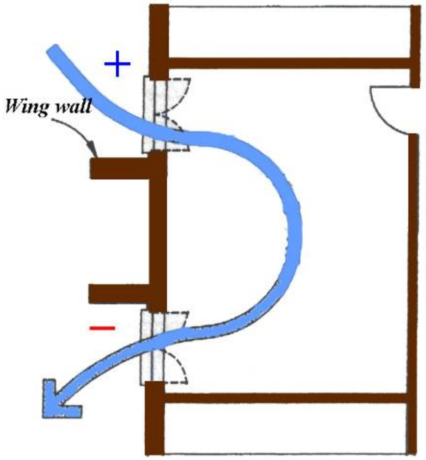


Figure 3-62: Using two wing walls to create an artificial cross-ventilation

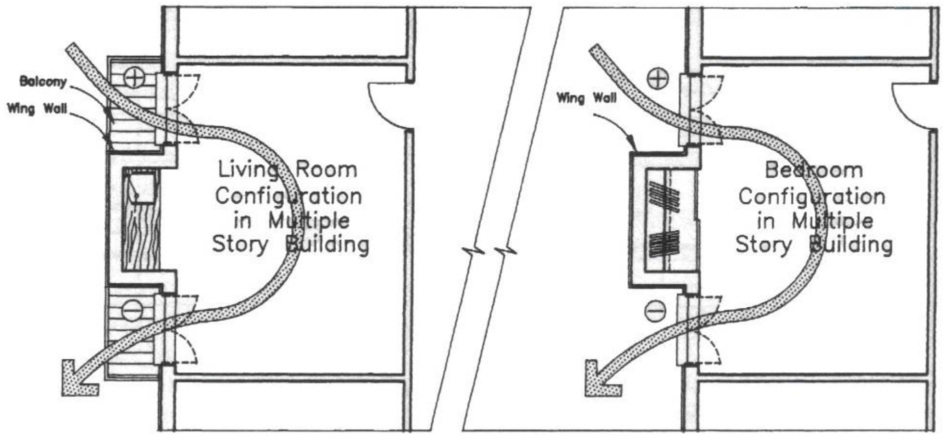


Figure 3-63: Using architectural functional design features as wing walls, after Givoni [38]

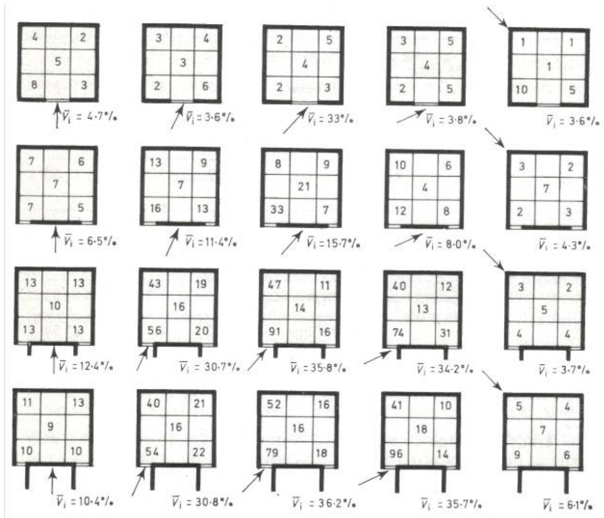


Figure 3-64: Internal airspeeds in models with wing walls of different depth, compared with values in models without projections (window width = 1/3 of wall width), after Givoni [19]

Givoni [65] highlighted that the depth of the wing wall, in multi-space buildings, should not be too large to interfere with the adjacent room ventilation. He advised that it should not be more than one-half the distance between the wing wall of the first room's outlet and the beginning of the second room's inlet.

3.4.5.2.Ventilation shafts

Ventilation shafts are one of the widely used ventilation and cooling devices from the past until now [176]. These are tall structures that rise high above the building to either capture the free air stream or exhaust it out. From the readings, they are found to have many names according to their technical function such as; wind towers, wind catchers or scoops and ventilation chimneys. They are called wind catchers or scoops when they collect breeze from above the roof level and deliver them down the building to the living quarter (Figure 3-65) [33, 176]. When they work in reverse, i.e. expel the air from the building's space to outside under the thermal buoyancy forces' effect, they are called ventilation chimneys. When they do both jobs, they are called wind towers and considered effective in creating airflow even when the wind outside is fairly calm [177]. In common, they were used in a variety of forms within the hot arid part of the world, especially the area between North Africa at west and Pakistan at east [34, 176], where the windows' main functions (*light, ventilation and view*) need to be individually considered to achieve comfort [33]. Wind catchers were used 3500 years ago in the Egyptian context, when they were used as wedge-shaped inclined scoops in the Egyptian tombs. Numerous traditional houses in Cairo used them in the same way with the local name of "*Malqaf*" (Figure 3-66) [176]. Recently, wind catchers are being incorporated in many

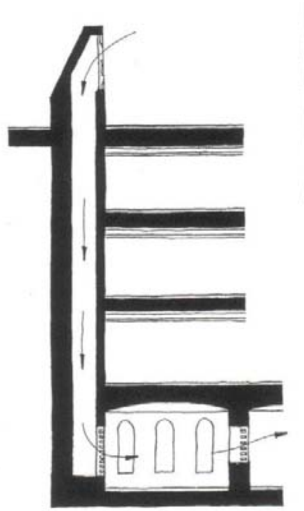


Figure 3-65: Section in a typical traditional wind catcher showing the airflow through it, after Oliver [176]

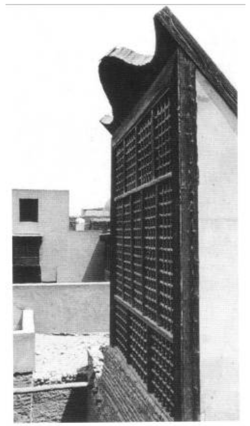


Figure 3-66: Traditional wind catcher (*Malqaf*), Cairo, Egypt, after Oliver [176]

residential buildings within hot parts of US and Australia [178]. In Iran, Iraq and Gulf states, a similar counterpart with more sophisticated structure called locally "*Badgir*" has been used in buildings since 14th century [52]. The Badgir is a wind tower with different number of openings at its head (one-sided, two-sided, four-sided and octahedral catcher). Each opening has a row of tall vents (Figure 3-67) [176, 179]. For ventilation chimneys, they are commonly used in many modern buildings, especially in cold climates, in order to provide ventilation through stack effect and achieve reduction in energy consumption [180].

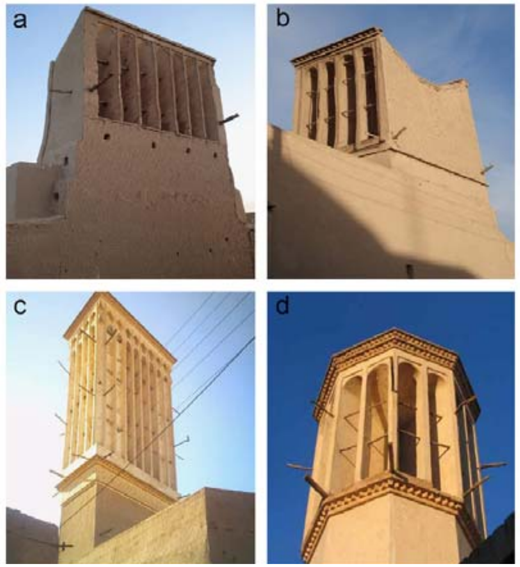


Figure 3-67: Several traditional Badgir with different number of openings: a) one-sided, b) two-sided, c) four-sided and d) octahedral catcher, after Montazeri and Azizian [179]

Wind catchers as ventilation and cooling devices can deliver a high rate of ventilation, where ventilation is required and the use of windows is restricted due to the risk of intruders and rain penetration [181]. The highest cooling effect of the wind catcher can be found in the dense cities and humid regions, where the dense urban pattern obstructs airflow and makes the ventilation through windows not enough. Wind catchers' cooling capability is confirmed to be very effective and can make an up to 8^o C reduction in building interiors compared with exterior temperature [182]. However, these cooling capabilities are conditional on providing maximum airflow and speed by proper design of the wind catcher. The wind catcher is also useful in reducing dust as the wind captured by it in high level carries less dust and solids [33]. The wind catcher has typically a head with one opening that should be directed to the predominant wind direction and located high enough to trap the free streamline flow zone away from the surrounding effect [34, 45, 183]. These configurations secure high positive pressure around its opening. The deviation of its opening from the normal wind direction could make its ventilation less effective at an angle of 30^o and completely ineffective at an angle of 50^o. Many modern modifications were added to the wind catcher's design in order to increase its ability to capture the wind wherever it comes from and capture the maximum volume from the airflow. These modifications include; rotated heads (*Cowls*) controlled by vanes and different shapes of inlets (Figure 3-68) [45]. A famous example of these rotated cowls' use is the Beddington Zero Energy Development (*BedZED*) in London. The project was designed by the architect Bill Dunster in co-operation with the Urup Enginners in techniqal environmental design systems. Urups designed a ventilation system based on providing each dwelling with a wind tower equipped with a movable cowl (Figure 3-69) that provide pre-heated air to the internal spaces and meanwhile expel the vitiated air from interiors [184].

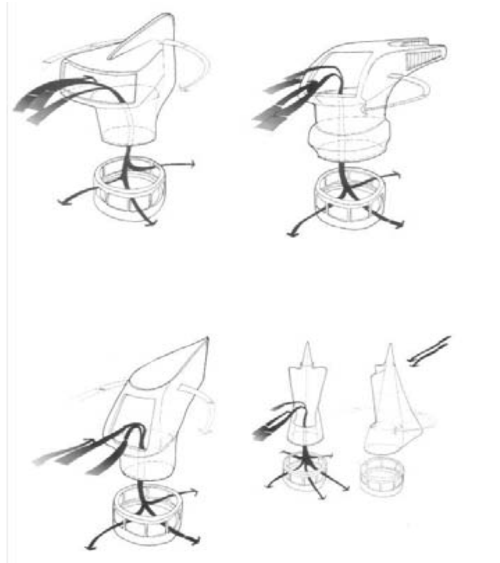


Figure 3-68: Examples for modern design of wind catcher's rotated head controlled by vanes, after Battle McCarthy Consulting Engineers [45]

Figure 3-69: BedZED ventilation cowls, after Twinn [184]

Montazeri and Azizian [179] investigated the best configurations and orientation for optimum natural ventilation performance of a typical wind catcher that located exposed or within an urban context. They concluded that the wind incident angle and the context greatly affect the airflow rate, direction and pressure distribution over the catcher's body. They found that the maximum ventilation conditions were obtained, when the wind blows perpendicular to the catcher's head opening. Montazeri [185] argued that the most effective design configuration to affect the wind catcher performance are; its height, cross-section of its air passage and the head opening number and place. He conducted a comparison study between the ventilation performance of circular wind catchers with 2,3,4,6 and 12 openings and rectangular ones with one and two openings. Montazeri ended up with some conclusions as follows:

- The airflow rate through the wind catcher decreases by increasing the number of its head openings;
- Increasing the number of openings decreases the sensitivity of the device to the wind direction;
- Best performance of ventilation was found when the wind catcher had a rectangular cross-section with one opening directed to the wind. Its performance was four times better than it circular counterpart with two openings;

He justified that by the ability of sharp geometries in creating regions of flow separation and high pressure difference across the device. In addition, he emphasized the ability of the one opening rectangular wind catcher to work as a suction device when locating its opening in the wake area of the catcher's body with its high negative pressure.

In terms of the best wind catcher height and size, Khan et al [148] reported that the wind catcher's cooling capability and airflow speed are not significantly affected by the height of the catcher after it exceeds (*9m*) above the roof level. They advised that it is enough to use wind catcher with height of (*4m*) and cross-section of (*0.57m * 0.57m*) in order to provide a ventilation rate of ($0.3\ m^3/s$) and reduce the internal dry bulb temperature from (36^o *to* 25^o *C*).

The airflow through wind catchers could be significantly enhanced if attached to a building in conjunction with other passive strategies. Bansal et al [186] (quoted from [148]) suggested the use of wind catchers with a specifically designed solar chimney exits in order to enhance

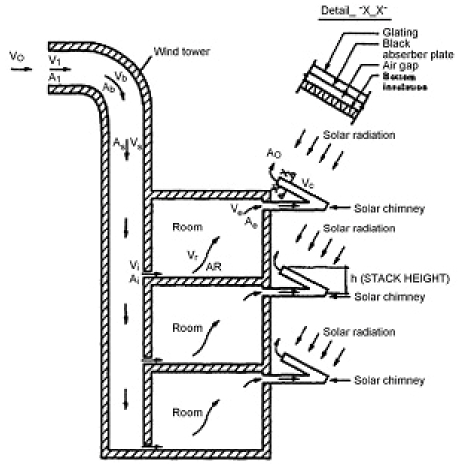


Figure 3-70: Solar chimney assisted wind catcher ventilation system, after Bansal et al [186]

ventilation performance through stack effect during the periods of low wind (Figure 3-70).
The cooling capabilities of the wind catchers can be also enhanced, if they are equipped to provide an evaporative cooling effect [177]. This is not a new idea as it was used by traditional Egyptians. They were putting water pots or intervening a soaked straw mat in the lower opening of the catcher's shaft and sometimes a wetted charcoal tray was put at the shaft bottom [176].

As for a wind tower to do both jobs of funnelling the air down to the interior and expelling it out through its multi-opening head, Allard [33] determined on three kinds of physical mechanism whose combination controls the wind tower performance. They are:

- *Downdraught*: When there is no wind, the hot air enters the tower from its side, contacts its high inertia walls, cools down and then washes down to the tower bottom;
- *The wind effect:* Moving wind has a stronger effect on cooling the air that enters the wind towers speedily. When the tower is connected with the down spaces of the building that have openings in the leeward side, effective cross-ventilation could be created. However, using the air that comes from the tower for cooling is less effective at night than at day time. This is because the cool night air gains some heat from the tower walls, which gain heat during daytime and radiate it during night, while it travels down through the tower; and
- *The stack effect:* In the absence of the wind at night, the heat released by the tower fabric heats up the air and creates a differential in its density with the low pressure area

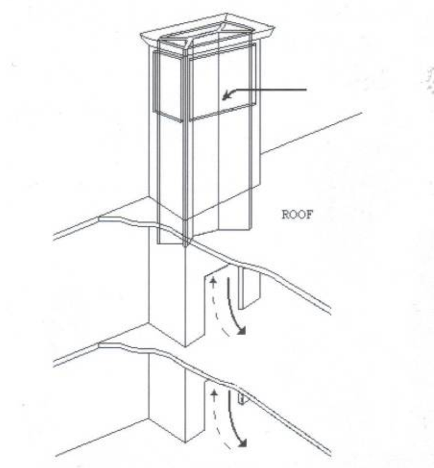


Figure 3-71: Airflow patterns through a wind tower (daytime: solid line, night-time: dashed line), after Allard [33]

at the tower's top, which causes an up draught (Figure 3-71).

The Persian conventional wind tower (*Badgir*) is one of the best known wind towers that is perfect in areas with variable wind directions as it has head openings in all directions (Figure 3-72) [187]. The wind tower system can be associated with ground cooling by building it separately away from the building and so connect it to the building through an underground tunnel that helps in keeping the air cool (Figure 3-73) [33]. Adding an evaporative cooling device to the wind tower greatly improves its effectiveness. Traditionally, Persians passed the air through the wet underground region to achieve this [177]. Bahadori [187] tried to modify the conventional tower design, in order to maximize its cooling effect and avoid some of its disadvantages as follows:

- The conventional tower head allows dust, insects and small birds to enter the building. This was treated in the new design by adding screens that cover the tower head openings;
- With the multi-opening tower head, some of the air is normally lost through the other openings that do not face the wind. In the new design this was overcome by adding gravity dampers or swivel versions to the head openings, which allow air to move through the opening facing wind direction, while closing the dampers at the other head openings. These dampers are operated by the effect of wind pressure; and
- The limited use of the evaporative cooling capabilities of the tower. Therefore, a deep clay grill (i.e. c*lay conduits*) is added to the top part of the tower to maximize the

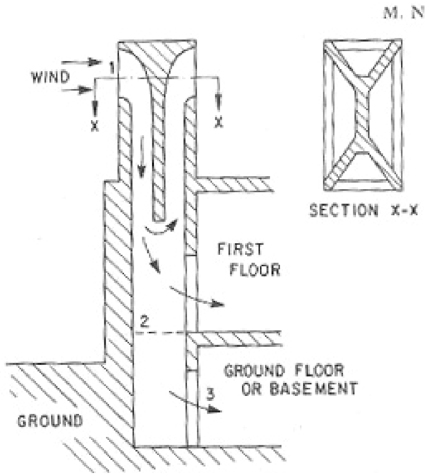


Figure 3-72: Airflow patterns in conventional wind tower, after Bahadori [187]

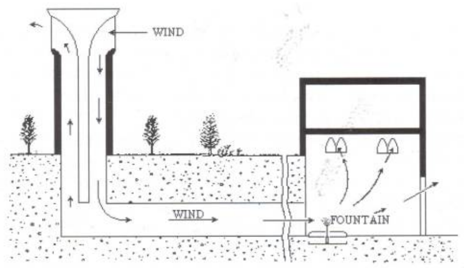


Figure 3-73: Wind tower system associated with ground cooling, after Allard [33]

contact area with the air and enhance heat transfer. In addition, spray devices are added at the top of the clay conduits in order to keep them fairly moist and enhance the evaporative cooling (Figure 3-74).

The best height of the clay conduits element, in Bahadori's design, that gives best cooling effect was investigated by Saffari and Hosseinnia [188]. They found that the (*10m*) height of these conduits gives the best cooling effect with (12^o *C*) reduction in air temperature and (*22%*) the increase in air humidity. The same issue stimulated Bouchahm et al [189] to look into the effective height and size of those clay conduits that give optimum cooling effectiveness. They reported that optimum cooling was obtained when the height and the size of the clay conduits ranges between (*h= 5.5, 4.5 m and size= 0.14, 0.116m*).

Bahadori [190] and Bahadori et al [191] replaced the clay conduits with two ideas of evaporation devices. The first one was to add wetted columns consist of wetted curtains hung in the tower across its section. The second idea was to place a wetted evaporative cooling pad on the tower head opening. They found that the tower with a wetted curtain performs better with high wind speed, while the tower with the wetted pad performs better with low wind speed. They advised the use of these ideas with different sizes and heights in modern building designs.

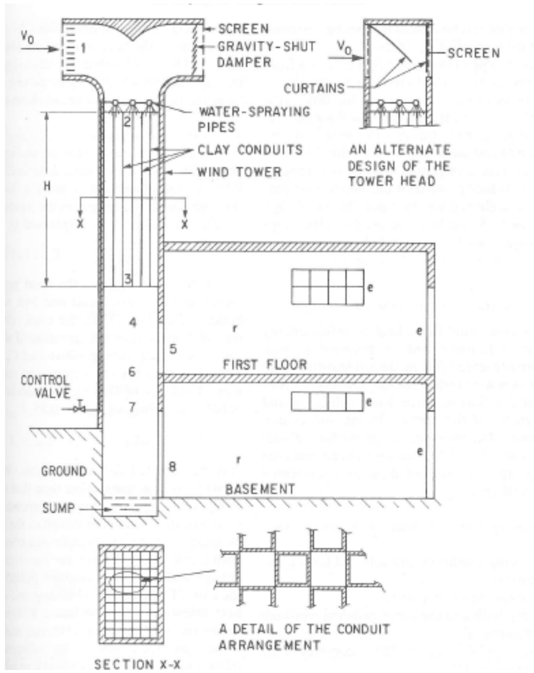


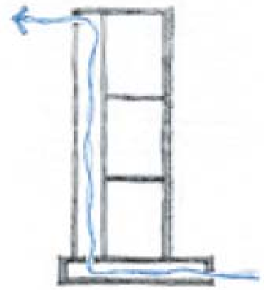
Figure 3-74: Bahadori's proposed design of wind tower, after Bahadori [187]

3.4.5.3.Double skin façades

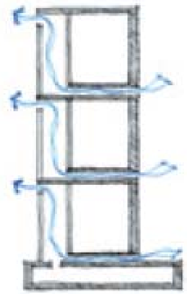
Double skin façade (*DSF*) is an arrangement with a glazed skin on the exterior of the inner façade separated by an air cavity in between [192]. These first appeared in Europe in commercial buildings and their performance remains widely debated because of the absence of any suitable thermal performance analysis tool [193]. Three different types of double skin facades were identified by Cook and Patton [194]; the full height DSF, the floor to floor *DSF* and the natural ventilation system *DSF* (Figure 3-75). Many advantages of *DSF* were reported by Etheridge and Ford [145] and Perino [192], such as:

- It can provide a thermal and acoustic buffer between interior and exterior, which in turn keeps the inner façade temperature close to the indoor temperature;
- It can provide a partial ventilation system in a tall building that controls the daily and seasonal variation of ventilation requirements;
- Its cavity can be a good place to install solar control devices away from sever weather conditions and air pollution;
- It is mainly designed as a ventilated cavity to benefit from the air flowing through it in cooling and heating purposes;
- Its ability to control the wind pressure over the inner façade;
- It can be designed to induce airflow and ventilation driven by either stack or wind forces; and
- The hot air that flows upwards within its cavity can be collected and reused in preheated air for interior conditioning.

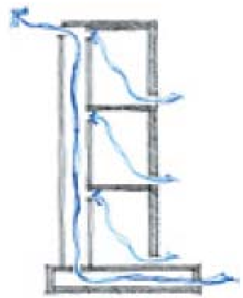
The only reported disadvantage of the *DSF* is its tendency to overheat and increase the cooling loads of the attached internal space. The solution of this problem was found to considerably



a) Full height DSF



b) Floor to floor DSF



c) Natural ventilation system DSF

Figure 3-75: Different types of Double Skin Façade DSF, after Cook and Patton [194] increases the building envelope cost [145].

3.4.6. Space height

The space height was found not to have any significant effect on the internal airflow pattern. It was found only that a very high ceiling could have an important role in allowing thermal stratification and improving stack ventilation [87, 141]. This in turn could help in passive cooling through providing a lower cool space at the occupants' level [87]. However, Evans [157] argued that this effect is limited only to very high heights. In moderate height spaces, increasing the ceiling height would not provide any more significant difference in comfort level than normal modern heights of (*2.5 to 2.7m*). No other studies were found in the available literature concerned with the effect of ceiling height on airflow and natural ventilation inside spaces.

3.4.7. Internal planning

Internal planning has a great effect on airflow pattern, speed and ventilation efficiency throughout buildings [87]. Wind-driven ventilation is mainly affected by the horizontal distribution of internal spaces, while the vertical distribution has its greatest effect on the stack-driven ventilation [33]. Therefore, the internal spaces should be designed properly in a way that facilitates airflow inside the building [33]. In general, straight flow through interiors provides the highest speed of airflow [161, 163]. When the incoming air has to change its direction many times inside the building to reach its outlet, the air circulation will be impeded due to the high resistance imposed by the internal partitions [34, 65]. For maximum ventilation performance, the proposal is to increase the internal overall porosity through providing large connections between spaces and reducing the number of spaces through which the air has to pass in order to reduce the resistance to the incoming airflow [34, 128]. The internal design form that offers the optimum natural ventilation performance is the partitionless open plan form. However, this form of internal design is not always possible to be provided for the whole house for privacy reasons. It is only applicable in small apartments or parts of houses where privacy is not required [34]. Many studies were found that deal with this issue and introduce design guidelines for well designed interiors for naturally ventilated buildings. Most of them have similar conclusions.

Givoni [174] studied the effect of sub-division of internal spaces on the airflow pattern and velocity, he reported that good ventilation conditions could be obtained, in an apartment building, by allowing air to pass from one room to another and by providing an opened connection between rooms when required. Also, he found that better ventilation conditions could be provided when the partition was near the outlet rather than the inlet. So he advised the design of the upwind room should be larger than others.

In a study by Tantasavasdi et. al. [153] that aims to produce guidelines for natural ventilation design within Thailand through quantifying the effect of several design parameters using CFD, it was advised that the open plan design allows the air to flow freely in the dwelling, while keeping its velocity up to its possible highest value. They added that if partitions are necessary, they should be kept to their functional minimum. They advised also, to locate the larger and longer rooms in the upwind side in order to avoid stagnation over them, which would occur if they located in such downwind side.

Much advice and guidelines were introduced by many researchers in order to be followed by the designer to present a balanced plan for the building that incorporates ventilation and functional requirements. Watson and labs [34] advised on the use of some architectural features that can be used by the designer to facilitate the internal airflow and meanwhile keep a good level of privacy such as; louvered doors, transom windows and louvered walls (Figure 3-76). These features could be useful in avoiding solid obstacles in the air path. However, they do, in general, slow down the airflow speed through interiors. It is advised, where possible, to locate the internal partitions between spaces in ways that help in channelling the airflow rather than cut it off. Louvered doors can also help in enhancing the airflow without breaching privacy and create cross ventilation through the spaces. Also, when less of a condition of outside breeze exists, the airflow potential due to thermal buoyancy is possible through designing tall spaces (*stair wells and atriums*), open walled balcony rooms as well as in-floor metal grates (Figure 3-77).

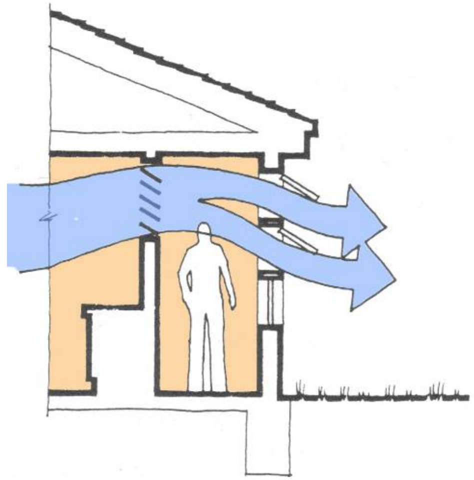


Figure 3-76: The use of louvered wall panel to facilitate the horizontal airflow, while providing privacy, reproduced after Watson and Labs [34]

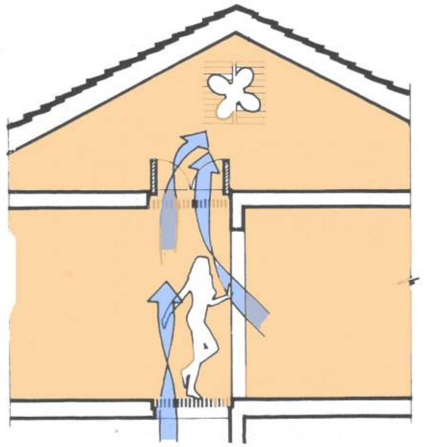


Figure 3-77: The use of in-floor metal grates to facilitate the vertical airflow, reproduced after Watson and Labs [34]

It was advised by Allard [33], in residential buildings, to locate kitchens and bathrooms with large outlets on the leeward side of the building so to help in exhausting the air that comes from the other rooms on the windward side. In addition, the living rooms should be placed on the windward side to allow maximum exposure to the wind, while locating bedrooms in more protected areas on either side. In office buildings, he advised the design of the internal partitions in a staggered manner to avoid obstructing the airflow. He added that the distribution of offices on a single row layout is preferred over their distribution in a double row in terms of ventilation and day lighting.

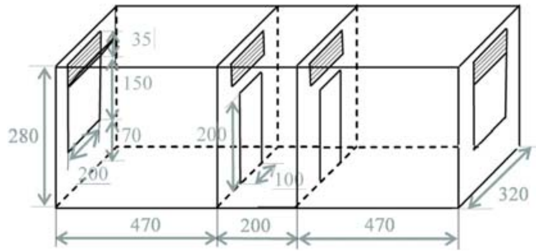


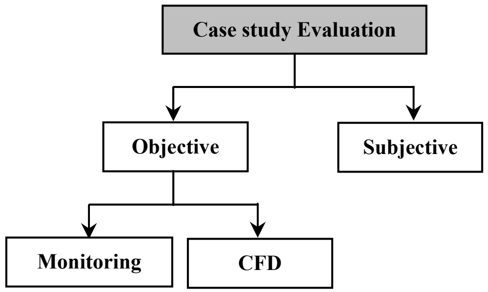
Figure 3-78: The use of transom windows to facilitate night ventilation and cross-ventilation with internal doors closed, after Breesch and Janssens [196]

Van Passen et al [195] (quoted from [196]) Advised adding night ventilation openings over the doors and windows (*transom windows*) to enhance cross-ventilation between space at night, when spaces' doors and windows are kept closed for privacy (Figure 3-78).

Kukreja [163] introduced design guidelines to be followed in tropical housing to provide maximum airspeed within interiors. He advised the design of internal partitions parallel to the incoming air stream, providing wall porosity of more than 50%, locating furniture to avoid conjunction with air flow and also locating kitchen and bathrooms on the leeward side of the building to avoid odour penetration to interiors.

The reviewed design measures in this chapter form the base, on which the selected case study in the evaluation part will be analyzed. Also, their studied performance will help in formulating the proposed design measures in enhancing natural ventilation performance inside the case study later in the thesis.

Part 2:
Case study evaluation



Chapter 4:
Case study analysis

4.1. Chapter four introduction

This chapter presents the case study employed in this work in order to identify and investigate the problems associated with using natural ventilation for passive cooling purposes in walk-up public housing block built in the Egyptian desert climatic design region. This is through conducting an in-depth evaluation to the selected case study.

In general, the evaluation study employed the diagnostic methodology that was developed for natural ventilation studies by Allard [33] (Figure 1-25). The diagnostic study in this methodology is conducted through quantitatively monitoring the building by using either; the basic measurements[1] or else detailed monitoring[2] and then qualitatively enquiring matters of the building user or the facility managers. The detailed monitoring and users' enquiry are the research techniques adopted in the case study evaluation within this work as shown in Figure 4-1.

In this chapter, the criteria used to choose the main case study are presented. It, also, presents the detailed analysis of the case study. The case study design measures and their parameters' settings that could possibly be related to the air movement and natural ventilation performance are highlighted. The design measures, which act as natural ventilation drivers, are analysed in the different levels; from macro level to micro level according to the classification introduced in chapter 3. In general, this chapter aims to identify the research case study and the properties of its design measures in terms of natural ventilation.

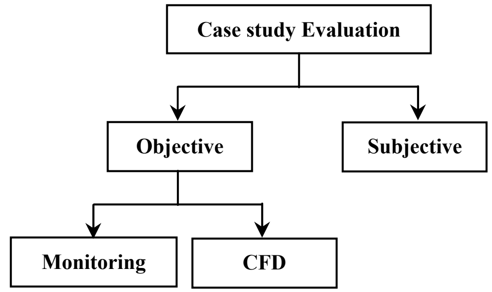


Figure 4-1: Case study evaluation methodological over view.

Note1:
Undesigned instant measurements for temperature, ventilation measurements, air velocity or external climate. This is in order to get basic indication about the measured variable's performance [33].

Note2:
Monitoring the variables of temperature, ventilation measurements, air velocity, external climate or any mix of them in details through conducting a designed experiment to reach specific conclusions [33].

4.2. Choosing the case study

Based on Yin [197] definition of case study, Groat [198] defined it as "*An empirical inquiry that investigates a phenomenon or setting within its real life context*".

Since, the case study acts as a test vehicle for the research's aims and objectives as well as the methodology. Therefore, choosing the case studies is argued to be one of the most important factors that can affect the success of any research project [6].

Gado and Mohamed [32] suggested generic criteria for choosing a case study for environmental performance investigations. These criteria are:

- Significance of the case study location to the investigations;
- Regional climate;
- Building technology used;
- Context of the case study including social, economical, geographic and political contexts;
- Case study microclimate;
- Accessibility to the case studies including the accessibility to the case study users, facility manager and owner, as well as physical accessibility and availability of data including drawings and any essential information; and
- Building typology.

In this research three main criteria have driven the choice of the case study. These criteria are:

- Availability of the data;
- Physical accessibility to the case study; and
- Quantitative volume of dwellings produced from the housing prototype.

The availability of the data and accompanying drawings for the case studies were one of the main factors that controlled the choice of the proposed case study. As mentioned in section (1.5.1), seven different walk-up public housing block's prototypes were identified in *New Al-Minya* city. These can be grouped under the following three groups:

1. Prototypes built before 1995:
    a) Housing blocks prototype 1 "*Masaken1*"; and
    b) Housing blocks prototype 2 "*Masaken2*".
2. Prototypes built from 1995 to 2005:
    a) Youth housing project – Stage 2, prototype *"Asfor Al-Gana* ";
    b) Youth housing project – Stage 3, prototype *"Al-Bondok* ", and
    c) Future housing project, prototype *"Kamar El-Deen"*.
3. Prototypes built or are being built after 2005:
    a) Youth housing project – Stage 4, prototype "*Al-Mokhtara*"; and
    b) National housing project, prototype "*Al-Talet"*.

Figure 4-2 illustrates each prototype and its location in *New Al-Minya* city.

No data or drawings were found for the first two prototypes (*Masaken1* and *Masaken2*) and they are not built by the government since 1995. Therefore, those two prototypes were excluded.

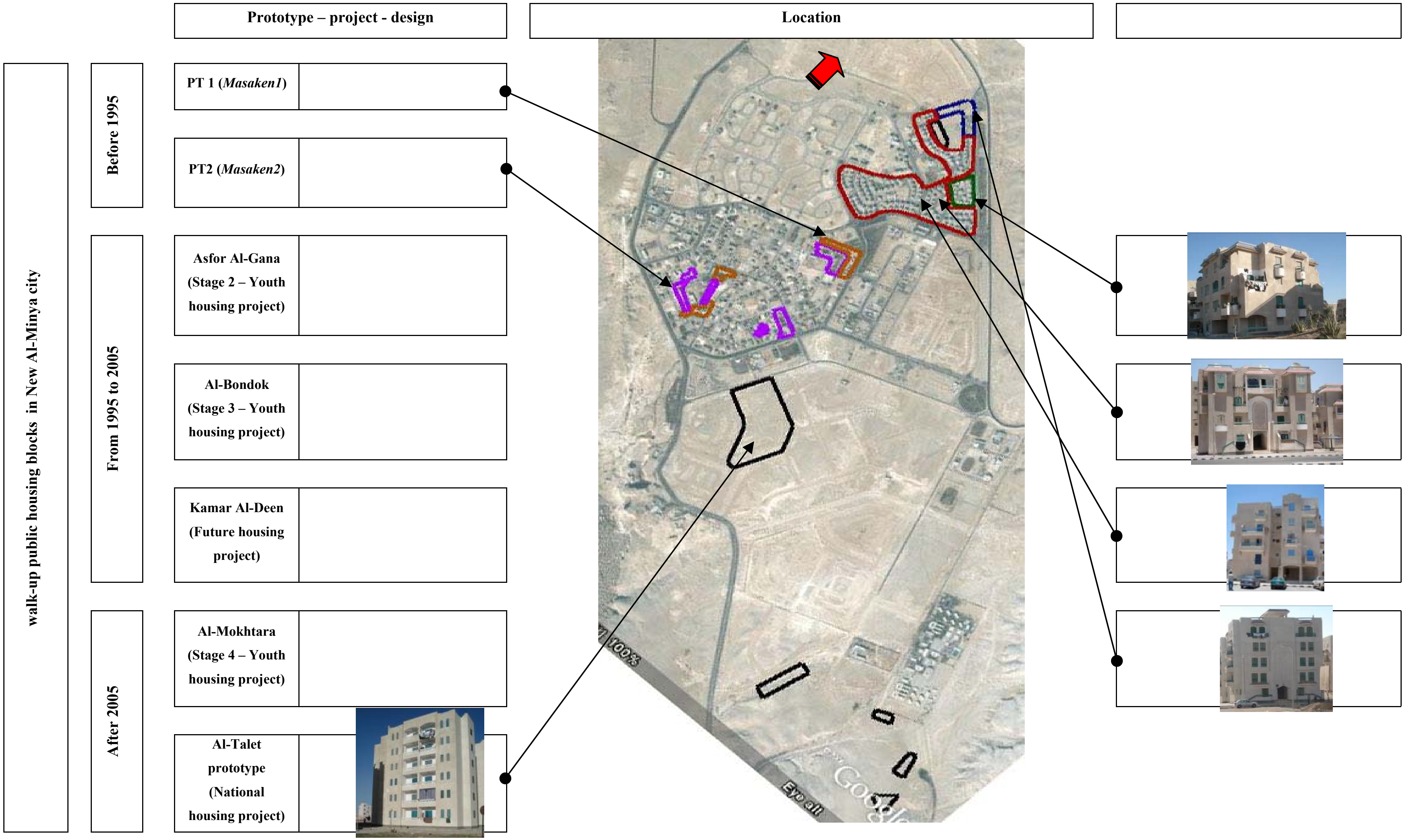


Figure 4-2: All available public housing prototypes in *New Al-Minya* city and their locations within the city

The physical accessibility to the case study is an important factor that affects the case study choice in the Egyptian context due to several social requirements. In most cases, it is extremely difficult to access homes in Egypt to interview the users or install monitoring equipment. This is due to the social nature of Egyptians, who would not easily allow access for strangers to their homes. Consequently and because of the researcher having worked for a long time in the *Al-Minya* city, he relied on his colleagues and friends based in *Al-Minya*, who facilitated accessing the case studies.

Access to "*Asfor Al-Gana" and "Al-Bondok"* prototypes were not possible at all, so they were excluded from the study. However, some friends facilitated the access for; one flat in "*Kamar El-Deen prototype*" and one flat in "*Al-Mokhtara prototype*". Full access was facilitated to non-inhabited "*Al-Talet prototype*".

Quantitative volume of dwellings produced from the housing prototype: It was the intention to choose a prototype that is widely used nationally and across Al-Minya to allow applying the results on a wide scale. Between the three prototypes left (*Kamar El-Deen*, *Al-Mokhtara*, and *Al-Talet)*, *The Al-Talet* prototype was found to be the most suitable one to be the research case study.

Al-Talet is the most widely used prototype as part of the "*Ownership of housing units approach*" and the *"63m^2 dwellings for rent approach*" of the largest ever public housing project in Egypt; *The* n*ational housing project*. It is planned to build just under 340,000 dwellings by using this prototype. Only *"61119"* dwellings are already built to date [13] (Figure 4-3). Locally, in *New Al-Minya* city, *Al-Talet* prototype was widely used in the past and will remain so in future, with "*3456*" dwellings to be built across the city. Only "*576*" dwellings are built to date [199] (Figure 4-4). The available case studies in the research context and the case study's choice process are illustrated inTable 4-1.

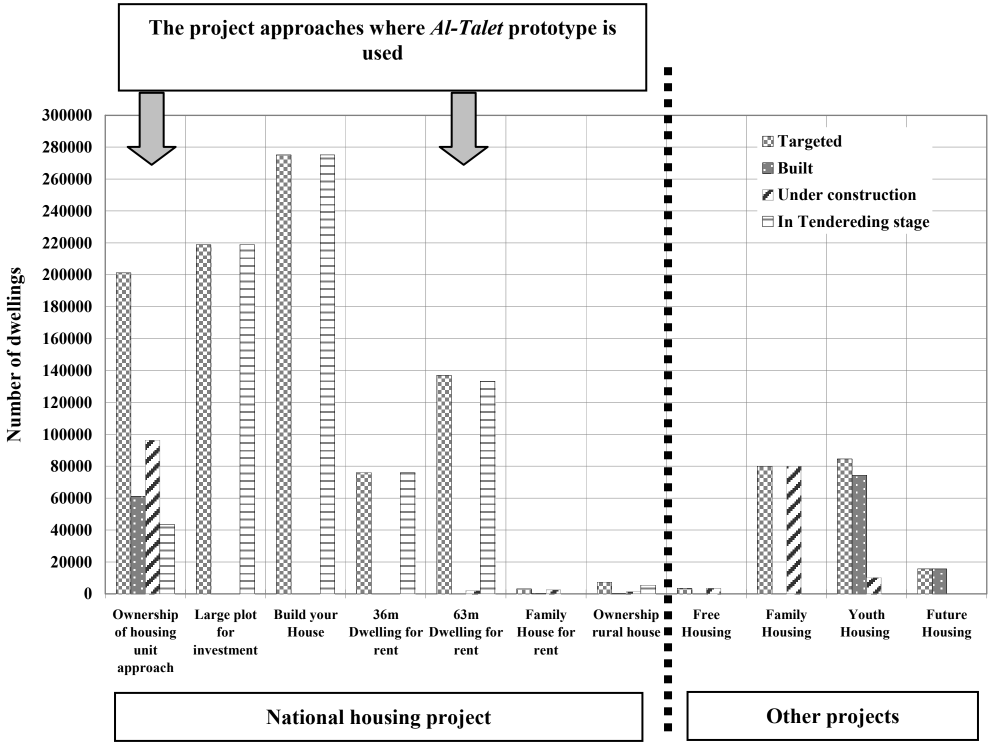


Figure 4-3: Number of targeted and completed dwellings within public housing projects across the country with *Al-Talet* prototype indicated, by the author using data from NUCA [13] and MHUUD [200]

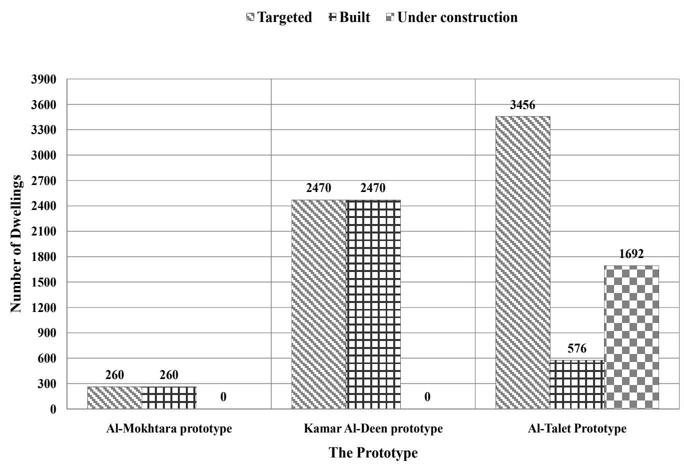


Figure 4-4: Number of the planned and completed dwellings of the three prototypes; *Al-Mokhtara, Kamar Al-Deen*, and *Al-Talet* in *New Al-Minya city*, by the author using data from city's local authority [199]

Table 4-1: The available case studies in the research context and the case study's choice process with the selected case study prototype highlighted

		Walk-up public housing prototypes in New Al-Minya city						
		Before 1995		From 1995 to 2005			After 2005	
		Masaken 1	Masaken 2	Asfor Al-Gana	Al-Bondok	Kamar Al-Deen	Al-Mokhtara	Al-Talet
Choosing criteria	Availability of the data	X	X	OK	OK	OK	OK	OK
	Accessibility to the case study	Excluded		X	X	OK	OK	OK
	Quantitative volume of the produced dwellings			Excluded		X	X	OK

4.3. Case study description

The case study is a massive walk-up housing block built in an isolated form. Each block consists of six levels with six flats in each story. See Figure 4-5 and Figure 4-6. 96 blocks are due to be built in six locations across the city. Four out of these locations are located on the edges of the newly established neighbourhood at the far south edge of the city where *33 blocks* are planned to be built. Another 5 blocks were built in the heart of the fourth district to the north of the city. The only large compound of this prototype is that being built in the sixth district consisting of *58 blocks* (Figure 4-7). This large compound will be used in the proposed case study analysis. For full Architectural working drawings of the case study, see (*Appendix A*).

Figure 4-5: The case study prototype - image from the site

In the following sections the case study will be analysed in terms of the design measures and their parameters that could possibly affect and drive the air movement in and around it for ventilation purposes. These measures and parameters are; site givens and master plan design (*on macro-level*), landscaping elements along with adjacency profile and building arrangement (*on intermediate-level*), and finally building mass; building orientation, building envelope and internal spatial planning (*on micro-level*).

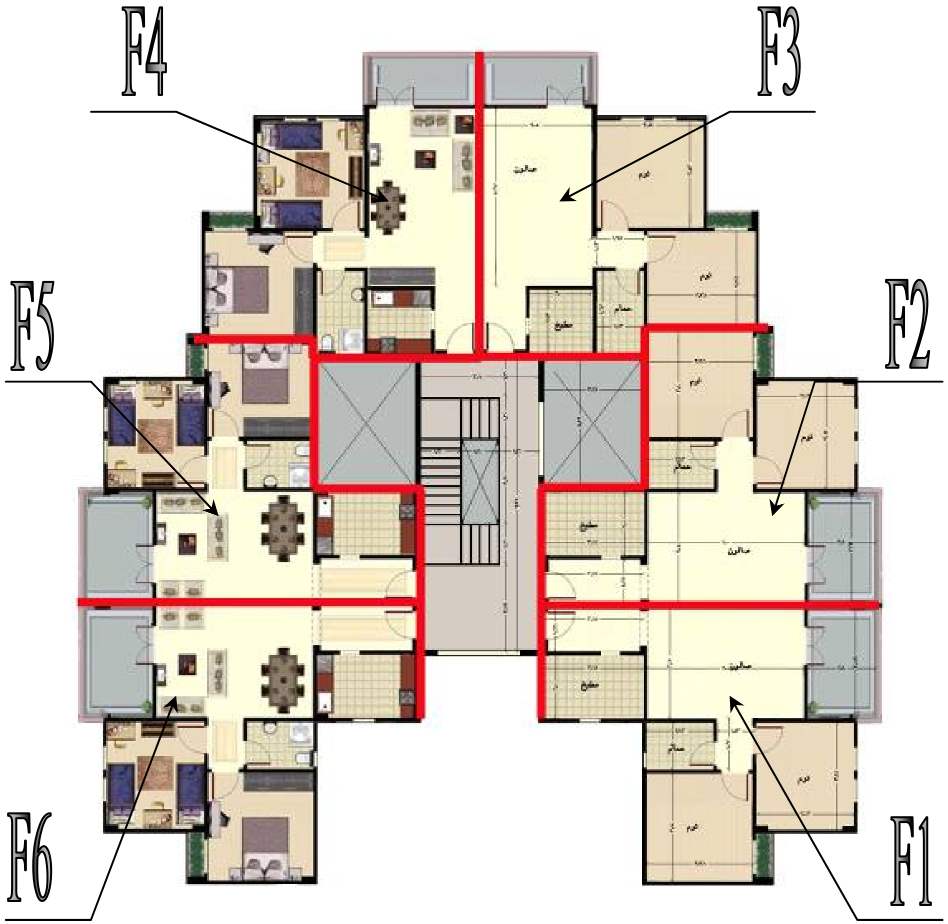


Figure 4-6: The case study plan with flats borders highlighted

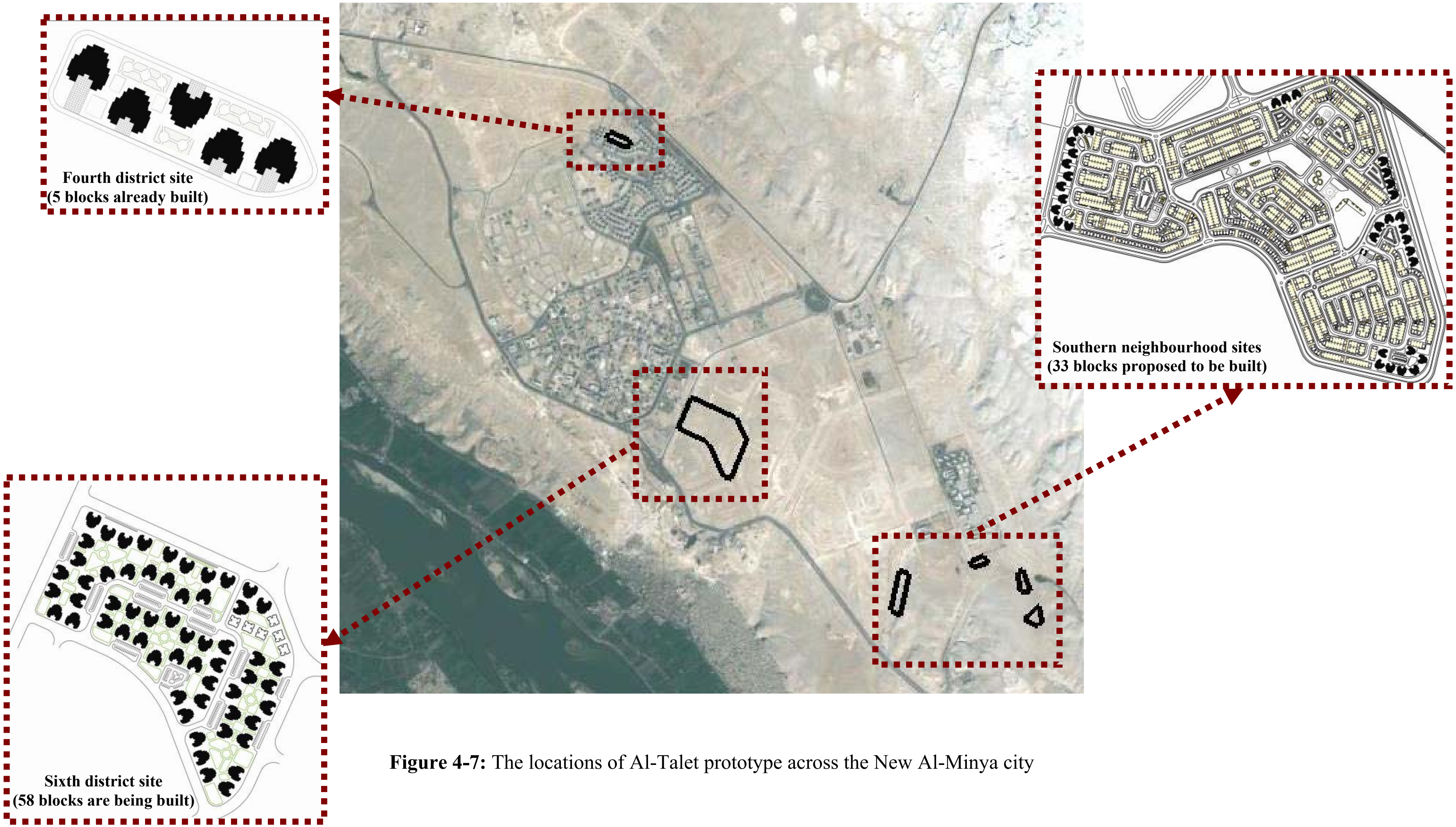


Figure 4-7: The locations of Al-Talet prototype across the New Al-Minya city

4.4. Case study Analysis

4.4.1. Site

In terms of the landform of the case study site, it is flat with no significant difference in levels as seen in Figure 4-8 . No heat sinks such as seas, lakes or forests are found near the site within a radius of almost 2 Km. The river Nile lies approximately 2 Km south west of the site. The river Nile has no effect on air movement, air temperature, or air pressure distribution over the site, as the most frequent wind direction is north and north west direction. In addition, the site is *130 m* higher than the river Nile level. See Figure 4-9.

Figure 4-8: The flat terrain profile of the case study's site

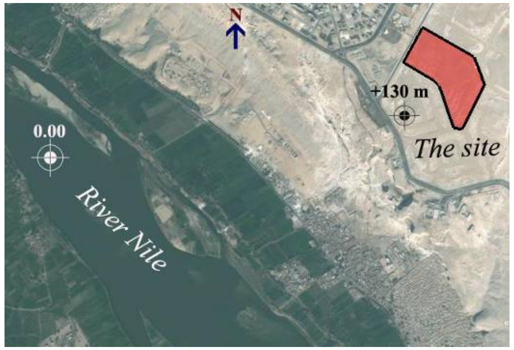


Figure 4-9: Satellite image shows the relationship between the case study's site and the river Nile.

4.4.2. Master plan

By analysing the master plan of the case study including street layout and street wind orientation, the following could be observed:

a) There are 11 public open spaces in the site around which the blocks are built. The spaces vary in size and shape. They are connected by a grid of short length streets as seen in Figure 4-10. The building density ratio over the site is found to be 20.43%.

b) The majority of the streets are aligned in the north east – south west direction or north west – south east direction. They are oblique by angles of 24^{o} and 114^{o} respectively with respect to the north direction as seen in Figure 4-10.

Figure 4-10: The case study master plan with the wind orientation of the majority of street illustrated

Analysing the street geometrical configurations of the case study site showed that street width (W) ranges between 5.5 m and 77 *m* with the majority of streets (*33.7%*) having a width of 10m. The other widths can be found in the site only once or eight times maximum with an existence ratio of 1.05% or 8.42% respectively. According to this analysis and considering H = 19 m (*The block's height*), the H/W in the site ranges from 3.45 to 0.25 with the majority of them have H/W = 1.9. See Figure 4-11.

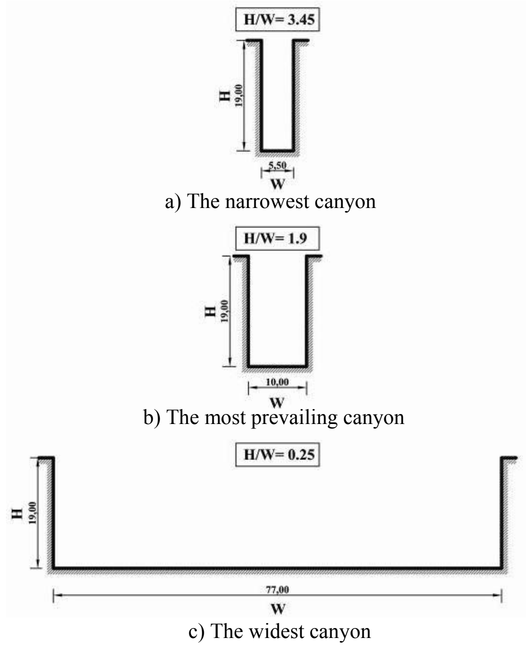


Figure 4-11: Street canyon profile across the case study master plan.

Given the fact that the blocks are built in a disperse urban form, the lengths of streets (*L*) are defined by the block dimensions (*23.94 m width and 25.69 m length*). From the analysis, it can be clearly seen that the L/H ratio ranges between 1.25 and 1.35.

According to the canyon classification mentioned in chapter 3 and from the site analysis stated above, so it can be concluded that the most common canyon configuration across the site is deep canyon. Also, it can be reported that all canyons within the site are short canyons. By applying the most prevailing H/W and L/H ratios of the case study's master plan to Oke graph (Figure 3-13), it can be recognized that the expected airflow, when the street canyon is normal to wind direction, is the skimming flow (*SF*). This in turn could possibly reduce the potential of using airflow in ventilating interiors.

4.4.3. Landscape

From the provided design of the case study master plan, no mature trees or bushes were found. Vegetation is limited to small lawns over the public open spaces and between the blocks

(Figure 4-12). The total area of the lawns is 22019.3 m^2, i.e. 15.9% of the site. These lawns are not expected to affect the airflow profile over the site. However, they might play a reasonable role in cooling the air through evaporation (*refer to section 3.3.3.1*). The site analysis also showed that no ponds or fountains have been designed to be located on the site.

Figure 4-12: The lawns profile in the case study master plan.

4.4.4. Blocks adjacency profile

The blocks are built in isolated form with no attachments to any of the adjacent blocks. Therefore, all blocks are surrounded by either streets or large open spaces. The adjacency profile of each block was analysed considering the block's sides that face large open space or a street with larger width than the block's length (*25.69 m*) as free adjacency sides. Nine adjacency profiles were found in the site. The most common adjacency profiles are:

a) The block faces another block from the front and the left sides (*24.14%*);
b) The block faces another block from the right and the left sides (*22.41%*); and
c) The block faces another block from the front, the right and the left sides (*20.69%*).

Figure 4-13 shows the nine adjacency profiles with the common cases highlighted in gray.

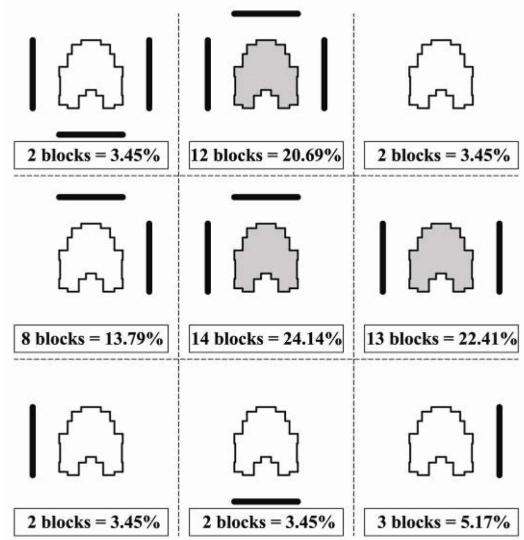


Figure 4-13: Buildings' adjacencies status in the site with the most prevailing status highlighted in gray.

According to literature, designing the blocks in isolated form gives the opportunity to provide openings in both windward and leeward sides of it, which could enhance natural ventilation performance (*refer to section 3.3.1*). However, the resultant most common block adjacency profile within the case study site along with the small canyon width could possibly hinder the benefits of the blocks being free from all sides.

4.4.5. Blocks arrangement

All blocks are arranged around eleven outdoor open spaces in three clusters separated by the main roads. The majority of the blocks are arranged in parallel rows in general. Most of blocks in the first northern cluster are arranged in staggered profile (Figure 4-14). According to literature in chapter three (*section 3.3.2*), the existence of the eleven outdoor spaces could possibly enhance and accelerate the airflow in the site. However, no expectation of the airflow pattern could be drawn because of the mix use of different building arrangements found in the site.

4.4.6. Building mass

The blocks are of compact deep mass with a dimension of L= 25.69 m, W= 23.94 m and H= 19 m (Figure 4-15) and a W/L ratio of 0.93. Each block is six storeys high with footprint area of 458.5 m^2 and volume of 8711.5 m^3. Two 15 m^2 light wells penetrate the building mass as seen in Figure 4-16. These light wells are used to provide light and ventilation to kitchens and bathrooms. Also, they are used as ducts for all sewage and water supply connections.

The nature of the deep plan design of the blocks along with their high density are against the recommendations derived by literature and could reduce the potential of using ventilation. (*refer to section 3.4.1*).

Figure 4-14: Buildings' arrangement in the site

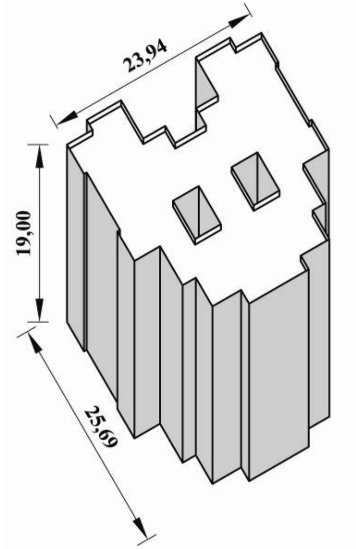


Figure 4-15: The blocks' dimensions and shape.

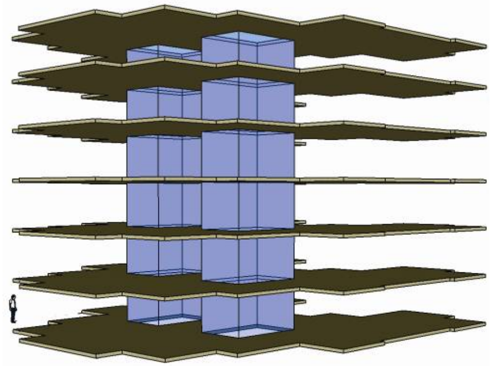


Figure 4-16: The blocks' storeys penetrated by the two light wells.

4.4.7. Blocks wind orientation

Six wind orientations were found as shown in Figure 4-17. The majority of the blocks (*15 blocks / 58 = 25.86%*) are oriented to the south west direction with an angle of 156^o anti-clockwise from the north direction (Figure 4-17). Two other orientations are widely used in the site with percentages of 22.41% and 20.69%. They are respectively, blocks oriented towards the north west direction with an angle of 66^o anti-clockwise from north and blocks oriented towards the north east direction with an angle of 24^o clockwise from north. As the wind in the case study's context prevails from the north and north west directions, it can be argued that this oblique orientation of the block to the north can enhance ventilation performance (*refer to sections 3.2.4.1 and 3.4.3*) . However, it could be hindered by the wrong opening positioning and the building mass shape.

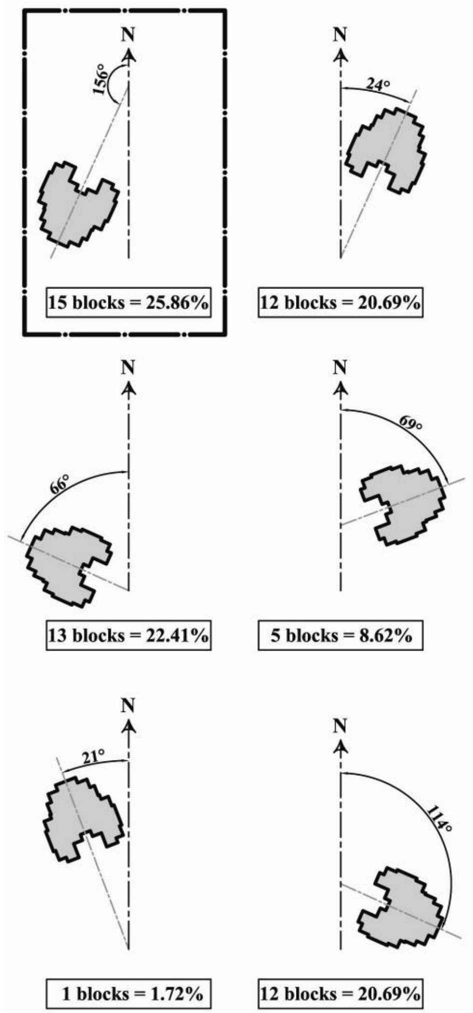


Figure 4-17: Blocks orientation cases with the most common case indicated.

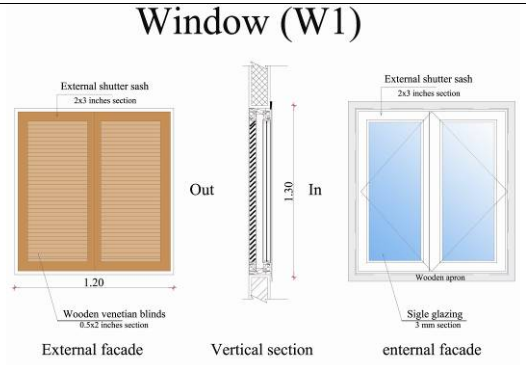
4.4.8. Building envelope

The blocks have flat roofs with no vertical projections designed for ventilation. Also, no devices were found to be installed in order to drive air pressure and induce the air into internal spaces. In terms of windows and opening design of the case study, the size, position, morphology and numbers of windows and openings were analysed.

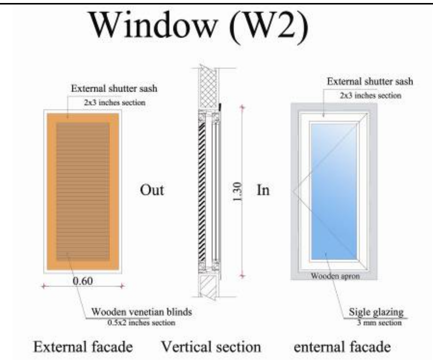
Five different sizes of windows were identified in the case study; W1, W2, W3, W4 and W5 (Figure 4-18). W1 (*1.2 * 1.3m*) services all bedroom2 (*B2*) within all flats, W2 (*0.6 * 1.3m*) services all bedroom1 (*B1*) within all flats, W3 (*0.9 * 0.7m*) services all Kitchens (*K*) within all flats, W4 (*0.7 * 0.7m*) services all Bathrooms (*Br*) within all flats and W5 (*1.5 * 2.2m*) services all Living rooms (*L.R.*) within all flats. The windows' size was found to range from *12.92% and 18.20%* from the served area.

In terms of opening position, horizontally, windows W1 are positioned in the corners of the walls that contain them in flats *F2, F3, F4 and F5*. However, they are positioned in the centres of the walls that contain them in flats F1 and F6. Windows W2 are positioned in the centres of the walls that contain them in all flats. Windows W3 are located near the corner of the walls that contain them in all flats except flats F1 and F6, where they positioned at the centre of the kitchens' walls. Windows W4 are located in the centre of the walls that contain them in all flats except flats F1 and F6, where they positioned at the corner of the wall because of the pipes' duct. Finally, the balconies' doors W5 are located near the corner of the walls that contain them in all flats (Figure 4-18). Vertically, W1 and W2 have sills' height of 0.9 m above the floor level. However, W3 and W4 have sills' height of 1.5 m above the floor level. W5 is a balcony door with zero sills' height.

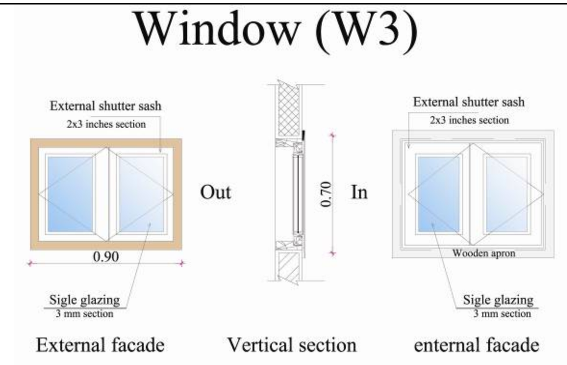
Morphologically, all case study windows are vertical-vane openings type with side-hinged casement design. Windows W1, W2 and W5 have external Venetian shutters (*2 for W1, 1 for W2 and 3 for W5*) with internal timber frame – single glazed shutters (*2 for W1, 1 for W2 and 2 for W5*). However, windows W3 and W4 have only 2 timber frame – single glazed shutters (Figure 4-18). In addition, all internal doors are solid timber frame claded with plywood plates with no vents provided.



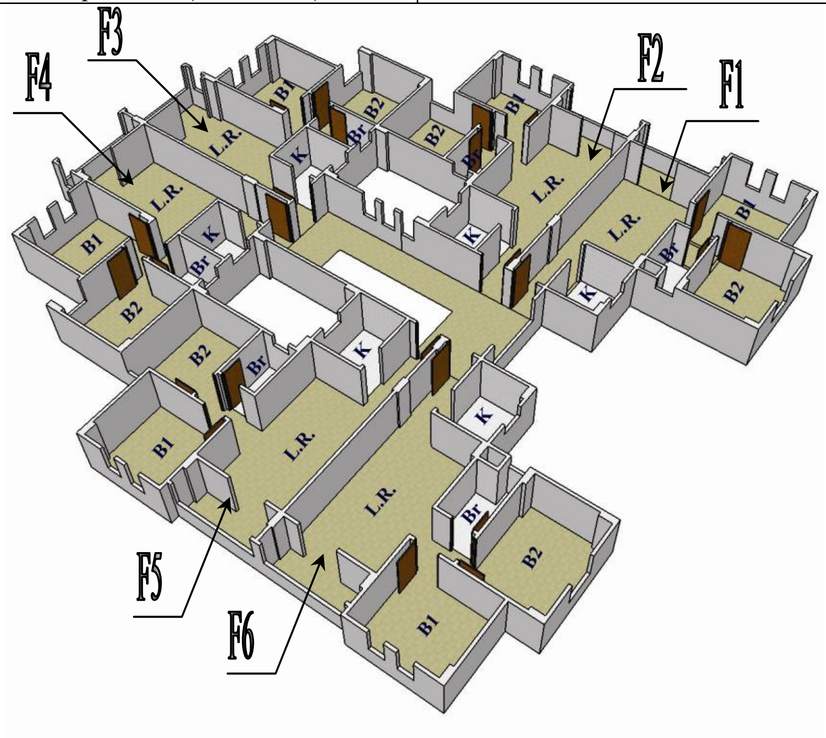
The window for spaces B2 (Bedroom 2)

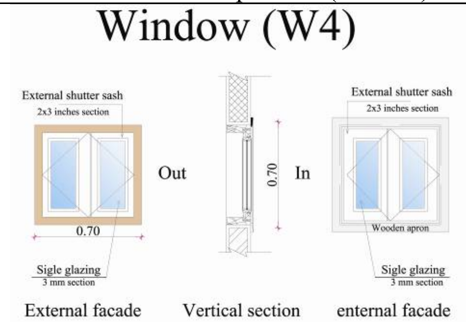


The window for spaces B1 (Bedroom 2)

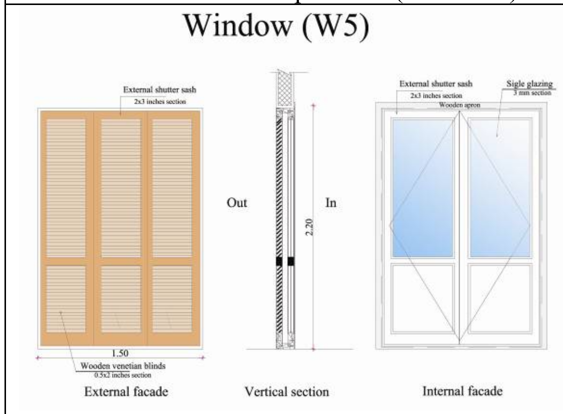


The window for spaces K (Kitchen)





The window for spaces Br (Bathroom)



The window for spaces L.R. (Living Room)

Figure 4-18: The details of building's openings and their places in the floor spaces.

In terms of opening number, all spaces within the case study have only one unit of windows and one door, except spaces (*B1*) which contain 2 windows (*W2*) (Figure 4-18).

4.4.9. Internal spatial planning

The case study blocks are designed in six identical floors. Each floor consists of six flats. The blocks were designed in symmetrical manner into two identical halves (Figure 4-19) containing by such three different flat designs. This design made flats F1, F2 and F3 are the same as F6, F5 and F4 respectively (Figure 4-19). A kind of similarity can be identified between the design of flats F1 and F2 and accordingly F6 and F5 (Figure 4-19). All of them have almost the same net floor area of $63m^2$. Each flat consists of a rectangular shape living room with a balcony attached and another two bedrooms served by a bathroom that all are accessible from a corridor. The kitchen is always located just off the main entrance of the flat (Figure 4-19). The internal distribution of the spaces has no pattern in terms of their arrangements in regard to the upcoming wind or their orientation (Figure 4-19). In terms of the internal space height, all spaces of the case study flats have a clear height of 2.8m (*See appendix A*).

In terms of the ventilation techniques that could be offered by the internal spatial planning of the case study, the current internal design only offers single-side ventilation techniques in all spaces through their windows (Figure 4-19). However, cross ventilation could be activated when opening the spaces' doors along with their windows. This situation could not easily be provided for privacy reasons. Also, no vents were found above the doors to replace their role in cross ventilation.

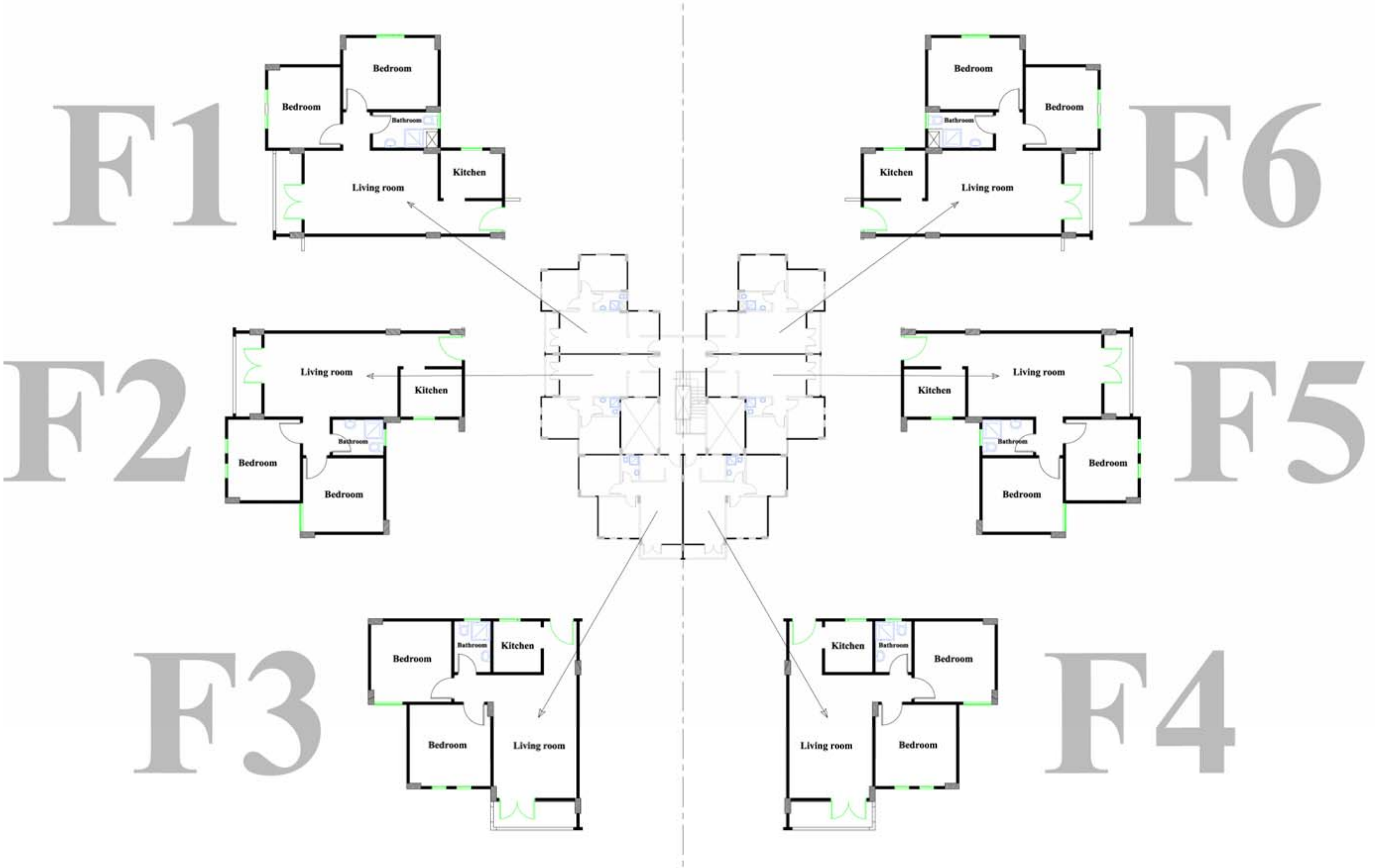


Figure 4-19: The internal spatial planning of case study floors and flats.

4.5. Summary

A representative case study was chosen to be used in this research. The case study was analysed in this chapter in terms of identifying the properties of its design measures which could possibly affect the airflow and natural ventilation performance. The analysis of design measures was conducted under three levels of design; macro-level, intermediate-level and micro-level. The results of the case study analysis could be concluded as follows:

- The site is flat with no slopes nor any nearby heat sinks;
- The master plan is designed in 11 public open spaces connected by a grid of short-length streets that were found to mostly be oriented to the north east – south west direction and north west – south east direction;
- The most common canyon configurations within the site were found to be deep short canyons with width of 10m, H/W ratio = 1.9 and building density ratio of 20.43%;
- No mature trees, bushes or water ponds were found in the site with only designated flat lawns on 15.9% of the site.
- The blocks in the site are designed to be built in disperse form with no attachments to any of the adjacent blocks;
- The most common adjacency status was found to be that of the block faces another block from the front and left sides (*24.14%*);
- The majority of the blocks are arranged in parallel rows except in the first northern cluster where they are arranged in staggered profile;

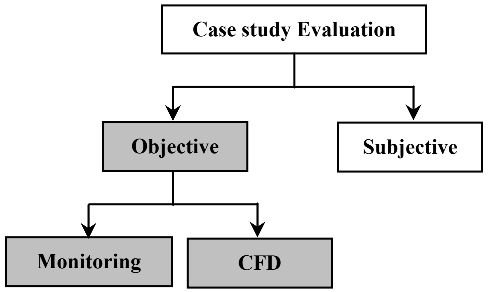
- The majority of the blocks are oriented to the south west direction with an angle of 156^o anti-clockwise from the north direction;
- The case study was designed as an arrowhead shape flat blocks with only 2 light wells penetrate the block's mass;
- Each block has a footprint area of (*458.5* m^2), a volume of (*8711.5* m^3) and width/length ratio (*W/L*) of (*0.93*);
- Five different sizes of windows were identified in the case study ;
- These windows were found to be positioned horizontally either in the centre of or the corner of the walls that contain them with vertical sill height ranges from zero to 1.5 m above the floor level;
- Morphologically, all windows are a side-hinged casement type and consist of external Venetian shutters and internal timber frame – single-glazed shutters. Only W3 and W4 consist of 2 timber frame – single-glazed shutters;
- All internal doors are solid timber frame (claded with plywood doors) with no vents included in their design;
- All case study spaces have only one unit of windows and one door, except spaces (*B1*) which contain 2 windows (*W2*) each;
- No air pressure devices were found to be installed in order to induce the air into internal spaces;
- All internal spaces of the case study have a ceiling height of (2.8m); and
- The internal design only offers a separate single-side ventilation techniques in each

space through its window.

From the outlined above analysis, it can be concluded that there is no natural ventilation system designed for this case study at any of the design levels analysed.

The quantitative evaluation through objective assessment and the qualitative evaluation through subjective assessment of the natural ventilation performance and airflow profile within the case study is the subject of the following chapters.

Chapter 5:
Objective assessment of natural ventilation inside the case study



5.1. Chapter five introduction

In this chapter, the detailed methodology, the results and their discussion of the objective assessment are widely explained. Firstly, the objective assessment methodology including the monitoring experiment design and the computer based assessment study are set out. Secondly, the results of the objective assessment are shown, discussed and analyzed according to the explained methodology. The discussion starts with the results of the case study monitoring and then proceeds to show the air movement simulation results.

5.2. Objective assessment methodology overview

The objective assessment study was conducted in two parts (Figure 5-1). The first part used detailed monitoring approach for the thermal performance of different natural ventilation strategies in two stages. The first stage monitored the thermal behaviour of a flat under different ventilation scenarios. The second stage monitored the thermal behaviour of different case study flats under the application of night purge ventilation strategy (*the recommended strategy in the research context*).

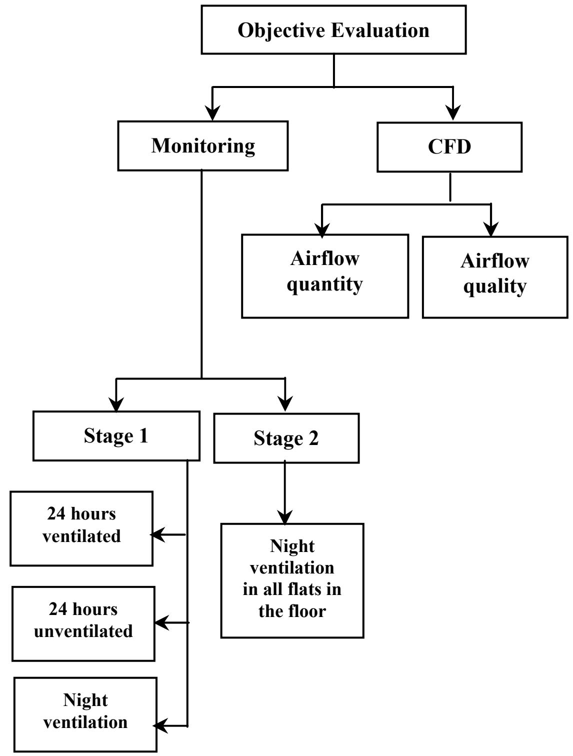


Figure 5-1: The objective assessment methodology overview

The second part employed computational fluid dynamics (*CFD*) software *FloVent* in order to quantitatively investigate the airflow in and around the case study (Figure 5-1). The methods, techniques and steps of conducting both parts, are explained below.

5.3. Monitoring methodology

The aim of monitoring the case study was to assess the performance of natural ventilation systems in use and investigate their capabilities in cooling down the dwellings. In order to eliminate all other factors and heat gains that could possibly affect the monitoring results, it was essential to conduct the monitoring in an uninhabited block. By doing this, the heat gain from the occupants, lighting and equipments were eliminated and the only active parameter was the ventilation setting. Only one uninhabited whole block within the site had allowed access (Figure 5-2). This block was the only block that has five stories height among the 11 already built blocks within the site (Figure 5-2 and Figure 5-3). The monitoring process was conducted through monitoring the air temperature inside the case study's spaces in two different stages. The internal air temperature was recorded over than other variables that could be measured because of the availability of its monitoring equipments as well as the effect of convection and radiation form building mass and surroundings is implemented in it.

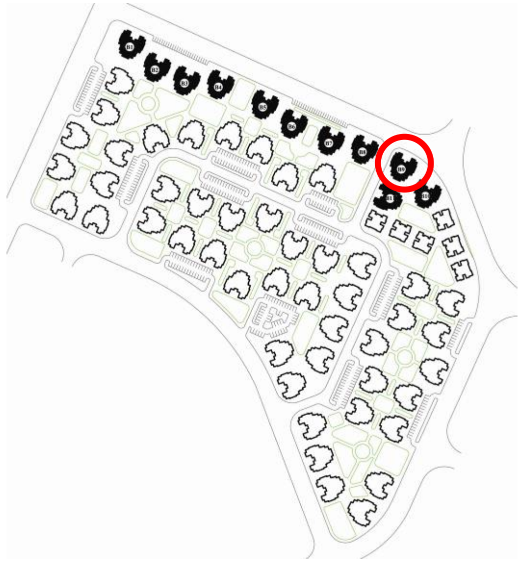


Figure 5-2: The 11 blocks already built with the accessible block indicated (Block 9)

Figure 5-3: Block 9 subject where the monitoring is conducted

The first monitoring stage was conducted vertically through monitoring three flats above each other and which have the same optimum wind orientation (*facing the wind direction*) (Figure 5-4). At this stage, three natural ventilation scenarios were applied within three flats set in the middle floors of the block. The top and ground floors of the block were excluded in order to avoid the heat gain from the roof in the top floor and the weak air movement near the ground in the ground floor. The three natural ventilation scenarios applied were (Figure 5-4):

- (S1) Ventilated 24 hours. All windows were opened for the flat in the third floor all the time,

- (S2) Unventilated 24 hours (infiltration only). All windows were closed for the flat in the first floor all the time, and
- (S3) Ventilated in night time only when the outside temperature had dropped down. All windows were opened during the night (21:00 to 6:00) and closed during the day (6:00 to 21:00). Windows were opened approximately an hour after sunset and closed approximately an hour before sunrise on the next day. This was applied for the flat in the second floor.

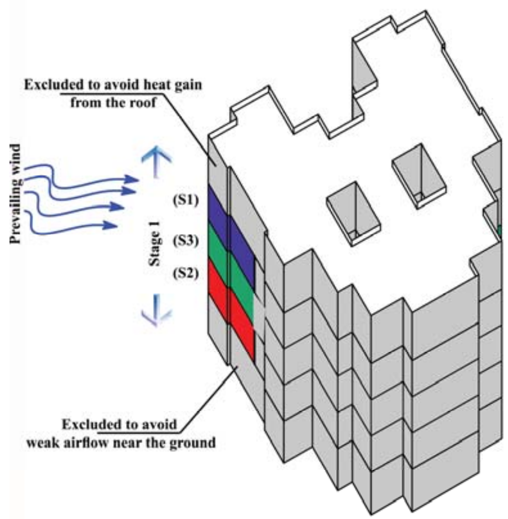


Figure 5-4: Stage 1 monitoring experiment design

The Second monitoring stage was conducted horizontally through monitoring all six flats in the second floor (Figure 5-5). In this stage, the recommended natural ventilation strategy, night purge ventilation (S3), was applied to all second floor flats.

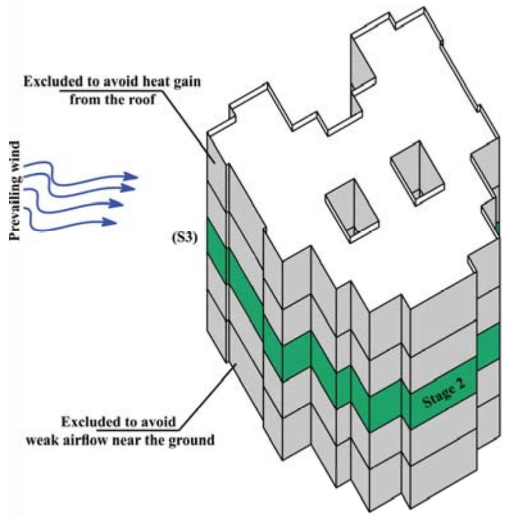


Figure 5-5: Stage 2 monitoring experiment design

The internal air temperature inside the flats was monitored, in both stages, over a period of five days; starting at 3.00 pm on Monday 20-07-09 and ending at 3.00 pm on Saturday 25-07-09.

It was important to choose a reliable data logging system that could be easily and quickly set up and installed. In addition, it has to accurately and reliably store the data for the duration of the investigation. Hobo U12 instrument (*Hobo U12 Temp/RH/2 Ext Channels Logger*) which records the internal air temperature and the relative humidity was used. Its dimensions are 48, 74, 22 mm and its memory size is 64 KB which can keep up to 43,000 measurements. It can measure a temperature range from -20^{o}C to 70^{o}C [201]. Due to the limited number of the data loggers available, It was decided to monitor only the living room in each flat also with all internal doors opened all the time during the experiment. All loggers were set up to take readings every hour starting at 15.00 on Monday 20-07-09 and ending at 15.00 on Saturday 25-07-09. The hobos were then installed in the living rooms; LR1/1, LR1/2, LR2/2, LR3/2, LR4/2, LR5/2, LR6/2, and LR1/3 (Figure 5-6). The researcher has been notified by the site engineer not to put any nails, screws or sticky tapes on the walls as this will cost them in repair before handing the block over to the local authorities. The only place that was found to be suitable for the installation was the light switch aluminium cover because it is not affected by sticky tapes. The hobos then were stuck to them using double face sticky tapes on the height of (*1.35 m*) from the floor level.

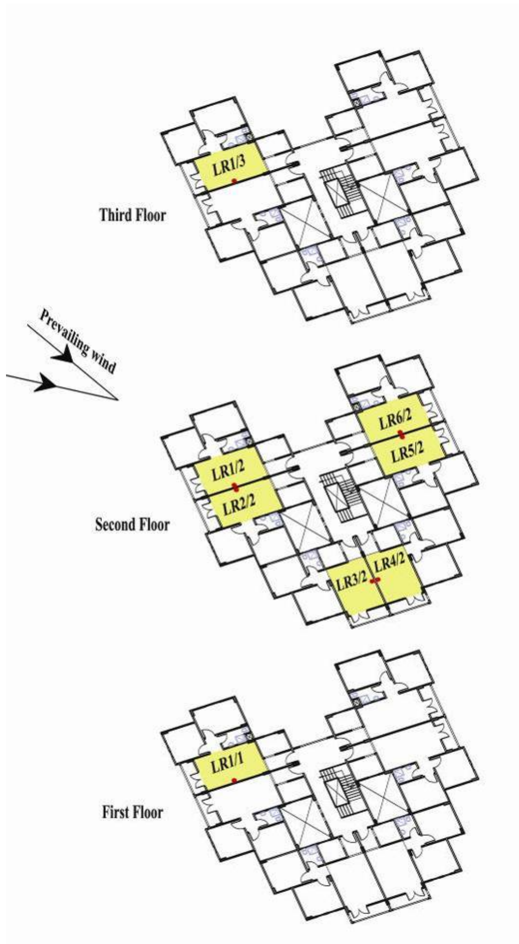


Figure 5-6: The living rooms where the hobos were installed

At the end of the monitoring period, all the monitored data were downloaded from the loggers and then analyzed. The relevant climatic data from the nearest weather station (*Al-Minya weather station*) were bought from the US National Climatic Data Centre (*NCDC*) [202]. The data provided by the (*NCDC*) contains readings that recorded at every third hour only. Also, the dry bulb temperatures were given in Fahrenheit at GMT time. Therefore, some work on the acquired raw climatic data was required in order to be ready for use in the monitoring data analysis. The dry bulb temperatures were converted into Celsius and the reading times then were converted into Egypt time (*GMT+2*). In addition, a regression analysis was conducted in order to determine suitable values for the missing points. The regression analysis was based on the expected statistical association between the observed temperature and the (*Sin*) function of the observation time. The equation of the best-fit line for each day was obtained through the coefficients of determination of association values of more than 0.9. The raw climatic data for the monitoring period along with the interpolation process can be found in (*Appendix B*).

The average monthly outside temperatures over the month of investigation (*July 2009*) from the raw climatic data (*30.86^o C*) were used to calculate the thermal comfort threshold temperature above which an overheating sensation is likely to occur using the thermal neutrality model adopted by ASHRAE according to Equation 4-1 (quoted from [203]).

$$Tc = 17.8 + 0.31*To \qquad \text{(Eq: 4-1)}$$

Where:
Tc = Comfort temperature
To = monthly average outside temperature

Many forms of this equation have been developed by Auliciems [204], Griffiths [205], Nicol and Roaf [206] since the adaptive model was firstly established by Humphreys [21]. These equations were widely studied by de Dear et al. (1997) [207] and he recommended the accuracy of the above equation (Eq: 4-1). In addition, this equation was adopted by well known ASHRAE standards. This encouraged the research to use it.

In the first stage, the monitored temperatures in the three ventilation scenarios (*S1, S2 and S3*) were compared to the interpolated climatic data along with the calculated comfort temperature (*27.37^o C*). In order to assess the effectiveness of each natural ventilation scenario in terms of achieving thermal comfort, The three sets of monitored data were statistically analysed in terms of descriptive statistics (*means and variations*) and the significance of differences around the calculated comfort temperature value. This analysis was conducted using the one-sample T-Test. Given the fact that the aim of this analysis is to test the difference between the sample *(namely the monitored data - the internal temperature*) and the known value of the population mean (*namely the calculated comfort temperature*), it should be indicated that the most appropriate statistical tool to be employed in this case is the one-sample T-test (*where a statistical decision as to whether or not the sample mean is different from the population mean could be made*) [208-211].

The hourly monitored internal air temperatures (*Ti*) inside each flat under ventilation scenarios S1, S2 and S3 were averaged over the monitored period in order to evaluate the cooling capabilities for each scenario. The cooling effect (C_e) due to the use of each ventilation scenario was then calculated using equation 4-2:

$$C_e = [\ (To - Ti\ ) / To\ ]\ x\ 100 \qquad \text{(Eq: 4-2)}$$

Where:
C_e = Cooling effect
To = average outside temperature over the monitoring period
Ti = average inside temperature over the monitoring period

In the second stage, The monitored temperatures in the six living rooms under night purge ventilation scenario (*LR1/2, LR2/2, LR3/2, LR4/2, LR5/2 and LR6/2*) were compared graphically and statistically to the calculated comfort temperature (27.37^o C). The following rules could be applied to asses the cooling efficiency of night purge ventilation.

1. Givoni's rule of thumb which states that the indoor maximum temperature could be less than the outside maximum temperature by nearly half the diurnal range in outdoor temperatures [19, 38];
2. Using Nicol's graph for the study's climatic context, where the potential of cooling capabilities of night ventilation for a specific month could be obtained [36];
3. Expecting a reduction of 2^o – 3^{o}C in the average indoor temperature when compared to another building that night ventilation strategy is not applied to [38];

4. The rule of Shaviv et. al which states that the reduction in the indoor maximum temperature, due to night ventilation, is a linear function in the diurnal temperature range and can be calculated using equations 2-10, 2-11 or 2-12 according to the ventilation rate provided [78]; and
5. Givoni's thermal mass rule which states that buildings with high thermal mass and exposed to reasonable night airflow, can achieve reductions in their mass' temperature of up to 3^{o}C closer to the outdoor minimum temperature.

Because of that no thermal mass temperature were measured from the site, this work actually only uses the first four indicators for evaluating the efficiency of night ventilation inside the monitored spaces. The way of using these four rules is explained below.

Firstly, the monitored temperatures inside the case study were tested against Givoni's rule of thumb. The outside temperature during the monitoring days were analysed in terms of average maximums, average minimums and average diurnal difference over the whole experiment's period (Table 5-1). The maximum monitored temperature in each monitored living room was then calculated. The difference between the maximum inside and maximum outside temperature was then compared to the average outside diurnal difference in order to investigate the reduction ratio in temperature in relation to the diurnal difference value.

Secondly, the Nicol's graph for *Al-Minya* weather station, using the most recent *TMY*[1] file, was created in order to extract the potential cooling capabilities of night ventilation during July (The month of monitoring) (Figure 5-7). From the graph, it can be seen that the use of

Table 5-1: Outside temperature analysis during the monitoring period

	Tmax	Tmin	Tdr (Diurnal difference)
Day 1	36.67	25.70	10.97
Day 2	37.84	26.53	11.32
Day 3	38.33	26.16	12.17
Day 4	38.21	25.50	12.71
Day 5	37.50	25.32	12.18
Averages	**37.71**	**25.84**	**11.87**

Note 1:
Stand for Typical Metrological Year

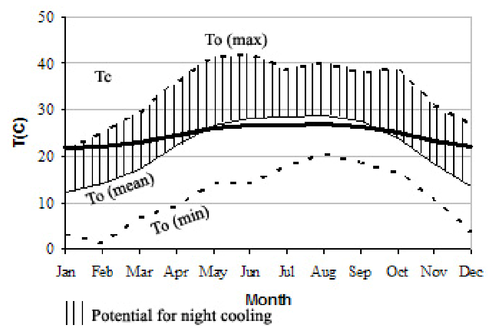


Figure 5-7: Nicol's graph for Al-Minya weather station with night ventilation cooling potential indicated

night ventilation could provide maximum internal temperature less than the outside maximum temperature by (10.30^o C) and keep it around (28.40^o C). The maximum inside temperature and the difference between the maximum inside and maximum outside temperature in each monitored space were then compared to these values from Nicol's graph.

Thirdly, The average indoor temperature in each monitored space under night ventilation was compared to the average temperature inside the *LR1/1* where no ventilation was used (*S2*). This was to investigate the truth of the third indication that expected a difference of 2^o – 3^{o}C between both cases.

Finally, Shaviv's equation (*Eq 2-10*) for calculating the drop in the indoor maximum temperature was used. This equation was chosen because it provides the case in which high night ventilation rates of 20 ach was used. All windows and doors of the monitored flats in this stage were opened during nights allowing cross-ventilation to occur and providing by this high ventilation rate. This is why the equation of the highest ventilation rate was used. The average diurnal difference over the period of monitoring was used in that equation as follows:

$$Td_{max} = 0.810 * T_{dr} - 1.627 = 0.810 * 11.87 - 1.627 = \mathbf{7.99^oC}$$

Where:
Td_{max} = The drop in the indoor maximum temperature
T_{dr} = outdoor diurnal range

According to this prediction equation, the night ventilation could possibly achieve an indoor maximum temperature less than the outdoor maximum temperature by (7.99^oC). This value was then compared to the difference between the maximum indoor and maximum outdoor temperature in each monitored space.

5.4. CFD methodology

This part of the objective assessment aims to evaluate the air movement patterns in and around the block. This is important as it allows best understanding to the airflow profile as well as helps in justifying some monitoring results. Three methods of evaluating airflow patterns and speed where considered; monitoring [47, 80], wind tunnel [48, 212-215] or computational fluid dynamics (*CFD*) [215-218]. Using the monitoring method could be performed using techniques such as tracer gas for measuring the rate and data loggers. Both monitoring techniques require very expensive equipments which are not available to the researcher. Apart from that and for security reasons the equipments could not be left unattended in the case study site. As for wind tunnel, it requires physical modelling of the case study. In it, the airflow in and around the case study could be tested visually and quantitatively. The wind tunnel facility is not available in the school and building it costs too much. Therefore, it was decided to conduct this study using one of the computational fluid dynamics (*CFD*) software, owing to the unavailability of either the required equipments to monitor the airflow patterns in and around the case study, or the wind tunnel facility. It is known that the simulation research methods can be effectively used where the experimental work in the real world cannot be performed due to unacceptable ethical, economical or dangerous restrictions [198].

In simple terms, Computational Fluid Dynamics (*CFD*) technique uses a complex mathematical model that is represented and solved by a computer programme. The results are graphically presented, usually on a 3D model. They are computer based tools that can predict the following variables [80, 213, 215]:

- Internal and external air movement patterns and air flow path;
- Building behaviour in ventilation studies;
- Temperature distribution inside spaces;
- Stack and wind pressure inside and outside the buildings and their interaction; and
- Heat transfer within the building.

Several *CFD* softwares were considered; *IES*[1], *TAS*[2], *Fluent*[3], *FDS*[4], *Flair*[5] *and FloVent*[6]. Regardless of the interface, all softwares use two mathematical fundamentals which are [14]:

- Solving physical equations such as; the Navier-Stoke equation, the energy equation, the mass conservation equations, concentration equations, and the transport equations (for turbulence and its scale); and
- Turbulence's model type that controls the results' accuracy.

These equations can be solved using two methods: Finite volume method (*FVM*) or finite element method (*FEM*). Most of the CFD available tend to use the FVM method and to use the standard kinetic energy turbulence model (*K-E*) [14]. These methods of solution are working within grid cells that are constructed in and around the physical form of the simulated domain. Two different types of solution grids are being used by the *CFD* software available; structured grid and unstructured grid as shown in Figure 5-8 [219]. The structured grid is also known as an orthogonal or Cartesian grid and is based on the fact that each cell has the same adjacent cells. These grids are normally constructed in hexahedral or quadrilateral shapes and are defined along the Cartesian X, Y and Z axes [219]. The unstructured grid is built from a

Note 1:
Integrated Environmental Solutions software. This is whole environment simulation software with an integrated *CFD* tool.
http://www.iesve.com/UK-Europe/

Note 2:
The complete dynamic building simulation package. http://edsl.net/main/Software.aspx

Note 3:
CFD software for simulating fluid flow, heat and mass transfer, and a host of related phenomena involving turbulence, reactions, and multiphase flow. http://www.fluent.co.uk/

Note 4:
Fire Dynamics Simulator (*FDS*) is a computational fluid dynamics (*CFD*) model of fire-driven fluid flow. http://fire.nist.gov/fds/

Note 5:
Flair from Phonics is a tool which simulates processes involving fluid flow, heat or mass transfer, chemical reaction and combustion in engineering equipment and the environment. http://www.cham.co.uk/products.php

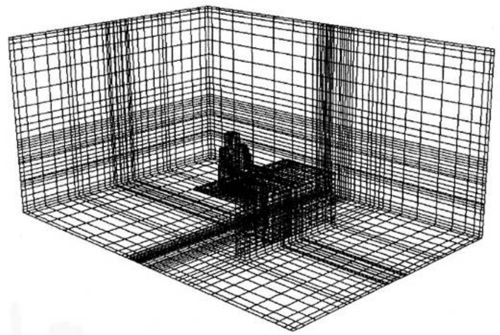
Note 6:
FloVent is Computational Fluid Dynamics software that predicts 3D airflow, heat transfer, contamination distribution and comfort indices in and around buildings of all types and sizes.
http://www.mentor.com/products/mechanical/products/flovent

number of geometrical primitives such as triangles and tetrahedra. Although such grids are flexible in following any complicated shape , they have restricted user control and should be pre-processed before they are used [219].

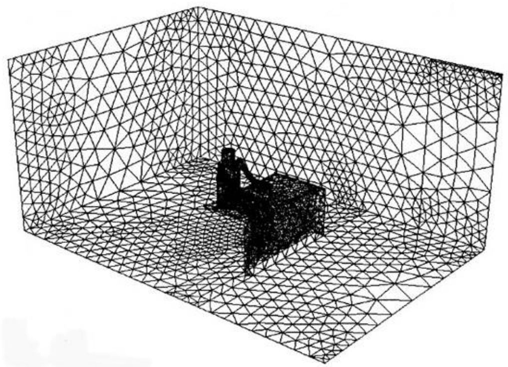
Since this work is concerned with studying the wind driven airflow in and around the buildings and estimating the internal airspeed for thermal comfort evaluation, it was necessary to select CFD software that can meet certain criteria and capabilities. These capabilities can be summarized as follows:

- Allow a replica of the selected slice of the real world to be modelled as accurately as possible including the real boundary layer conditions with wind profile and airflow turbulence;
- The physical configurations of the simulated environment could be constructed easily;
- Has an architectural-user friendly interface which is easy to edit and navigate around a facility;
- It should have an efficient and clear way of introducing results that can allow the user to manipulate and communicate with such results easily and effectively;
- It should have well designed help and support menus and the after-sale support should be promptly responsive for facilitating modelling problems' solutions; and
- The software should be economical and its licence cost should be within the available fund for the study.

FloVent was found to fulfil the above outlined criteria for choosing the simulation tool.



(a) Structured *CFD* grid



(b) Unstructured *CFD* grid

Figure 5-8: Different types of CFD solutions' grid, after Den-Hartog [219]

FloVent uses the computational fluid dynamics (*CFD*) technique, in which the calculations of the airflow and heat transfer rely on the conservation laws that are implemented in a partial differential form within Navier - Stokes equations. These equations are converted in volume form to be solved by the finite volume method (*FVM*). Because of the volume form required for calculations, the simulated slice of the real world is modelled in the volumetric space form called "*The solution domain"*. This solution domain is then split up into a number of Cartesian structured small volumes called (*The grid cells*). The greater number of grid cells presented in the model, the better resolution of the results could be obtained. However, this could increase the solution time. Because of their coupled and non-linear nature, the conservation equations within FloVent are solved in an iterative manner, as in other softwares, until the errors within them are at an acceptable level and a steady state solution is converged [220]. The simulation process within the *FloVent* is user-dependent and starts from defining the requirements, setting up the mathematical modelling parameters, constructing the geometry, adding a solution grid, solving the domain and ends with displaying the results [220]. These steps could be performed through the multi-window environment that *FloVent V8.2* uses. This multi-window environment of the software can present different views of the project data and provides an interlink to other software packages [221]. The multi-window environment of the *FloVent* consists of six different windows These windows are (Figure 5-9) [221]:

- The Project Manager window (*PM*): In it the user can create new projects, or load existing ones. It displays the loaded project data in a tree hierarchy starting with the (*Root Assembly*) at the start of the geometry tree, to which the objects are added parametrically to create the flow model;

- The Drawing Board window (*DB*): In it the geometry can be created graphically by dragging the boundaries across a 2D work plane. It displays four (2D and 3D) wire-frame views of the model's elements displayed in the Project Manager tree;
- The solver window (profiles window): It displays a convergence plot showing the numerical errors in the calculated flow as the solution proceeds. This is in the form of a plot of residual error against iteration number for steady solutions;

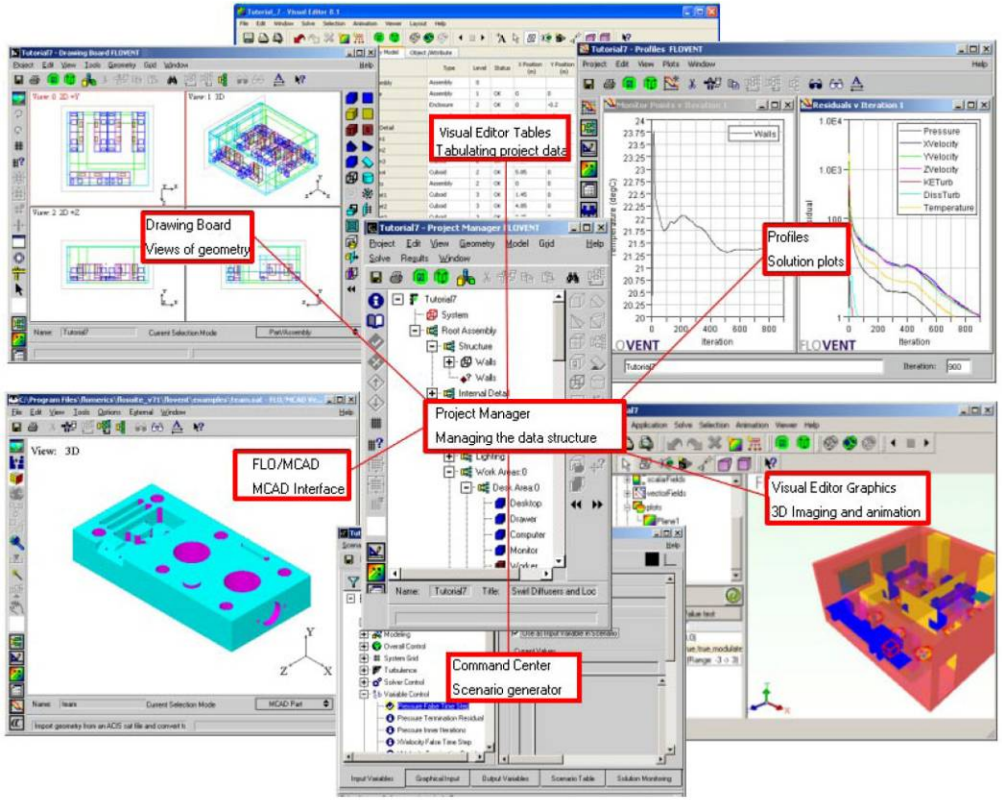


Figure 5-9: The multi-window environment of the FloVent, after Mentor Graphics[221]

- The visual editor window: It has two modes; the visual mode and the tabulation mode. In the visual mode, the results can be visualized in a 3D real-world view with huge flexibility in the view adjustment. In the tabulation mode, the details of different types of project data can be listed out in tables;
- The *FloMCAD* bridge window: In it, the geometry of the model can be loaded from either the current *FloVent* project or an external MCAD file; and
- The Command Centre window (*CC*): It can be used to conduct a parametric analysis through applying different scenarios with variable parameters for a *FloVent* project.

The reliability of the *FloVent* in simulating the airflow and estimating the air velocity was proven [222]. A validity study was conducted not only to check the reliability of the software, but also to validate the process of model representation within the software.

5.4.1. Validating the CFD modelling:

The complete and comprehensive validation for the model is generally not possible. No model can have an absolute validity [223]. It should be valid for the purpose for which it is constructed [224]. Since this work focuses on the airflow pattern and airspeed, validating the accuracy and reliability of the *FloVent* was focused on those two variables.

The validation was carried out in two steps using the technique of comparison to other models. In this technique, the outputs of the simulation model are compared to those of already proven valid models' outputs [224]. The first step was the validation of airflow patterns and the second step was the validation of airspeed.

Givoni conducted several experiments on ventilation performance inside a room model inside a wind tunnel. Those experiments aimed to quantify the effect of different natural ventilation design features [65] such as; window positions [225], window numbers [225], wing walls [174, 226] and internal sub-divisions [174]. The measured variables in all those experiments were the mean internal airspeed as a percentage of the outside wind speed and the airflow patterns.

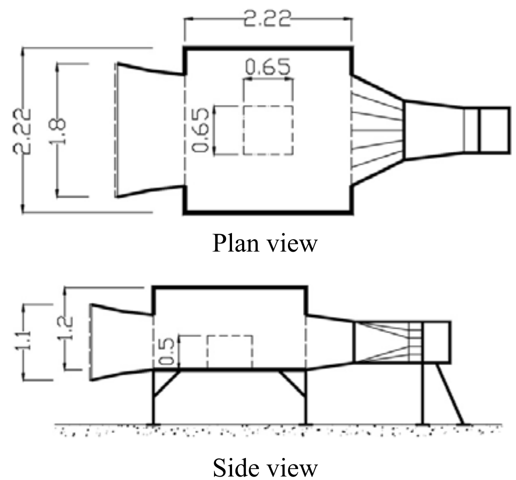


Figure 5-10: Givoni's open-throat type wind tunnel with the room model located in its centre , after Mak, et al [175]

Two experiments out of Givoni's were selected and were modelled in *FloVent*. Givoni's results from the experiment of testing the airflow pattern within a room model with different internal sub-division configurations were used in the first step of validation in order to validate the airflow patterns that result from the *FloVent*. Also, Givoni's experiment of testing the effect of different configurations of the wing wall feature was used in the second step of validation in order to validate the internal airspeed. The later one was also simulated by Mak, *et. al* [175] using the *Fluent* software. This was found to be a good opportunity for comparing the FloVent results with both wind tunnel results from Givoni and Fluent's results from Mak *et. al*.

Both the selected Givoni's experiments were conducted on a physical model with the dimensions of 0.65 m length, 0.65 m width, and 0.50 m height. The model was tested in an open-throat type wind tunnel that has a working section's dimensions of 2.22 m length, 2.22 m width, and 1.20 m height as shown in Figure 5-10. In Givoni's first experiment that is being used in this work to validate the airflow pattern, he tested the airflow pattern within the room model with different sub-division configurations in the case of cross ventilation. This was provided through two windows in opposite walls. Each window had an area of 1/9 of the wall area that contains it with dimensions of 1/3 wall's dimension in each direction. Eight different cases with different combinations between the internal sub-division and windows' positions were tested. The models of these eight cases were constructed in 3D within the *FloVent.* The solution domain was constructed to match the wind tunnel's working section dimensions and the room model was allocated to its centre (Figure 5-11). The following ambient boundary conditions were attached to the *FloVent* models:

- Fine 3D solution grid type with total number of uniform grid cells of 64000;
- Steady state solution type;
- K-Epsilon turbulence model;
- Wind speed of 2.00 m/s was provided normal to windows from (Z) direction; and
- The default air properties that set by *FloVent.*

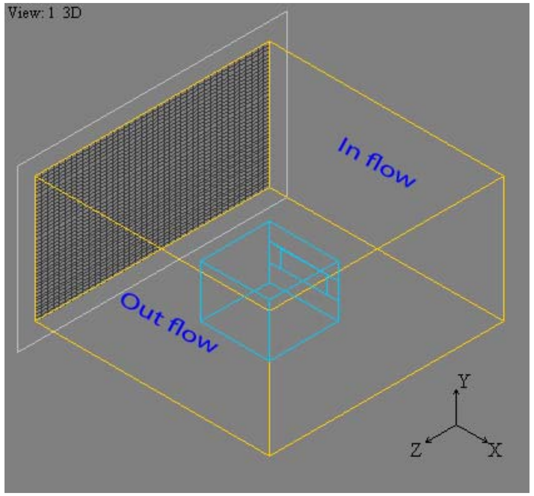


Figure 5-11: The physical model for computer simulation

The visual results of airflow pattern within the room's model in each case were then compared to their counterpart from Givoni's experiment as shown in Figure 5-12. Generally, it can be clearly seen from the figure that the airflow patterns' trend result from *FloVent* in all cases were almost similar to Givoni's results though there are some slight discrepancies. These discrepancies might be presented due to the limitation in *CFD* code, solution grid construction and turbulence model used. However, the results introduce clear evidence of the reliability of *FloVent's CFD* code in predicting the airflow pattern and the correct representation of the model.

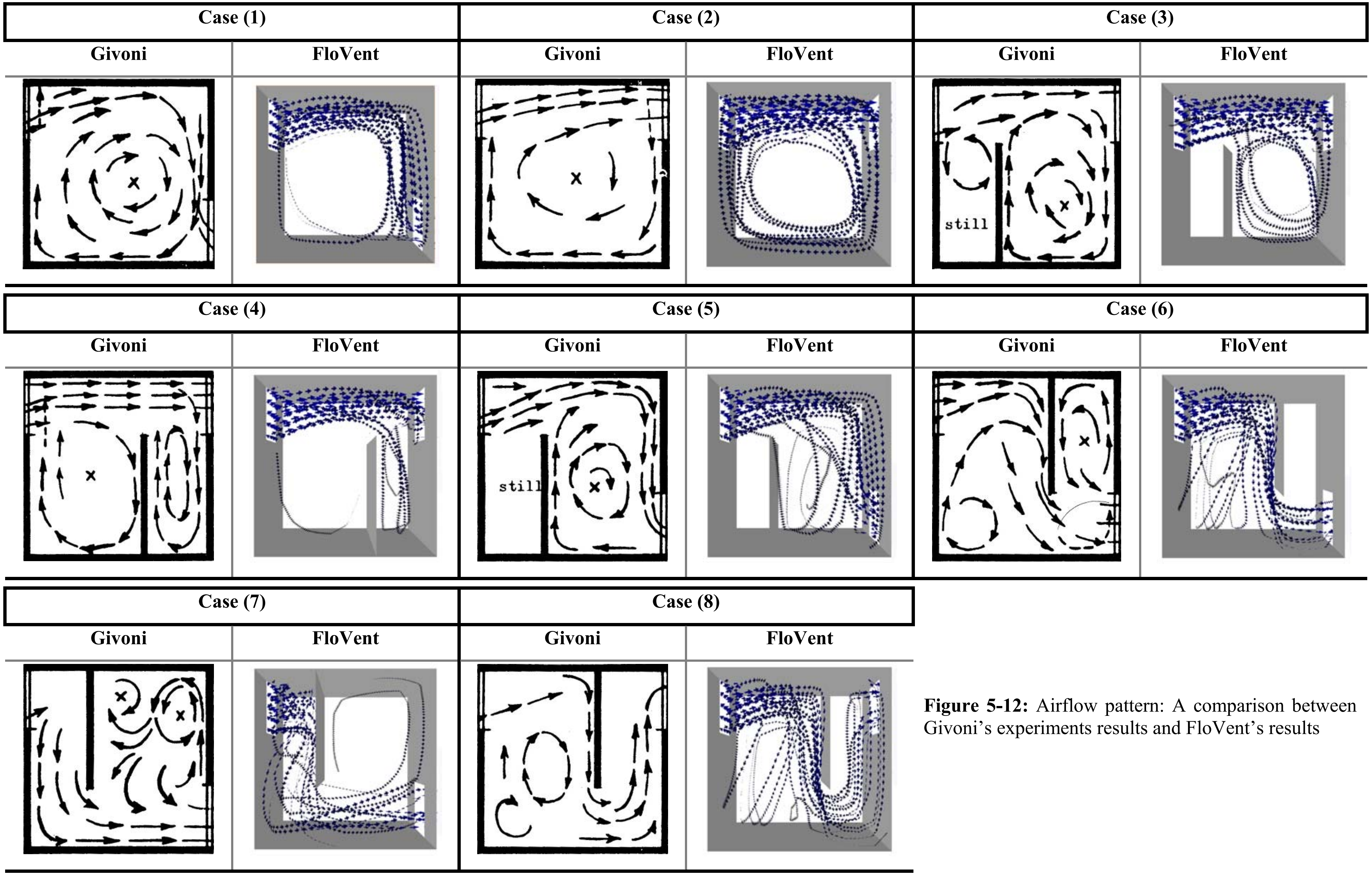


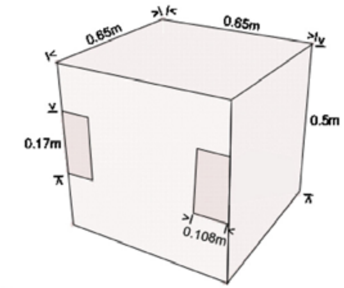
Figure 5-12: Airflow pattern: A comparison between Givoni's experiments results and FloVent's results

In Givoni's second experiment that is being used in this work to validate the airspeed, he tested the mean airspeed within the room model with different wing wall configurations in the case of single side ventilation which was provided through two lateral windows in the same wall. Three cases were investigated in this experiment as follows (Figure 5-13) [175]:

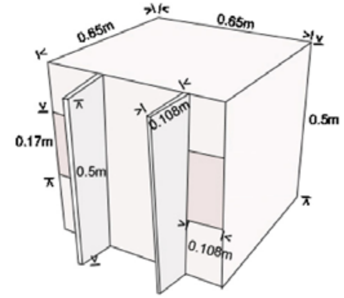
- ***Case (1):*** Two lateral windows, with total dimensions 1/3 of wall and with no wing walls;
- ***Case (2):*** Two lateral windows, with total dimensions 1/3 of wall and with installed wing walls of depth equal to the window's width; and
- ***Case (3):*** Two lateral windows, with total dimensions 1/3 of wall and with installed wing walls of depth double the window's width.

In the wind tunnel experiment, the three cases were tested with different uniform airspeeds (*1.27, 1.68, 1.83, 2.00, 2.95, and 3.35 m/s*). Different wind directions were applied with those speeds that ranged between (0^o *to* 135^o) with 22.5^o increment (Figure 5-14). The average internal airspeed was then obtained by taking the average of all values at different input airspeeds for each orientation and expressed in percentage from the input airspeed. The derived measurements were based on five monitoring points inside the room model [175].

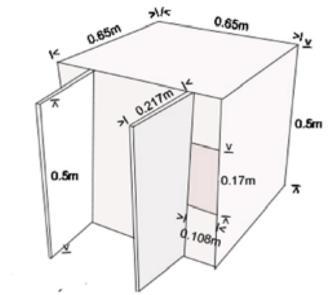
The same experiment was simulated by Mak et al[175] using *Fluent* version 6.0. The standard *K-E* turbulence model along with structured 3D triangular uniform grid's cells of around 60000 to 68000 cells, were attached to the *Fluent's* model. Mak based the calculations of the average internal airspeed on all the grid points' values inside the room's model rather than using only five monitoring points as Givoni did [175]. In this work, the same experiment was



a) Case (1)



b) Case (2)



c) Case (3)

Figure 5-13: Different wing wall configurations' cases tested in Givoni's experiment, after Mak et al [175] simulated using *FloVent* version 8.2. The K-Epsilon turbulence model along with structured 3D quadrilateral shape uniform Cartesian grid's cells of around 64000 to 86400 cells, were attached to the FloVent's model. The calculations of the average internal airspeed percentage were based on all the grid points' values inside the room model as Mak et al did. The results of FloVent were compared to those of Givoni's wind tunnel experiment and Mak's 3D Fluent simulation. Figure 5-15, Figure 5-16 and Figure 5-17 show the comparison of the three sets of results in the three tested cases.

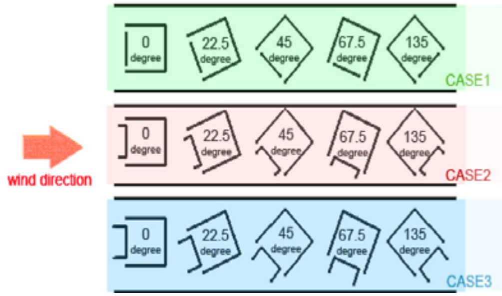


Figure 5-14: Different orientations tested in Givoni's and Mak's experiments, after Mak et al [175]

From these figures, it can be clearly seen that *FloVent* had presented almost the same trend as Givoni's and Mak's results. Discrepancies between wind tunnel results and *FloVent* results were justified by the mathematical limitation in *CFD* code and its difference in contrast to wind tunnel. In addition, the different airflow pattern simulated in both cases, as *FloVent* uses turbulence model in order to simulate the turbulent nature of the real airflow, while the airflow produced in wind tunnels is almost uniform laminar airflow. Although *Fluent* and *FloVent* use the same solution method (*Finite Volume Method*), slight discrepancies were observed. These discrepancies might be due to the different solution grid's topology that was used in both programs.

In general, the results of simulating both experiments in *FloVent* prove its great reliability in predicting both; the airflow pattern and the indoor airspeed (*the two variables that will be studied in the current work*). According to this, the commitment of using FloVent in this work can be argued. The *FloVent* model, results and analysis of this experiments are in (*Appendix C*)

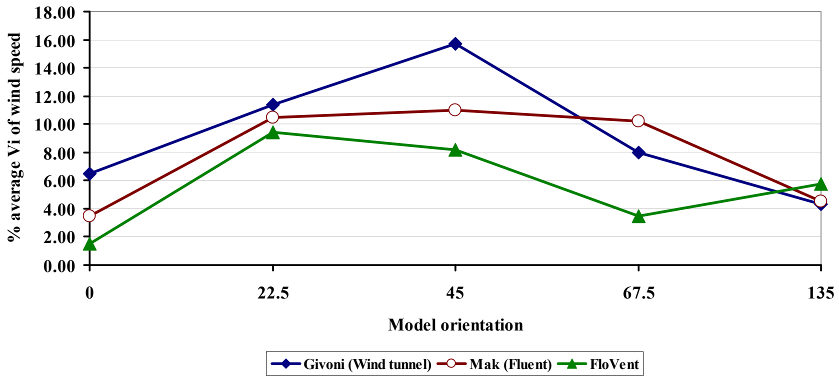


Figure 5-15: Percentage of average internal airspeed (Vi) to wind speed against different incident angle (Case 1 comparison between Givoni's (wind tunnel) , Mak's (Fluent) and FloVent's results

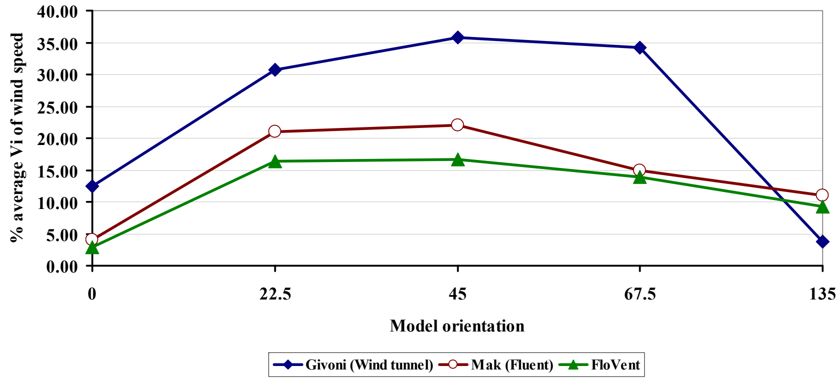


Figure 5-16: Percentage of average internal airspeed (Vi) to wind speed against different incident angle (Case 2 comparison between Givoni's (wind tunnel) , Mak's (Fluent) and FloVent's results

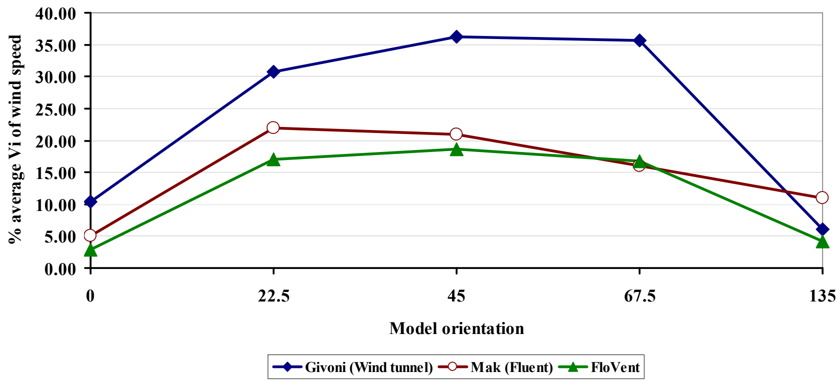


Figure 5-17: Percentage of average internal airspeed (Vi) to wind speed against different incident angle (Case 3 comparison between Givoni's (wind tunnel) , Mak's (Fluent) and FloVent's results

5.4.2. Building the case study model:

A model for the whole compound was constructed. All blocks in the site were modelled as solid blocks except the monitored block, which was modelled in details. The detailed block was modelled in three parts. In the first part, the second floor of the block was completely modelled in details with all internal doors opened (*cross ventilation allowed*). The other two parts are the floors under the detailed part and the floors above it. They were modelled as solid parts without details forming by such the lower part of the block's model and the upper part of it (Figure 5-18).

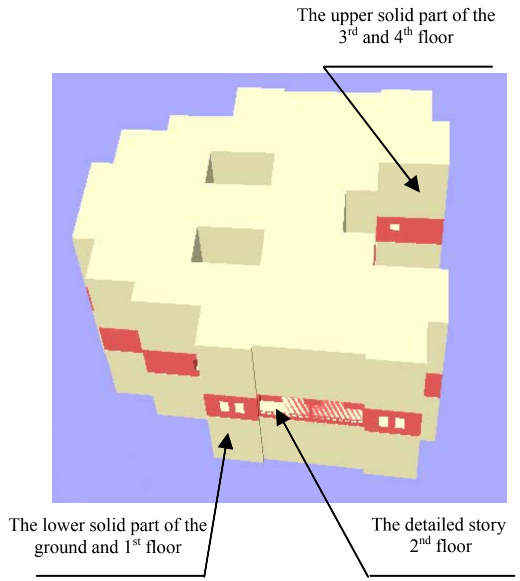


Figure 5-18: The monitored block's detailed model and its topology

FloVent uses basic building blocks that represent the lowest level building blocks called (Primitives). These primitives have mainly two fundamental shapes; the cuboids and prism by which any geometry in *FloVent* can be constructed. The solid cuboids and prisms are then assembled together in one assembly in order to form the final geometry shape [220].

The solid blocks of the case study's site are divided into cuboids and prisms in order to create the 3D geometry of each solid block assembly as seen in Figure 5-19. From the site drawings that were provided by the local council in *New Al-Minya* city, the coordinates (*X,Y,Z*) of each block were calculated in order to locate the blocks in the solution domain. The root assembly that contains all the blocks in the site was found to have dimensions of (*X=450m, Z=372m, and Y=18m*).

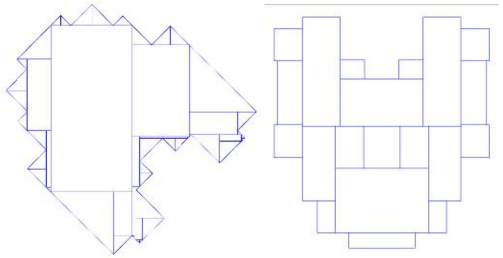


Figure 5-19: Splitting the geometry of the solid blocks into cuboids and prisms (Plan view)

In *FloVent*, the slide of the real world that is proposed to be simulated has to be defined as a cuboid, which contains all the geometry of the model and its boundaries. This cuboid is called an overall solution domain [220]. An overall solution with size of (*X=600m, Z=500m, and Y=40m*) was constructed and the site's root assembly was located in its centre (Figure 5-20).

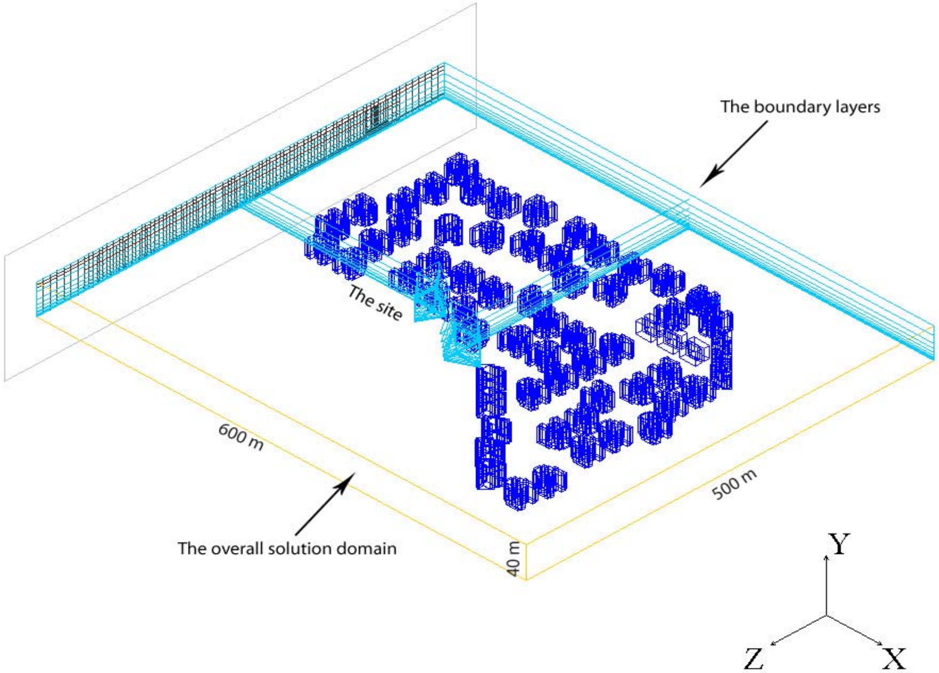


Figure 5-20: The FloVent case study model including the overall solution domain, the site's root assembly, and the boundary layer

The final step in building the *CFD* model is to define the solution grid within which the *FloVent* performs its calculations. FloVent offers the ability to specify a different grid's configurations (*more dense*) over a specific object or assembly within the model. This feature is called a localized grid [220]. Also, FloVent in conjunction with the PC system used to operate has a maximum allowed grid cells' number. For example, when solving for 5 variables on a 32bit operating system with 2GB of memory (*The same system as the one used in this work*), the maximum model size should be in the region of 5million grid cells [220]. However, 3 million cells are large enough to greatly increase the time required to reach a steady state solution [220]. In order to reduce the time required for the solution to be converged, reduce the complexity of the calculations, and insure the accuracy of results over specific parts of the model, three different grid levels were used. These three levels are; the base grid, the site assembly grid, and the detailed floor grid (Figure 5-21). The details of each level are described in Table 5-2.

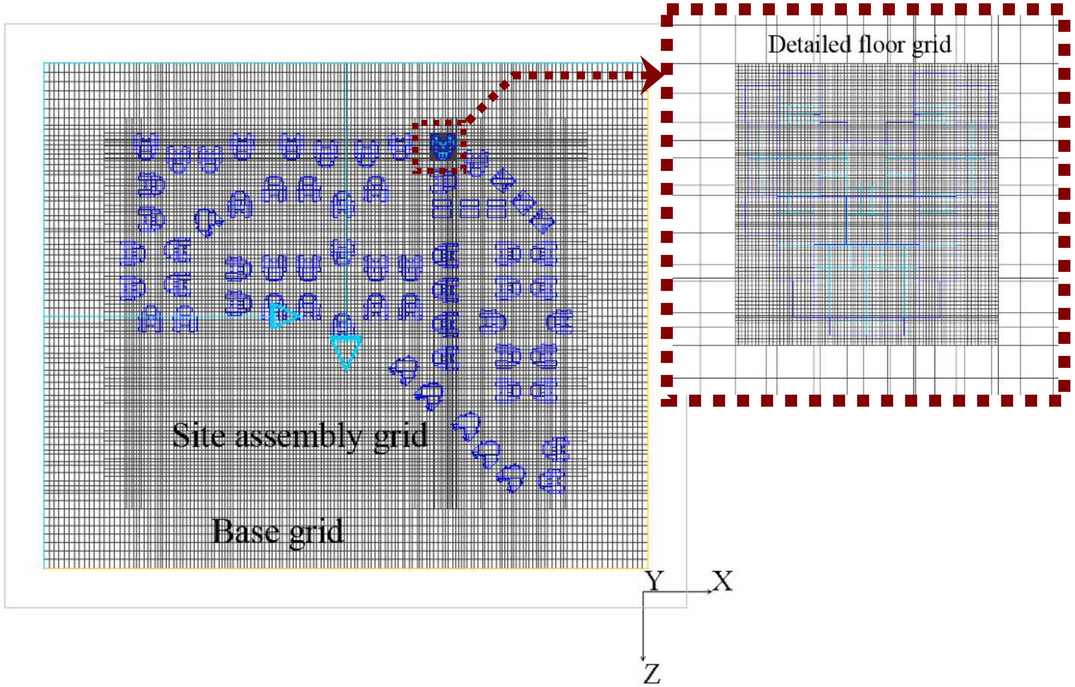


Figure 5-21: The FloVent case study model's grid and its levels (Plan view)

Table 5-2: The solution grid levels and their configurations

	Base grid	**Site's assembly grid**	**Detailed floor grid**
User specified configurations			
Max grid size specified	5.00 m	2.00 m	0.30 m
Min grid size specified	2.00 m	Not specified	0.20 m
Inflation outside the assembly	No inflation	Inflation of 15.00 m outside the assembly with max cell size of 2.00 m	Inflation of 1.00 m outside the assembly with max cell size of 0.30 m
Program created grid configurations after smoothing the grid			
Number of cells in (*X*) direction	162	153	83
Number of cells in (*Y*) direction	8	8	16
Number of cells in (*Z*) direction	80	100	92
Total number of cells	103680	122400	122176
Smallest cell size in (*X*) direction	0.212 m	0.212 m	0.212 m
Smallest cell size in (*Y*) direction	0.225 m	0.225 m	0.225 m
Smallest cell size in (*Z*) direction	0.207 m	0.207 m	0.207 m
Maximum aspect ration *Z/X*	38.051	38.051	1.887
Maximum aspect ration *Y/X*	38.440	38.440	1.887
Maximum aspect ration *X/Z*	14.706	14.706	1.928
Maximum aspect ration *X/Y*	2.778	2.778	1.778
Maximum aspect ration *Z/Y*	4.650	4.650	1.778
Maximum aspect ration *Y/Z*	24.870	24.870	1.928

FloVent automatically adjusts the grid lines to be aligned with the objects' edges and seeks to achieve the user-specified configurations for the grid as much as it can. It starts from the smallest localized grid's level so running through to the base system grid's level. By using the smoothing option of the grid, *FloVent* starts to add more grid lines around the localized grid and into the base grid. This action helps to reduce the difference in the aspect ratio between the lower and upper level of grids. As seen from Table 5-2, the maximum and minimum grid sizes were specified by the user for the detailed floor grid level (*the smallest level*) to insure enough accuracy for calculations within this area. In the site level, the maximum size of the grid was specified however the minimum size was left to be created by the program. Both the localized grids in both levels; the site assembly grid and the detailed floor grid, were allowed to inflate outside the borders of each assembly. This was to insure good accuracy for the calculations in the immediate adjacent areas of both assemblies. These configurations achieved a total accumulative number of grid cells across the model of (*292390 cell*).

5.4.3. The model's boundary conditions

After building the case study's model, the boundary conditions of the model had to be specified. The boundary conditions include the solution domain configurations, the ambient conditions, the system's fluid properties, the turbulence model, the solution type, and the wind boundary layers (*wind profile*).

The solution domain sides were specified to be opened, i.e. the airflow is allowed to flow through them. The following ambient conditions were attached to the solution domain:

- The gravity in the normal value of (*9.81 m/s*^{2}) and the normal direction (*-Y*);
- Ambient temperature of 28.53^o C (The average temperature over the summer period that obtained from the *TMY* file of the *New Al-Minya city*);
- The default system's fluid (Air with density of 1.19 kg/m^3); and
- The K-Epsilon turbulence model.

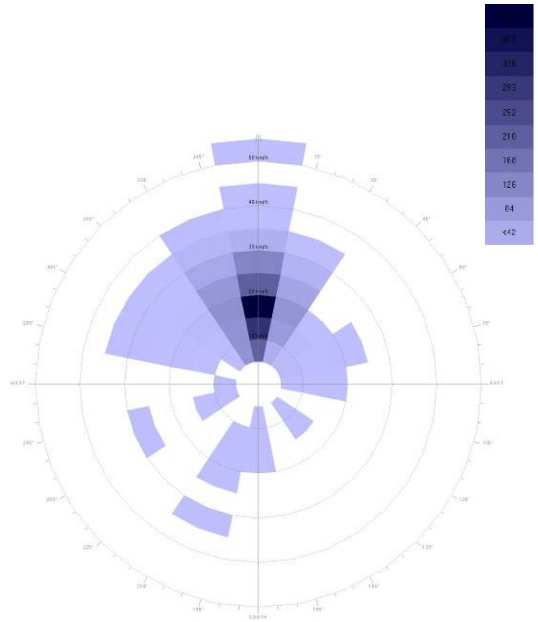


Figure 5-22: The frequency of Al-Minya wind over the summer period plotted on the wind rose

Because this work is investigating the wind driven natural ventilation only, the solution type was set to calculate the flow only rather than calculating the flow and heat transfer. In addition, the steady state solution approach had been selected to be conducted in the three dimensions multi-grid domain option.

The wind analysis using weather tool software along with Al-Minya *TMY* weather file was conducted in order to extract the most frequent wind speed and direction during the summer period to be attached to the model. The analysis showed that the most frequent wind speed over the summer is (20 km/h = 5.6 m/s) and blows from the north direction (Figure 5-22).

As for creating the wind boundary layers (*wind profile- see section 2.4.1*), *FloVent's* web based program called "*FloVent boundary layer generator*" was used. After providing some information, the program creates a *PDML* file containing the wanted boundary layer modelled as a series of fixed flows at the domain boundary (Figure 5-20). This file could be imported to the model as an assembly to impose the effect of the natural boundary layer. This is conditioned on using the K-E turbulence model along with a gravity direction of –Y or –Z. To create the file for the case study's model, the following inputs were fed in the program:

- The dimensions of the solution domain (X=600, Y=40, Z=500);
- Flow angle = 156^{o} (The north direction in regard to the model);
- Number of fixed flows = 10 (*the program's default*);
- The fixed flow size was set to be increased with height;
- Geometric progression index = 1.4 (*the program's default*);
- Reference height = 10 m (*The height at which the observations collected at the weather station*);
- The wind speed at reference height (*observed in weather station*) = 5.6 m/s
- Log layer constant = Sub-Urban at which zo = 0.1 m); and
- Gravity direction = -Y.

The wind boundary layer file was then attached to the model. The solving process was then operated using the configurations stated above. A long period of time (more than 6 hours) with difficulties in a steady state solution conversion was experienced in the model's solution. The relationship between the residual versus iterations for all variables was found to be suffering from low level oscillation profile. By referring to the part of controlling the solution in the FloVent user manual, a recommended value of the linear relaxation between 0.5 and 0.9 was advised to be applied in such case in order to dampen the extreme values [220]. The default value of the program was found to be 1.0 (*no dampening applied*). The relaxation actually works by multiplying the user defined factor (linear relaxation) to each solved variable at each iteration as in the following equation:

$$Ø = Ø^{/} + \alpha\,(Ø - Ø^{/}) \qquad \text{(Eq: 4-3)}$$

Where:
Ø = the value at the current iteration
$Ø^{/}$ = the value at the previous iteration
α = the linear relaxation factor

A sensitivity test to the linear relaxation value was conducted in order to get a steady state solution convergence within a reasonable time. The test started with 0.5 to 0.8 with an increase of 0.05 each run. The results revealed that at value of 0.5 a speed convergence was obtained. The calculations' time was increasing with the increase in the value of the linear relaxation. At linear relaxation of 0.8, no convergence was obtained. The maximum value, at which the steady state solution was converged, was 0.75. Therefore, the linear relaxation was fixed at this value for the final run.

At the final run, the steady state solution was converged in 35 minute and 52 seconds with 873 iterations. The qualitative and quantitative results of the airflow patterns and airspeed in and around the case study were then extracted and analyzed as follows:

- The airflow quality and distribution over the site were analyzed in several heights; the person's height (1.75 m above the ground level) and at the mid windows' heights in each storey (4.65 m , 7.65 m , 10.65 m , and 13.65m);
- The airflow quality, sources, paths, and distribution inside the detailed floor were analyzed; and
- The airspeed was volumetrically averaged within the main living spaces (living rooms and bedrooms) in each flat in the detailed floor and expressed as percentage from the prevailing wind speed observed at the weather station (5.6 m/s).

5.5. Results and discussion

The results of applying the objective assessment of natural ventilation, which were explained earlier in this chapter, are discussed. Two main study results are interpreted in this section; the monitoring result and the air movement CFD simulation result. The monitoring results are discussed in terms of the two stages explained in the methodology; stage one (*thermal performance of the case study under different natural ventilation scenarios*) and stage two (*thermal performance of different flats under the night purge ventilation scenario*). The full set of the monitoring data in both stages and its analysis could be found in (*Appendix D*).

5.5.1. Monitoring results

In stage 1, the monitoring results of the temperature under the application of different natural ventilation scenarios (*S1, S2 and S3*) show that the thermal performance of the monitored spaces significantly varies between ventilation scenarios. Figure 5-23 and Table 5-3 Illustrate the monitoring results of stage one and their statistical analysis respectively.

It can be clearly seen from the graph (Figure 5-23) that in the first scenario (*S1 = ventilated 24 hours*) the internal temperature tends to follow the profile of the outside temperature. This behaviour is readily expected as opening the windows all the time minimizes the effect of the building's thermal mass and provides immediate heat exchange between the outside and inside air. The average temperature over the period of the experiment in (*S1*) was found to be (31.26^{o} *C*) with the highest variation around the mean between all scenarios (*Std. deviation = 2.9*) (Table 5-3).

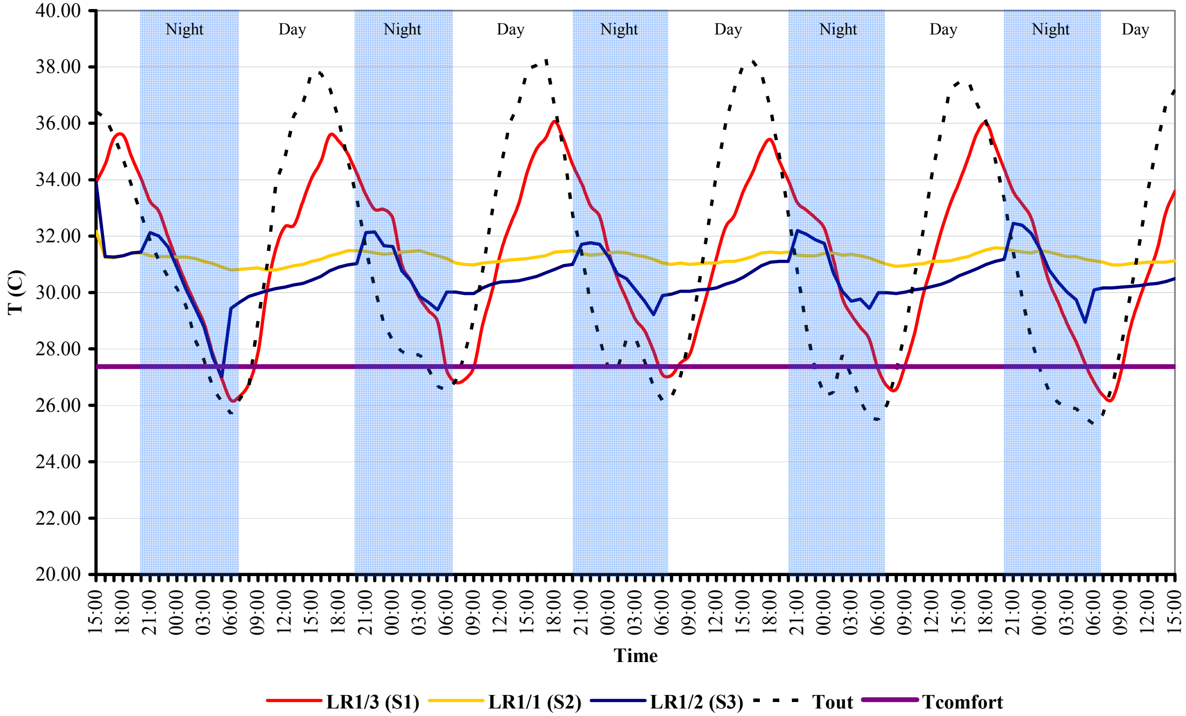


Figure 5-23: The monitored air temperature inside spaces; LR1/3, LR1/1 and LR1/2 under the application of ventilation scenarios; S1(24 hours ventilated), S2 (24 hours unventilated) and S3 (ventilated at night only) respectively

Table 5-3: The statistical analysis' results of the monitored data in the stage one of the monitoring process

Sample	One – Sample T-Test (Test value = 27.37 [Tc])			
	Mean	Std. Deviation	Sig.	Mean difference
S1 (24 hours ventilated)	31.26	2.9	P < 0.05	3.89
S2 (24 hours unventilated)	31.22	0.21	P < 0.05	3.85
S3 (Ventilated at night only)	30.55	0.92	P < 0.05	3.18

By comparing the inside temperature in (*S1*) to the calculated comfort temperature, it was found that the internal temperature dropped below the comfort temperature only in a few hours in the late night/early morning time (Figure 5-23). The statistical analysis of the *S1* data, using one sample T-Test, showed that the data set of the monitored internal temperatures in that scenario is significantly different from the comfort temperature ($P<0.05$) with a positive difference of (3.89^o *C*) (Table 5-3).

The case in the second scenario (*S2 = Infiltration only - unventilated 24 hours*) was found to be completely different than (*S1*). The internal temperature tends to be stable with average temperature over the period of the experiment of (31.22^o *C*) and the lowest variation around the mean between all scenarios (*Std. deviation = 0.21*) (Table 5-3). Without the existence of any kind of heat source inside the monitored flat, this behaviour gave an indication of the tight opening design of the flat which could keep stabilize internal temperature.

By comparing the inside temperature in (*S2*) to the calculated comfort temperature, It was found that the internal temperature was constantly higher than the comfort temperature (Figure 5-23). The statistical analysis of the *S2* data, using one sample T-Test, showed that the data set of the monitored internal temperatures in that scenario was also significantly different from the comfort temperature ($P <0.05$) with positive difference of (3.85^o *C*) (Table 5-3).

In the third scenario (*S3*), the internal temperature was found to be always lower than the internal temperature in (*S2*) during the daytime as well as the internal temperature in (*S1*) for most of the daytime period. During the night-time, the internal temperature in this scenario was lower than the internal temperature in (*S2*) for most of the night-time. The only exception was for some hours in the early night and just after opening the windows when the flat started rapidly gaining heat from the outside air that was still hot due to the heat gain by radiation from the road surface. However in comparison to the internal temperature of (*S1*), the internal temperature in (*S3*) was found to be lower than (*S1*) for half of the night times. The application of (S3) achieved an average temperature over the period of the experiment of (*30.55^o C*) and medium degree of variation around the mean between all scenarios (*Std. deviation = 0.92*) (Table 5-3). By comparing the inside temperature in (*S3*) to the calculated comfort temperature, it was found that the internal temperature was higher than the comfort temperature all over the time except for one hour in the late night of the first day (Figure 5-23). This scenario achieved the nearest average temperature to the comfort temperature in comparison to the other two scenarios. The statistical analysis of the *S3* data, using one sample T-Test, showed that the data set of the monitored internal temperatures in that scenario is also significantly different from the comfort temperature (*$P<0.05$*) with the lowest positive difference of (*3.18^o C*) (Table 5-3).

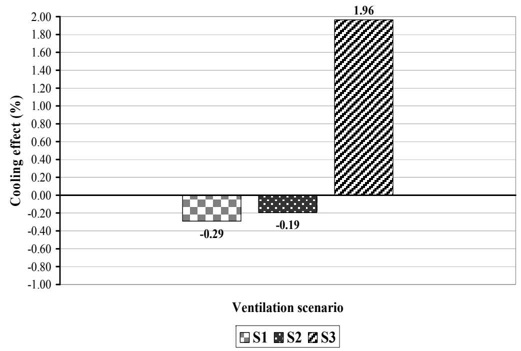


Figure 5-24: The cooling effect (Ce) for the three ventilation scenarios S1, S2 and S3 (derived from equation 4-2: $C_e = [(To - Ti) / To] x 100$)

In terms of cooling capabilities for each ventilation scenario, the calculation of cooling effect (C_e) for *S1*, *S2* and *S3* revealed that *S3* (*Night ventilation only*) is the only scenario that generally cooled down the internal spaces during the monitoring period (Figure 5-24). *S3* was found to have a cooling effect of (*1.96%*) in regard to the outside temperature, while the other two scenarios (*S1 and S2*) were found to have a heating rather than a cooling effect with negative C_e of (*-0.29% and -0.19%*) respectively (Figure 5-24).

From the discussion above, it can be clearly seen that *S3* (*Night ventilation only*) achieved:

- The nearest average temperature to the calculated comfort temperature over the monitoring period;
- The lowest degree of variation between both scenarios (*S1 and S3*) in which the ventilation was allowed; and
- The only observed cooling effect between all scenarios.

In general, the results of this stage confirmed the results from the passive strategies' analysis for *Al-Minya* climatic context, which suggested the use of night purge ventilation as the most effective strategy in achieving thermal comfort within such a climate. However, all the ventilation scenarios (*S1, S2 and S3*) were found to be very poor in achieving thermal comfort as all of them were significantly far from the comfort temperature.

In stage 2, the monitoring results of the temperature inside different living rooms, under the application of the night purge ventilation scenario, showed that the thermal performance of the monitored spaces has the same profile in each space. However, some significant discrepancies were observed between different flats, especially at early and late night times (Figure 5-25).

Figure 5-25 and Table 5-4 illustrate the monitoring results of stage two and their statistical analysis respectively. It can be clearly seen from the graph that all monitored spaces have very close internal temperatures during the daytime. However and strangely, the lowest internal temperature during daytime could be observed at LR4/2, which represents the worst possible orientation regarding both the sun and wind.

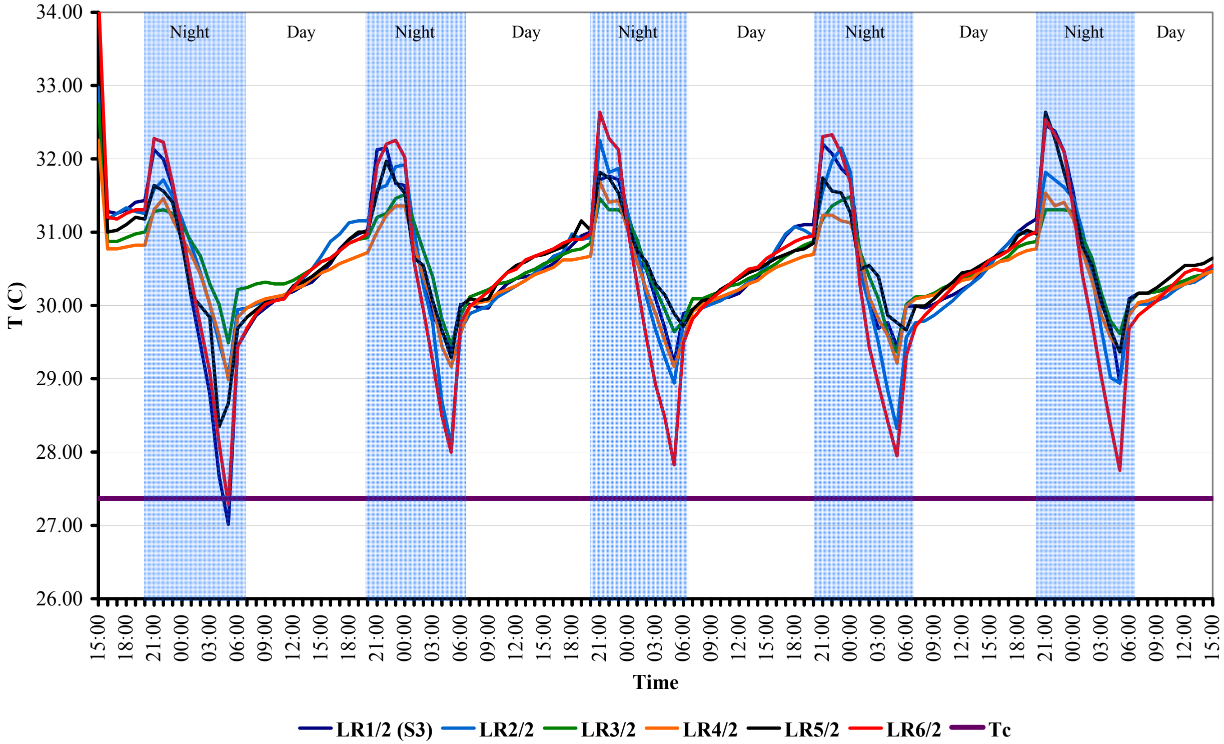


Figure 5-25: The monitored air temperature inside spaces; LR1/2, LR2/2, LR3/2, LR4/2, LR5/2 and LR6/2 under the application of night ventilation scenario.

Table 5-4: The statistical analysis' results of the monitored data in the second stage of the monitoring process

Sample	**One – Sample T-Test (Test value = 27.37 [Tc])**			
	Mean	Std. Deviation	Sig.	Mean difference
LR1/2	30.55	0.92	P < 0.05	3.18
LR2/2	30.51	0.85	P < 0.05	3.14
LR3/2	30.57	0.52	P < 0.05	3.19
LR4/2	30.43	0.57	P < 0.05	3.06
LR5/2	30.60	0.74	P < 0.05	3.23
LR6/2	30.44	1.14	P < 0.05	3.07

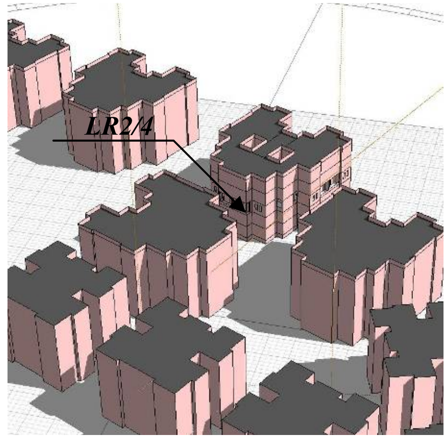
By looking closely to this, using Ecotect sun tool, it was found that during daytime (especially in early morning and late afternoon) most of the outer envelope of this flat was found shaded by the surrounding buildings and the other parts of the block, providing by such the lowest heat gain from the direct solar radiation (Figure 5-26).

However, during night time, some differences in performance between monitored spaces had been spotted. On one hand, during the early night time when the windows were just opened, the temperatures inside all monitored spaces rise. This can be justified by the immediate heat gain by radiation from the road surface which still keeps heat from the day time's sun radiation. The maximum rise was found in *LR6/2* (Figure 5-25). This was because it faces the prevailing wind direction observed at the early evening time (*10 to 30^o from the north*). This in turn allowed the maximum amount of air to flow through the flat providing by this the maximum heat gain through the air that is fully loaded by heat from the hot asphalt roads

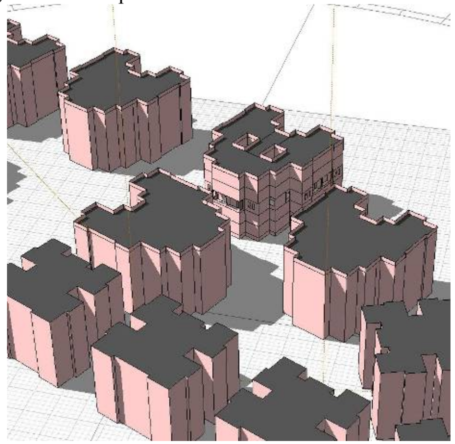
(Figure 5-27). However, the minimum rise in temperature, during the early night time, was found in *LR3/2 and LR4/2* (Figure 5-25). This was referred to the minimum amount of heat gain through the air, because the spaces face a tiled area (Figure 5-27) that keeps and radiates less heat than asphalt. In addition, their orientation (*opposite to the wind direction*) provides minimum heat that could be possibly transferred to the flat by the airflow at that time.

On the other hand, during the late night time when the outside temperature drops to the minimum, the internal temperatures in all monitored spaces were found to decrease up to its minimum simultaneously (Figure 5-25). The wind direction that was observed in the nearest weather station (*Al-Minya*) at that time was found to be in most cases between (*340^o from the north direction to the north direction itself*) (Figure 5-27). This in turn allowed the maximum cold airflow rate in *LR6/2* through the kitchen and bathroom's windows of the flat, providing by such a maximum drop in the internal temperature of *LR6/2* comparing to the other monitored spaces (Figure 5-25). This significant drop in internal temperature during late night time was, also, observed during some nights within *LR1/2* and *LR2/2* (Figure 5-25). Although these spaces face the wind direction observed at that time, the drop in their internal temperature was not as continuous as in *LR6/2*. This might be because of the flat's openings positions that do not allow an effective air circulation within their spaces.

The statistical analysis of the second stage results (Table 5-4) showed that the six monitored living rooms under night ventilation scenario have very close mean internal temperatures over the period of the investigation. The closest average internal temperature to the calculated



(a) The shadow pattern on the monitored block at 9.00 am



(a) The shadow pattern on the monitored block at 3.00 pm

Figure 5-26: The shadow pattern on the monitored block during early morning and late afternoon times comfort temperature (27.37^o *C*) was achieved in *LR4/2* (30.43^o *C*). The variation of the internal temperatures around the mean was found to be minimum in *LR3/2* and maximum in *LR6/2* with a standard deviation of (*0.52 and 1.14*) respectively (Table 5-4). In general, when the results compared to the comfort temperature using T-Test, all cases were found to be higher than the comfort temperature with significant difference ($P<0.05$). The nearest to the comfort temperature among cases (still significantly difference) was found to be LR4/2 with positive difference of (3.06^o *C*) (Table 5-4). In this space (*LR4/2*), the lowest mean internal temperature was achieved due to the minimum solar heat gain as it is shaded by surroundings during daytime. This in turn reduces the cooling loads required to be recovered by ventilation at night. The performance of the monitored spaces was then evaluated using different methods that explained in the methodology. Table 5-5 shows the result of applying the assessment rules.

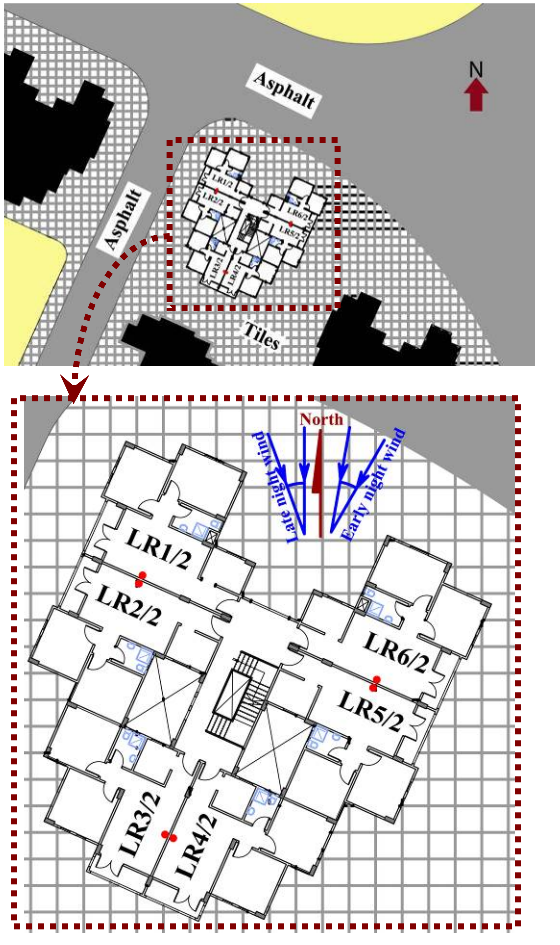


Figure 5-27: The monitored block with immediate surroundings with wind direction in different times indicated

Firstly, by comparing the ratio of the drop in the internal temperature from the diurnal difference ($Td_{max} / T_{dr} * 100$), none of the monitored spaces was found to achieve half the diurnal range that was stated by Givoni's rule of thumb [19, 38]. The drop in internal temperature ranged between 28.89 % (*in LR6/2*) and 45.97% (*in LR4/2*) of the diurnal difference. Spaces; *LR4/2* and *LR3/2* were found to have a closer drop ratio (*45.97% and 41.85% respectively*) to the datum (*50%*) proposed by Givoni (Table 5-5).

Secondly, according to Nicol's graph [36] for the *Al-Minya* climate (Figure 5-7), it showed that the use of night ventilation could provide maximum internal temperature less than the outside maximum temperature by ($Td_{max-Nicol}$ = 10.30^o C) and could keep it at around ($Ti_{max-Nicol}$ = *28.40^o C*). The comparison between the Td_{max} and the Ti_{max} observed in the monitored spaces with those from Nicol's graph revealed that none of the monitored spaces had touched Nicol's values. The drop in the internal maximum temperature (Td_{max}) of the monitored spaces was found to be between 3.43^o C (*in LR6/2*) and 5.46^{o}C (*in LR4/2*) (Table 5-5). The internal maximum temperature (Ti_{max}) inside the monitored spaces was found to be between 32.25^o C (*in LR4/2*) and 34.28^{o}C (*in LR6/2*) (Table 5-5).

Thirdly, The average temperatures inside the monitored spaces (Ti_{avg}) were compared to the average temperature of the unventilated flat *LR1/1* ($Ti_{avg-Unventilated}$) from stage one of this study. The comparison revealed that the internal average temperatures within the night ventilated spaces were always less than the average temperature in the unventilated flat. The difference ranged between *0.66^{o}C* (*in LR3/2*) to *0.80^{o}C* (*in LR4/2*) (Table 5-5).

Table 5-5: The assessment of the cooling capabilities of night ventilation monitored data in the second stage of the monitoring process

Monitored space	**Monitored data**		**Outside climate**		**The monitored drop in maximum internal temperature**	**Assessment indicators of night ventilation cooling capabilities**					
						Givoni's rule (50% of T_{dr})	Nicol's graph		Givoni's rule of (2:3^o C) difference between the night ventilated and unventilated cases		Shaviv's prediction equation
	Ti_{max}	Ti_{avg}	To_{max}	T_{dr}	($Td_{max} = To_{max} - Ti_{max}$)	$Td_{max} / T_{dr} * 100$	$Ti_{max-Nicol}$	$Td_{max-Nicol}$	$Ti_{avg-Unventilated}$	$Ti_{avg-Unventilated} - Ti_{avg}$	$Td_{max-Shaviv}$
LR1/2	33.91	30.55	37.71	11.87	3.80	31.98 %	28.40	10.30	31.22	0.67	7.99
LR2/2	32.98	30.51			4.74	39.89 %				0.71	
LR3/2	32.74	30.56			4.97	41.85 %				0.66	
LR4/2	32.25	30.43			5.46	45.97 %				0.80	
LR5/2	33.99	30.60			3.72	31.32 %				0.63	
LR6/2	34.28	30.44			3.43	28.89 %				0.78	

These results did not achieve Givoni's expectation that assumes a reduction of 2^o – 3^oC in the average indoor temperature when compared to another building that does not night purge ventilation [38].

Finally, the drop in indoor maximum temperatures (Td_{max}) inside the monitored spaces under night ventilation was found not to achieve any closer values to the calculated maximum drop using Shaviv's equation ($Td_{max\text{-}Shaviv}$ = 7.99^{o}C). The drop in the internal maximum temperature (Td_{max}) of the monitored spaces was found to be between 3.43^o C (*in LR6/2*) and 5.46^{o}C (*in LR4/2*) (Table 5-5).

In general, the results of this stage showed the poor performance and poor cooling capabilities of the night purge ventilation inside the case study. None of the night ventilated spaces satisfied any of the performance criteria provided by the evaluation methods stated above. Moreover, all the night ventilated spaces were found to be significantly higher than the comfort temperature. They did not achieve or even came close to the time spent under comfort conditions (81%) in July, which was suggested by the passive strategies' analysis for *Al-Minya* climatic context (Figure 1-9). These results indicate the poor cooling effect achieved by night ventilation. This could be possibly due to poor thermal mass design with insufficient exposure to the cool airflow at night. It can be concluded that the ventilation design of the monitored case study is not currently suitable for night-time cooling using night purge ventilation strategy.

5.5.2. CFD results

The *CFD* simulation results of the airflow quality and distribution over the case study's site at several heights (the person's height "*1.75 m above the ground level"* and at the mid windows' heights in each story "*4.65 m , 7.65 m , 10.65 m , and 13.65m"*) are shown in Figure 5-28, Figure 5-29, Figure 5-30, Figure 5-31, Figure 5-32, and Figure 5-33 respectively.

It is clearly seen from the figures that the airflow at all levels takes the same routes across the site. These routes are created by the parallel nature of the arrangement of the blocks in the site, which in turn forms straight higher speed streamlines of the airflow that penetrates the site between the blocks' rows.

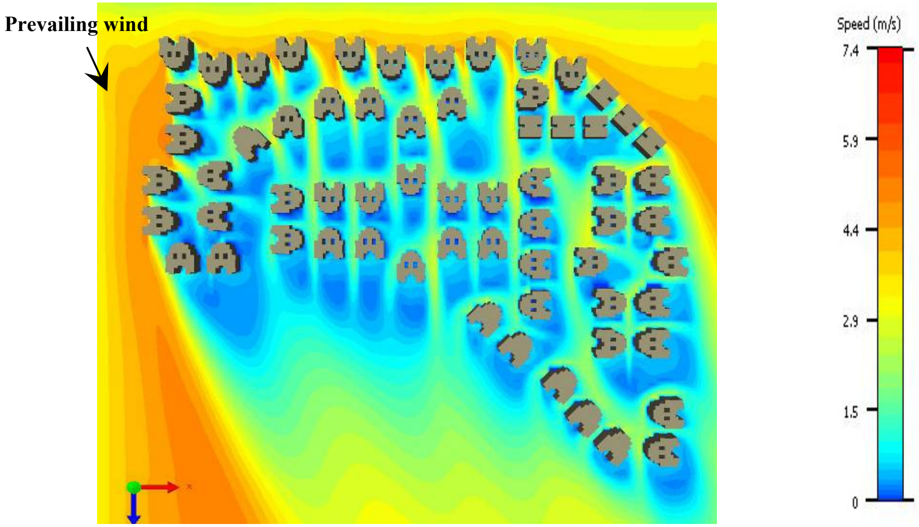


Figure 5-28: The Airflow pattern over the site at height of 1.75 m above the ground level (*the person's height*)

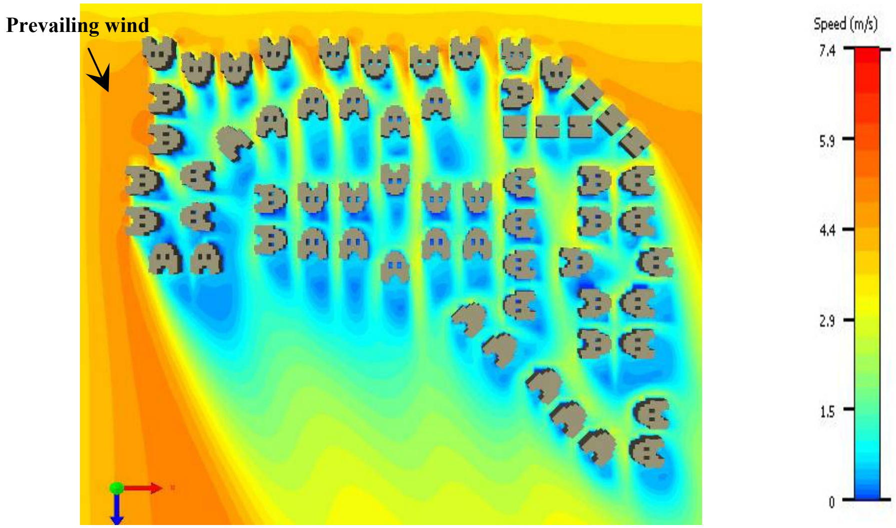


Figure 5-29: The Airflow pattern over the site at height of 4.65 m above the ground level (*the mid height of the first floor window*)

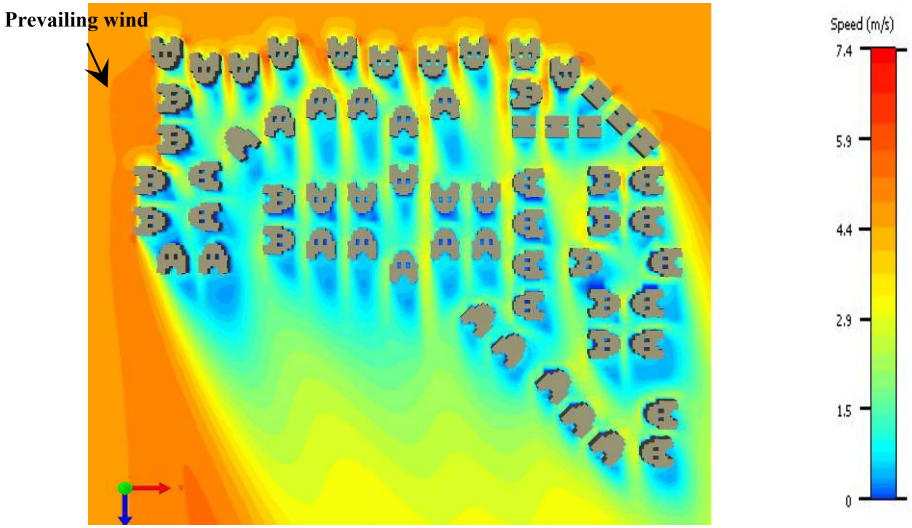


Figure 5-30: The Airflow pattern over the site at height of 7.65 m above the ground level (*the mid height of the second floor window*)

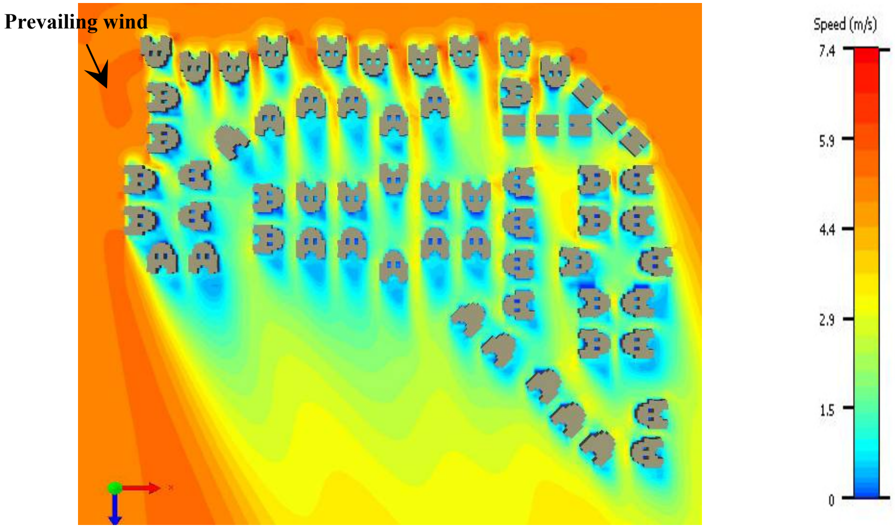


Figure 5-31: The Airflow pattern over the site at height of 10.65 m above the ground level (*the mid height of the third floor window*)

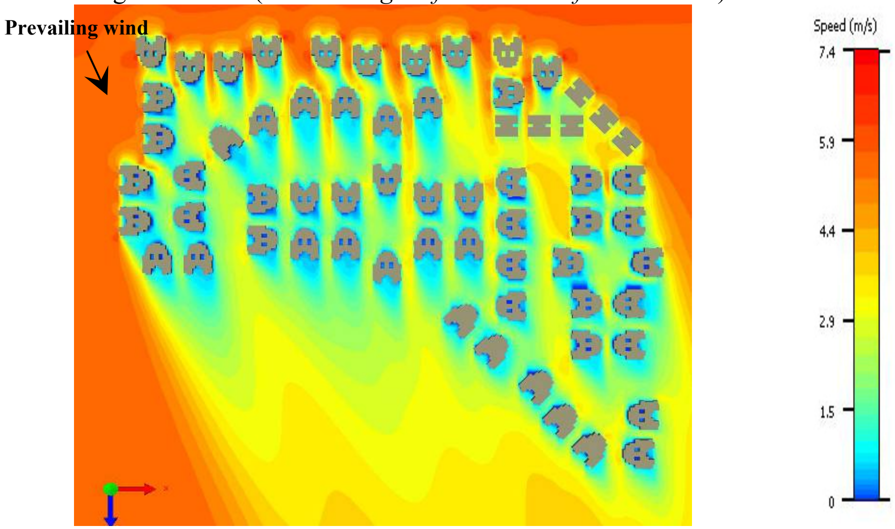


Figure 5-32: The Airflow pattern over the site at height of 13.65 m above the ground level (*the mid height of the fourth floor window*)

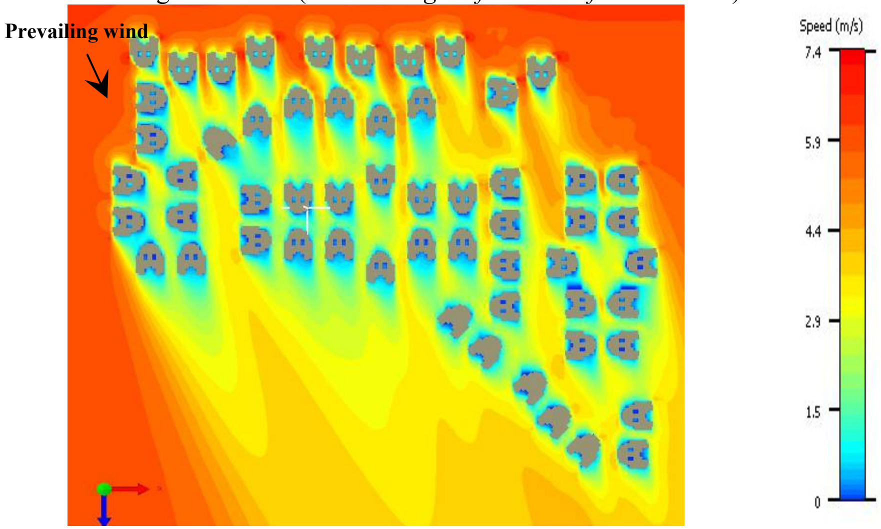


Figure 5-33: The Airflow pattern over the site at height of 16.65 m above the ground level (the mid height of the fifth floor window)

The airspeed in these routes increases when going to the higher levels planes of the site as a result of the wind speed increase due to the boundary layer profile (*refer to section 2.4.1*). No effective role of the eleven outdoor courtyards that are distributed across the site in redirecting the airflow was observed. This was due to the staggered arrangement of the blocks adopted in the northern cluster that blocked the air access to these courtyards. Apart from these airflow routes, the rest of the site is found to have low airspeed with the blocks' wind shading areas (*recirculation regions*) which are formed over its majority, especially at lower levels. At the lower levels of the site, large vortexes are formed and create large areas with airspeed almost 0 m/s (*still air*) at the leeward sides of the blocks. The area of these still air regions decreases as the height increases until they disappear completely at the fourth and fifth floors level. See Figure 5-28 - Figure 5-33.

The above described airflow profile over different levels of the site shows that the majority of the blocks are exposed to the airflow only on two sides. The upwind side of each block lies either in the wind shading area of another block or in a low airspeed area, while the downwind side of each block normally lies in a negative pressure area (*recirculation region*). In the absence of the ventilation design features on the blocks' envelope, these airflow configurations could not be able to provide reasonable ventilation potential for the flats' internal spaces since the air is just skimming over the side façade without entering the spaces. Also, the form of the blocks mass (*arrowhead shape*) paired with most common blocks' orientation could undermine the potential of ventilating most of the spaces in each floor, even when the upwind side of the block is exposed to reasonable airflow. This is because of the wide base of the block's arrowhead shape which always faces the upwind direction in this case, preventing such air from skimming over most of its parts (Figure 5-34). The airflow analysis of the case study's site showed a poor airflow pattern in all different levels. In addition, the analysis indicated the poor blocks' arrangement and orientation which could possibly undermine the possibility of the available airflow's use in ventilating internal spaces.

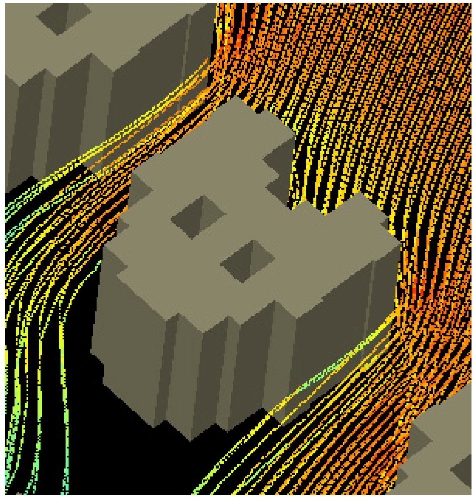


Figure 5-34: The most prevailing block orientation and its form's effect on airflow

The airflow inside the middle floor of the monitored block, which is exposed to the optimum airflow conditions, was simulated and further investigated by using the *Flovent CFD* software. The CFD results are shown in Figure 5-35, Figure 5-36 and Table 5-6. For the full set of quantitative data and a movie of air movement inside the case study, refer to (*Appendix E*).

From Figure 5-35 and Figure 5-36, it can be clearly seen that, in general, the airflow inside the flats in the detailed floor is very poor, except in certain spaces within flats 1, 2 and 6.

In flat (*1*), the main sources of air are (*W1, W4 and W5*) of bedroom (*B2/1*), bathroom (*Br1*) and kitchen (*K1*) respectively. (*W1*) faces the prevailing wind, while (*W4 and W5*) are gaining their input from the positive pressure area which is formed by flat (*6*) projection in front of them. The air enters the flat from (*W1*) then passes through (*B2/1*) forming a large vortex on its left side and achieving average volumetric airspeed of (*0.61 m/s*) (Table 5-6) before exiting from its door. After exiting from the door of (*B2/1*), some weak amount of air enters (*B1/1*) and circulates slowly inside with no chance to exit from windows (*W2 and W3*). It is given to be due to the high positive pressure in front of them.

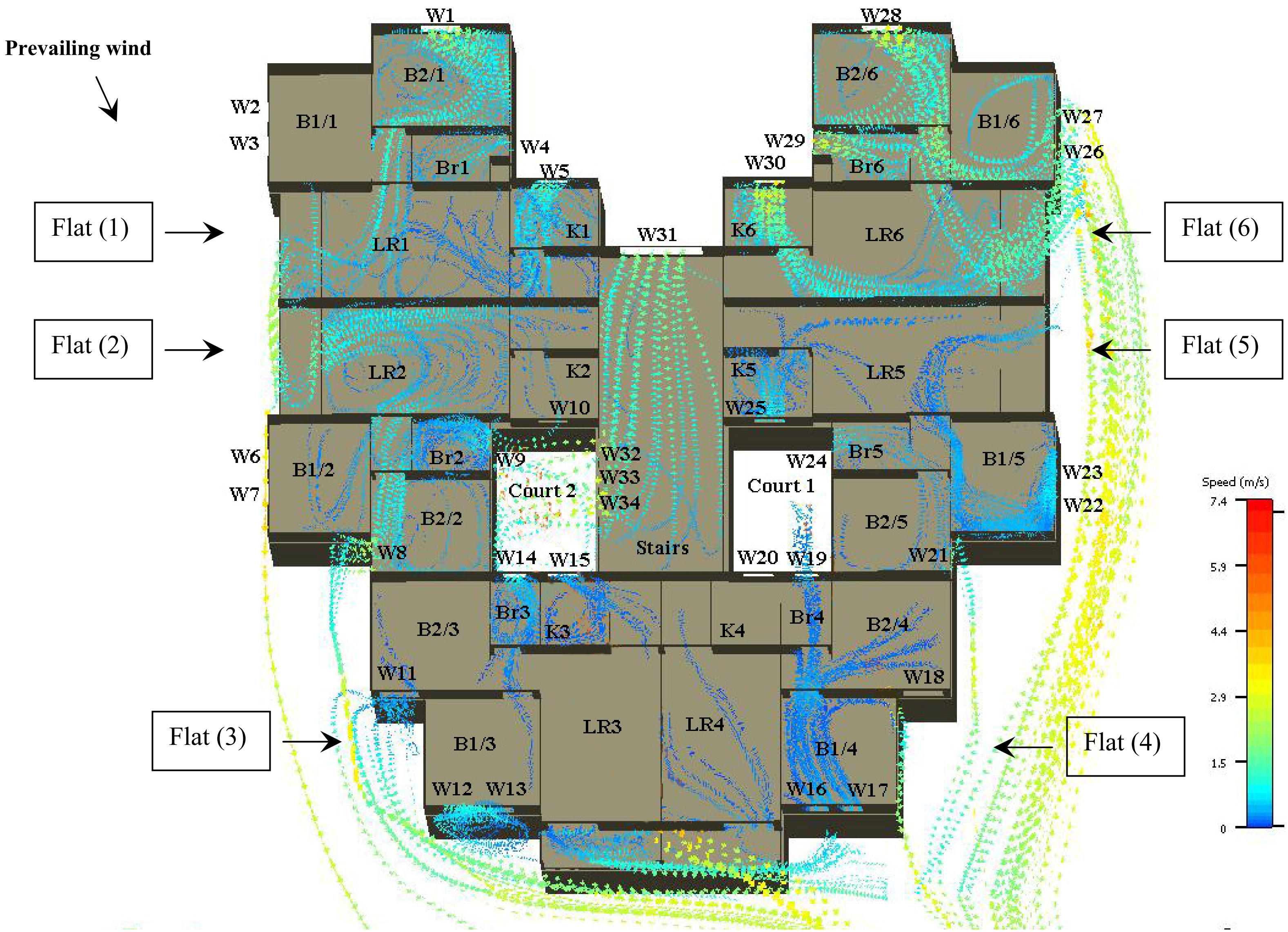


Figure 5-35: The airflow pattern inside the detailed floor of the monitored block with the most frequent wind conditions over the site

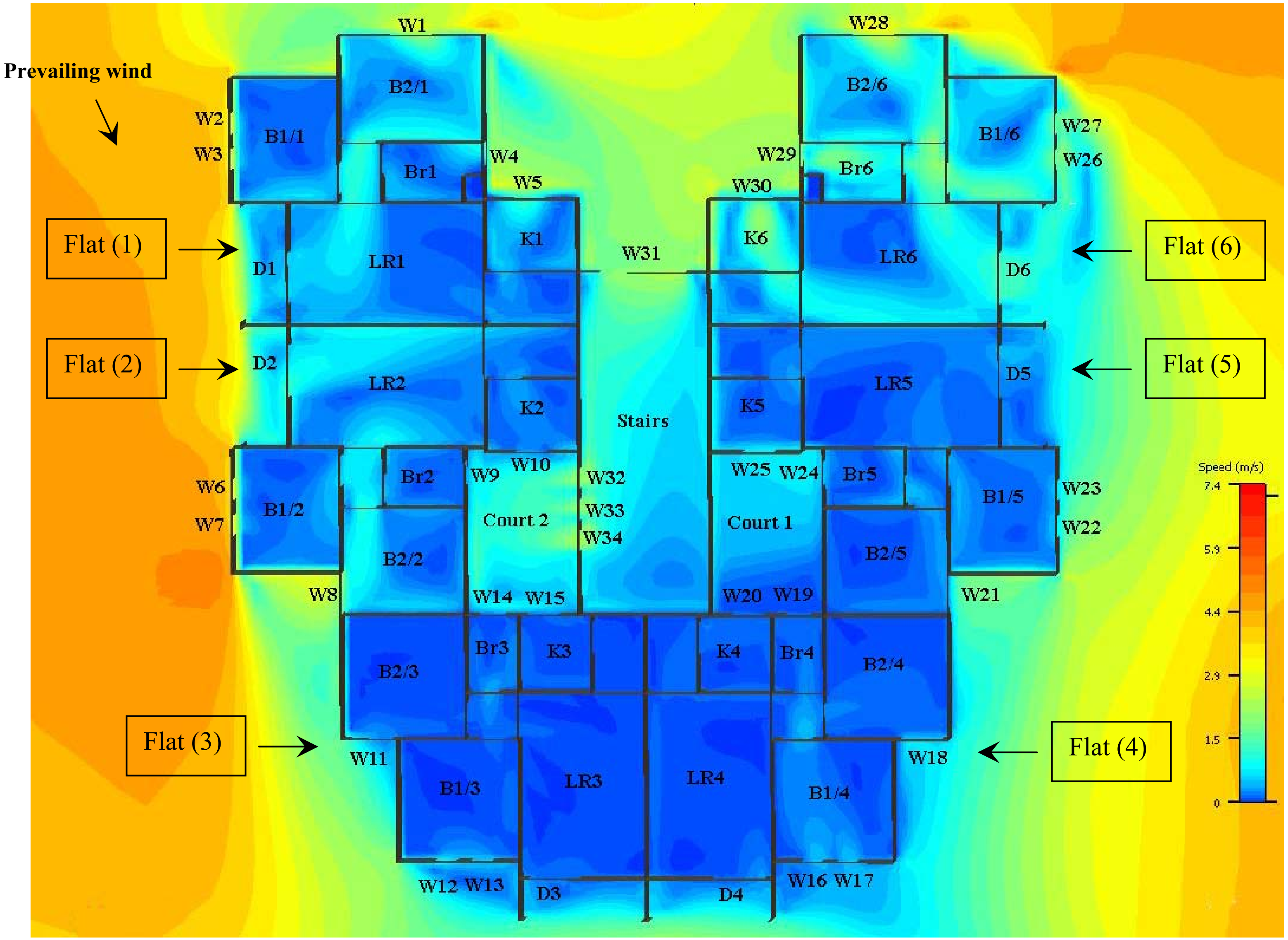


Figure 5-36: The airflow speed profile inside the detailed floor of the monitored block on the level of 1.00 m *AFL* when most frequent wind conditions in the site provided

Table 5-6: The volumetric average airspeed inside the main living spaces of the flats in the detailed floor

	Flat (1)			Flat (2)			Flat (3)			Flat (4)			Flat (5)			Flat (6)		
	LR1	**B1/1**	**B2/1**	**LR2**	**B1/2**	**B2/2**	**LR3**	**B1/3**	**B2/3**	**LR4**	**B1/4**	**B2/4**	**LR5**	**B1/5**	**B2/5**	**LR6**	**B1/6**	**B2/6**
Average internal airspeed (m/s)	0.258	0.241	0.613	0.392	0.191	0.338	0.042	0.063	0.056	0.065	0.120	0.080	0.108	0.223	0.119	0.410	0.648	0.749
Percentage from wind speed (%)	4.60	4.30	10.95	7.00	3.41	6.03	0.75	1.12	0.99	1.17	2.15	1.42	1.93	3.98	2.12	7.33	11.56	13.38

This pattern produces virtually still air inside (*B1/1*) with an average speed of (*0.241 m/s*) (Table 5-6) over the volume of the room. The rest of the air flows through the corridor and combines with the weak air current that comes from the bathroom (*Br1*) before entering the living room (*LR1*) and exits directly from the balcony's door (*D1*). The projection of the room (*B1/1*) creates a negative pressure area in the balcony of flat (*1*), which plays a big role in extracting the air from (*LR1*) The air that comes from (*W5*) flows through (*K1*) then exits from its door to the corridor before reaching the internal part of (*LR1*), where a weak vortex is formed and where almost still air is found. The average volumetric airspeed inside (*LR1*) is found to be (*0.258 m/s*). Although flat (*1*) is exposed to the best outside airflow, the airflow pattern inside it indicates poor potential of using either comfort ventilation or night ventilation. The maximum obtained average airspeed within its main spaces was very low (*0.613 m/s*) in (*B2/1*) (Table 5-6) and the flat's thermal mass in most parts was exposed to almost still air (Figure 5-35 and Figure 5-36). This undermines the possibility of using both; comfort ventilation and night ventilation strategies. In addition, the poor design that led to the kitchen (*K1*) and the bathroom (*Br1*) being among the air inlets of this flat would cause undesirable smells in these spaces to be circulated to the rest of the flat.

In flat (*2*), the projection of the room (*B1/2*) traps the air and induces it to enter (*LR2*) through (*D2*). The majority of the airflow rotates in (*LR2*) before passing through the corridor toward (*B2/2*) to exit from its window (*W8*). Through the air's way from (*LR2*) to (*B2/2*), some weak air streams enter (*B1/2*). Some few air streams go from (*LR2*) to (*K2*) in order to exit from (*W10*) on court (*2*), and then enter the flat again through (*W9*) along with the airflow that feeds in court (*2*) via (*W32, W33, and W34*) of the stairwell. The air jet comes from (*W9*) then exits through the door of (*Br2*) and takes the same route through which the air comes from (*LR2*) to exit from (*W8*) in (*B2/2*). The average volumetric airspeed of (*0.392 m/s, 0.191 m/s, and 0.338 m/s*) were observed inside (*LR2, B1/2, and B2/2*) respectively (Table 5-6). In this flat, the poor design of kitchen and bathroom being the air inlets was found to be repeated.

In flats (*3 and 4*), all spaces suffer from the air being almost still. Although all internal doors were opened and cross ventilation was allowed, no airflow's penetration within both flats was found except in (*K3, Br3, B1/4, and Br4*). In flat (*3*), the air only comes from the positive pressure courtyard (*Court 2*) via windows (*W14 and W15*) of (*Br3 and K3*) respectively. The air that comes from these windows has a weak airflow speed and magnitude. Most of it rotates inside (*Br3*) and (*K3*) forming a vortex and exits from the spaces through the same inlets. Very weak flow from (*K3*) escapes to pass through the upper part of (*LR3*) and ceases over its walls. (*W11*) in (*B2/3*) and (*W12, W13*) in (*B1/3*), exhaust out the weak air currents that escape from (*Br3*). The average volumetric airspeed of (*0.042 m/s, 0.063 m/s, and 0.056 m/s*) were achieved inside (*LR3, B1/3, and B2/3*) respectively (Table 5-6). Again, the poor design of kitchen and bathroom being the air inlets was repeated.

The same malfunctioning situation was found also in flat (*4*), where (*W16*) and (*W17*) in (*B1/4*) could pick some re-circulated air from the negative pressure area in front of them. The air enters (*B1/4*) through them and flows through its door either to mainly exit from (*W19*) in (*Br4*) or to go into (*B2/4*) as a weak breeze. Apart from that, the rest of the flats' spaces have no noticeable air movement. The average volumetric airspeed of (*0.065 m/s, 0.120 m/s, and 0.080 m/s*) were spotted inside (*LR4, B1/4, and B2/4*) respectively (Table 5-6). Having said that, the low average monitored temperature achieved by this flat in night ventilation scenario could not be achieved by this poor airflow inside this flat. This reduction came as a direct effect of the shaded thermal mass of the flat and the minimum heat gained as explained earlier

The situation in flat (*5*) is slightly better than the situation in flats (*3 and 4*). The flat was found to be penetrated by three main weak air streams through windows (*W22 and W23*) in (*B1/5*), (*W24*) in (*Br5*) and (*W25*) in (*K5*). The air enters from (*W22 and W23*) and skims over the walls of (*B1/5*) before exiting from its door flowing toward the outside via the balcony door (*D5*) of (*LR5*). (*W24*) picks up a weak current from the air that is expelled from flat (*4*) into the courtyard (*court 1*) then blows them into (*Br5*). The air then flows weakly to (*B2/5*) forming a large vortex before leaving the room through its window (*W21*). A similar scenario happens with (*W25*) that picks air from (*court 1*) and blows it into (*K5*). Little of the air stream leaves (*K5*) to (*LR5*) but vanishes before reaching the balcony door (*D5*). This airflow pattern achieves average volumetric airspeeds of (*0.108 m/s, 0.223 m/s, and 0.119 m/s*) inside (*LR5, B1/5, and B2/5*) respectively (Table 5-6).

The airflow performance inside flat (*6*) showed a significant difference, where the highest average volumetric airspeeds of (*0.410 m/s, 0.648 m/s, and 0.749 m/s*) were achieved inside its main living spaces (*LR6, B1/6, and B2/6*) respectively (Table 5-6). In flat (*6*), the main air sources are windows (*W28, W29 and W30*) of (*B2/6, Br6 and K6*) respectively. The air enters from (*W28*) into (*B2/6*), circulates across the room and exits from its door toward (*B1/6*) before leaving the flat through windows (*W26 and W27*). The air stream that comes from (*W29*) in (*Br6*) combines with the air stream that comes from (*W30*) in (*K6*) in the living room (*LR6*) before leaving through its balcony door (*D6*). Generally speaking, the air enters this flat from the openings in the positive pressure area that faces the prevailing wind and exits from the openings in the negative pressure area in the downwind façade. Although, the airflow pattern and speed in this flat introduces the best scenario achieved among all flats in the floor, the design faults of kitchen and bathroom acting as the air inlets was found to be repeated again.

The results of the CFD analysis clarified the results of the monitoring study and supported the justifications that were made to justify the living rooms' thermal performance, when the night ventilation scenario was applied. The airflow pattern analysis showed that flat (*6*) has the best air circulation over the monitoring equipments positions among other flats on the floor. Then it was followed by flat (*2*) and flat (*1*) in order. This was apparently reflected in the drop of the internal temperature during the night on those flats shown in Figure 5-25. In addition, the airspeed analysis showed a similar trend. It can be clearly seen from Table 5-6 that the highest achieved average volumetric airspeed is *0.749m/s* in *B2/6*, which represents *13.38%* of the wind speed observed at the weather station (*5.6 m/s*). The lowest achieved average volumetric airspeed is *0.042m/s* in *LR3*, which represents *0.75%* of the wind speed. The airspeed at the rest of floor's spaces ranges between *0.056 m/s* and *0.648 m/s*, which equal *0.99% and 11.56%* from the up coming wind speed.

To conclude, the airflow quality pattern result from the *CFD* simulation of the monitored floor of the case study could apparently hinder the potential for cooling down the thermal mass by night purge ventilation. Moreover, all the average airspeeds that were achieved inside the main living spaces of the flats were found to be less than the acceptable airspeed inside the naturally ventilated residential buildings (*1:2 m/s*) that advised by Givoni [38] Also, in terms of human sensation and according to Beaufort scale (Table 2-2), these speeds were found to be under the category of light air (*0.2 : 1 m/s*) that has no noticeable air movement sensation from humans. This in turn hinders the potential for enhancing thermal comfort via comfort ventilation. From results outlined above, it can be clearly seen that the current situation in the case study is not suitable for natural ventilation as in both main strategies. If this is the situation at the block that is supposed to be having the optimum boundary conditions that maximize the potential of using natural ventilation, then the question of what the situation looks like in the blocks in the depth of the site would arise.

5.6. Conclusions

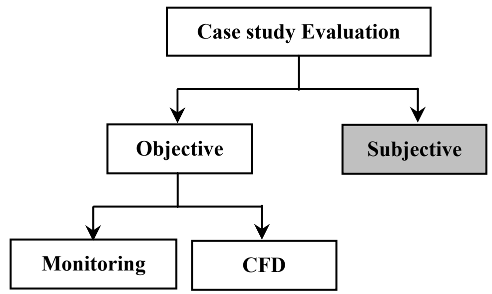
To summarize, in the objective assessment, the thermal effect of different natural ventilation scenarios (*S1=24 hours ventilated, S2=24 hours unventilated and S3=ventilated during night only*) was monitored, the cooling capabilities of the recommended ventilation strategy in the research context (*night purge ventilation*) in all the case study flats were monitored and the airflow in and around the case study was simulated. The following conclusions could be drawn from this study.

All ventilation scenarios were significantly different from the comfort temperature including night ventilation scenario that theoretically recommended as the most effective cooling strategy in this context. Although, applying night purge ventilation to the case study failed to achieve thermal comfort as theoretical analysis showed, it achieved the only observed slight cooling effect among all applied ventilation scenarios. In addition, it recorded the nearest average internal temperature to comfort temperature and the lowest degree of variation in temperature among both scenarios, in which the ventilation was allowed.

The monitoring results of the temperature inside different flats under the application of the night purge ventilation scenario showed that the thermal performance of the monitored spaces has the same profile in each space. However, some significant differences were observed between the different flats, especially at early and late night times. The performance of the monitored spaces was then evaluated using four evaluation methods; Givoni rule [19, 38], Nicol's graph [36], Givoni rule comparing the unventilated space to night ventilated one [38] and Shaviv equation[78]. None of the spaces under night-time ventilation satisfied any of the performance criteria predicted in literature by those evaluation methods. The results indicate that very poor cooling using night ventilation was achieved. This could possibly be referred to the poor thermal mass design combined with insufficient exposure to cool night airflow. It can be concluded that the ventilation design of the monitored case study is not currently suitable for night-time cooling. Therefore, the air movement patterns in and around the case study were then further investigated.

The airflow analysis in the case study's site showed a poor airflow pattern across the site at all the tested heights. In addition, the analysis indicated the poor blocks' arrangements and orientations which could possibly undermine the possibility of the available airflow's use in ventilating internal spaces. Also, the results of the internal airflow analysis explained the results of the monitoring study and supported the justifications that the case study has a problem in thermal mass exposure to the cool night airflow. To conclude, the airflow quality pattern result from the CFD simulation of the monitored floor of the case study could apparently hinder the potential of cooling down the thermal mass by night purge ventilation. Moreover, all the average airspeeds that were achieved inside the main living spaces of the flats were found not to meet both the acceptable airspeed inside the naturally ventilated residential buildings and also the human sensation with the air movement. This in turn undermines the potential for improving cooling by comfort ventilation. From the situation outlined above, it can be clearly seen that the current situation in the case study is not suitable for natural ventilation in terms of both its main strategies.

Chapter 6:
Subjective assessment of using natural ventilation in the case study



6.1. Chapter six introduction

This chapter introduces the second part of the evaluation study (*The subjective assessment of natural ventilation use in the case study*). Firstly, the detailed methodology of the subjective assessment including methods, techniques and analysing method as applied are illustrated. Then the discussion of the results of the occupants' subjective response towards using natural ventilation is presented.

6.2. Subjective assessment detailed methodology

The second part of the evaluation study is the qualitative evaluation through subjective assessment that is concerned with the response of case study users. It aims for the best understanding of the occupants' response toward using natural ventilation as a passive cooling strategy. Five main issues were targeted to be investigated through this study:

1. ***Studying natural ventilation drivers in the dwelling and occupants' behaviour towards using them:*** This issue aims to; a) know whether the occupants have made any modifications to the openings' design or not, and b) know the social and environmental reasons for doing these modifications.
2. ***Studying the residents' self-appraisal for thermal comfort inside the spaces in their dwellings:*** This issue aims to evaluate the residents' response toward the thermal performance of their dwellings' spaces during different seasons of the year by using

ASHREA seven points scale for thermal comfort

3. ***Studying the residents' use of natural ventilation for cooling purposes inside the dwelling's spaces during hot summer:*** This issue aims to evaluate the residents' use of natural ventilation as a passive cooling strategy during summer time in order to determine the incentives and constrains in the use of such a strategy.
4. ***Studying the residents' use of the mechanical ventilation assisting equipments (fans and air conditioners) for cooling purposes inside the dwelling's spaces:*** This issue aims to evaluate the pattern of the residents' use of the mechanical ventilation assisting equipments for cooling purposes during the summer time.
5. ***Studying the means of improving natural ventilation performance inside the dwelling's spaces:*** This part aims to know the opinion of the residents in how to improve the natural ventilation performance and air movement inside their dwellings. In addition, to measure their awareness regarding the other passive strategies that could possibly enhance thermal comfort.

6.2.1. Data collection

In order to collect the data from subjects, many data collection strategies could be employed. Most common are questionnaires and interviews. The suitability of each strategy is controlled by the nature of the research question, research scale and the time and fund limitations [227]. Questionnaires are preferred to be used in large scale research, where collecting the data from a large sample is required [227]. It is possible to be administered without the presence of the researcher and in a limited time in comparison to the interviews [227]. The interviews are more suitable for the small scale research as they are more time consuming and requires the development of many skills [228]. However, questionnaires can be used in small-scale research, where there are time and fund limitations [229]. Both strategies can be designed into either structured, semi-structured or unstructured style [227-229]. The structured interview comes more under Quantitative research methods as it is more like a questionnaire [227]. In addition, the question in both strategies can be designed either as open-ended questions or closed-ended questions formats.

This work chose to use the structured questionnaire with open and closed-ended questions in order to facilitate the quantitative analysis of the results along with allowing the informants to freely express their opinions, where required. A questionnaire is designed in Arabic (*the informants' mother tongue*) to investigate the five main issues mentioned in the previous section. In each issue, the questions were designed mainly in multiple choice formats with a given space to give the informants the opportunity to write down their own answer, if different from the list provided. For the full list of questions, please refer to (*Appendix F*).

In order to check the clarity and eliminate the ambiguities and difficulties in wording, a small-scale pilot study of the designed questionnaire was conducted by sending the questionnaire for convenience to some friends of the researcher, who live in the housing blocks within the research context. The questionnaire was then modified according to the feedback which came from them.

6.2.2. Sampling

Measuring the whole population of any case study is often very hard because of the limitation of time and funding [32]. Alternatively, sampling has to be used. Apart from the appropriate methodology and data collection methods of a research, the success and quality of the research strongly relies on using a suitable sampling strategy [227]. The sample size, its representativeness, the accessibility to it and the sampling strategy employed are the main factors that control the sample choice[227].

There are many sampling strategies that the researcher can follow, bearing in mind the nature of the research and the targeted population. In this work and due to the social nature and life style of the targeted population, accessibility to the sample was the main factor that controlled the sampling process. On one hand, the occupancy percentage of the case study under investigation is very weak. The only occupied blocks of the case study are 5 blocks in the 4th district (*180 dwellings*) (Figure 3-6). The occupancy percentage, according to the researcher's estimation, does not exceed 25% (*45 dwellings*). So the population size is a maximum of 45 informants. On the other hand, the life style of the occupants does not allow a good opportunity to meet informants or to collect the completed questionnaires. Most of them work from 8.00 am to 4.00 pm. During this time, the women will not open the door to strangers. The males return tired from work at 4.00 pm to have lunch and then rest for some time. They normally wake-up at 7.00 pm to either go out to meet others, escaping from the hot internal temperature or to stay in front of TVs until late night. This life style only provides very limited time slots to meet the informants and conduct the questionnaire.

According to the case study's circumstances mentioned above, it was found that using the convenience sampling strategy is the best option for this case. This strategy is sometimes called "*accidental sampling or opportunity sampling*" , in which the researcher chooses the nearest individuals from those who happen to be available and accessible at the time of study [227]. The questionnaire was then administered in a combination manner between a self-administered questionnaire and a face-to-face interview. The researcher and another two helpers would stay on the site all the day from early morning until late at night for a week in order to cover all the available time slots and get the maximum possible response.

16 completed questionnaires were collected from the informants in the case study under investigation. Because of the few number of the completed collected questionnaires in this study, it was decided to use them to take some indications rather than to over generalize the results.

Both graphical and statistical sheets were used to analyse the results. For the full list of informants and their responses, please refer to (*Appendix G*).

6.3. Results and discussion

In this section the result of investigating the five main aspects, for which the questionnaire was designed, are presented, discussed and analyzed.

6.3.1. Transformations applied to the natural ventilation drivers by the users

The majority of the informants (*87.5%*) have not applied any transformations to the openings design in their dwellings. However, only two informants revealed that they have applied some simple transformations for some reasons. One of them said that he blocked the holes of his bedroom window's Venetian shutters in order to decrease glare (Figure 6-1). The other informant declared that he had to install heavy curtains over the opening of the main living spaces (*lounge and bedrooms*) of his dwellings in order to provide a higher level of privacy (*as he lives in the ground floor*). He said:

> *"I have done that because of privacy as the ground floor is breached by all people in the street"*

Figure 6-1: Blocking the holes of the Venetian shutters to reduce sun glare

In general, the case study blocks are new and there are very few who have moved to live in them. This justifies such a very limited number of transformations in comparison with the transformations that were spotted in the other housing prototypes across the city.

6.3.2. The residents' appraisal of thermal comfort inside their dwellings

Regardless of the orientation of their dwellings, the majority of informants said that most likely they feel (*slightly warm*) inside the main living spaces of their dwellings during summer (Figure 6-2). However, less than 25% of them said that they are most likely feeling (*hot*) and another less than 25% of them declare that they are actually feeling comfortable (*neutral*). Only one informant was found to be feeling (*warm*) in his lounge and another two were feeling (*warm*) in their bedrooms. See Figure 6-2. This reflects the same profile as the monitoring results of the case study.

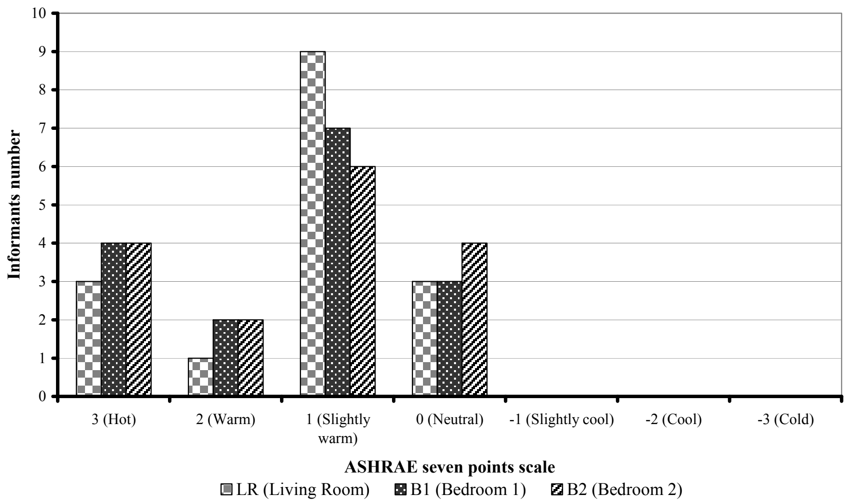


Figure 6-2: The informants' response toward evaluating their thermal sensation in their dwellings' spaces during summer on ASHRAE seven points scale

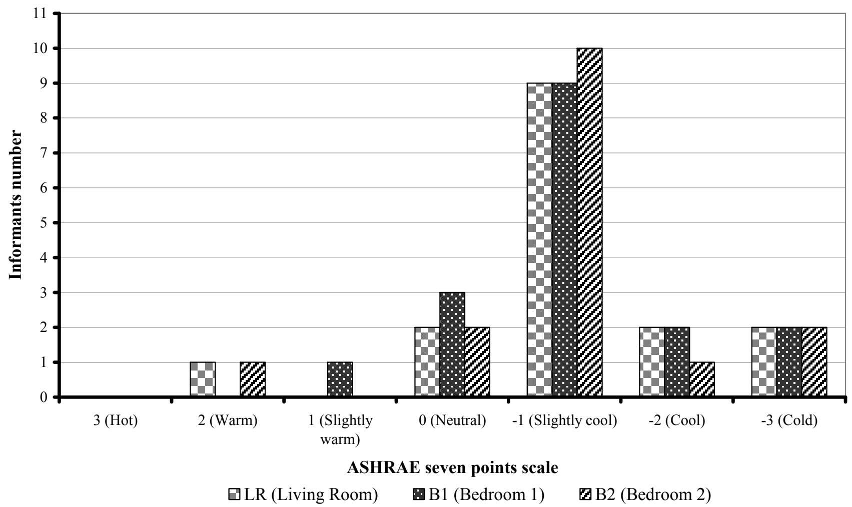


Figure 6-3: The informants' response toward evaluating their thermal sensation in their dwellings' spaces during winter on ASHRAE seven points scale

In winter, most of the informants (*more than 50%*) were found to be feeling (*slightly cool*). Less than 12.5% said that they most likely feel (*cool*), while 12.5 % said that they feel (*cold*). Meanwhile, less than 18.75% confirmed their status to be comfortable (*neutral*). Exceptionally, one informant claimed to be either (*warm*) or (*slightly warm*) in his dwelling's spaces. See Figure 6-3.

In general, the results showed that the majority of the informants are thermally uncomfortable during summer and winter.

6.3.3. The residents usage pattern of natural ventilation drivers for cooling purposes

The informants were asked whether they open the windows for passive cooling by ventilation when feeling hot in the main living spaces of their dwellings. Most of them (*11 out of 16*) responded that they always open windows in all spaces (Figure 6-4). Three out of them answered that they open windows sometimes, while only one said that he never opens windows at any of his dwelling spaces. Another one answered that he opens windows, when feeling hot, in some spaces only (*Living rooms rather than bedrooms*). See Figure 6-4.

The informant who claims that he does not open windows at all referred that to the noticeable increase in the internal temperature, when opening windows in hot days. The other informant who said that he did not open his bedrooms windows justified that by his feeling that his privacy in the bedrooms is breached by the neighbours through these windows. The three informants who reported that they sometimes opened windows and sometimes did not gave some reasons that prevented them from opening windows, especially in bedrooms. These reasons are:

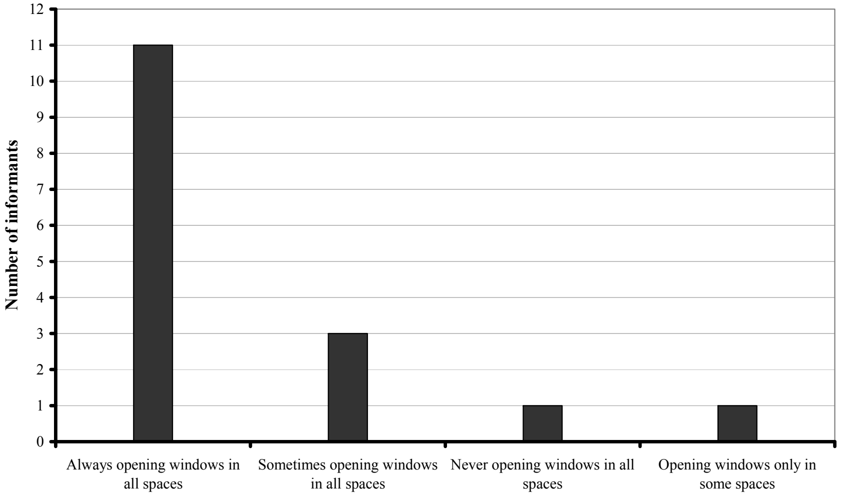


Figure 6-4: The informants' tendency to open windows when feeling hot for passive cooling through natural ventilation

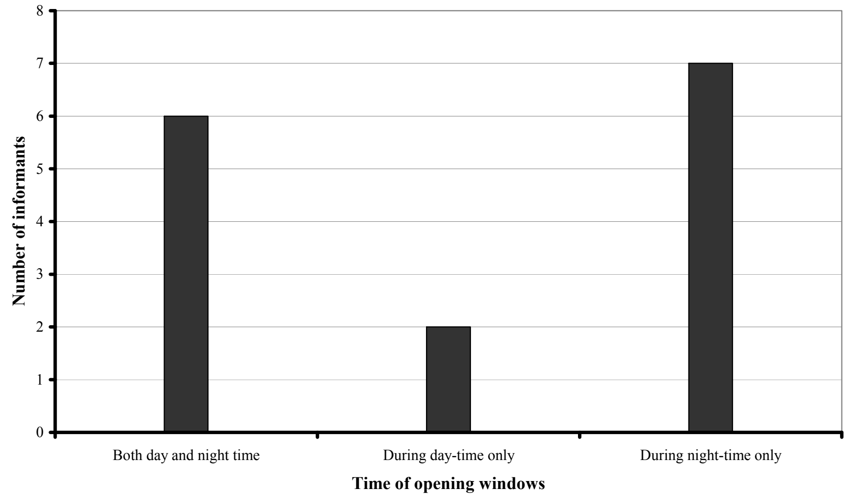


Figure 6-5: The preferred time in which the informants, most likely, open windows for natural ventilation

- Opening windows does not have an effectiveness in cooling down the room;
- Opening windows sometimes brings a lot of insects (flies) inside the space;
- Opening windows sometimes brings a lot of dust and pollutants inside the space;
- They feel that their privacy is breached when opening windows; and
- The tendency of using fans in bedrooms.

Moreover, instead of opening windows, those informants reported that they use fans, take off some clothes, or even use both in order to compensate and maintain the required air movement for cooling purposes. For those informants who normally open windows in hot weather, (*7*) out of (*15*) were found to prefer opening the windows during night only, while only (*2out of 15*) were found to prefer opening windows during day-time only (Figure 6-5). (*6*) Out of them emphasized that opening the windows either during day or night-time occurred as long as there was air movement outside (Figure 6-5).

Those who open the windows during night-time only reported that they reacted as such mainly to avoid the hot sun radiation during daytime. One of them added that the airflow at night-time is cooler and stronger than that of daytime. Those who open windows during either day or night-time referred to the strong need for airflow for both cooling purposes and for internal air quality. The two informants who open the windows during the day only justified that by the same reasons and added that they can not open bedrooms windows during the night for privacy reasons. These results indicate an intuitive use of night purge ventilation and comfort ventilation strategies by the informants as a sign of their adaptation to maintain thermal comfort.

When they were asked whether they find the incoming air effectively contributes to reducing the space's temperature and achieving thermal comfort, most of them reported that they clearly feel the positive effect of the incoming air in reducing the temperature inside their dwellings' spaces (Figure 6-6). (*12*) and (*9*) out of them (*15*) said that they can feel this positive effect in living rooms and bedrooms respectively. Less than one third of them reported that they just slightly feel that positive effect. However, only (*2*) informants said that they do not feel any positive effect at all for the incoming air in reducing internal temperature, especially in their bedrooms (Figure 6-6). When those bedrooms were looked into, it was found that they are oriented toward the south west direction. This orientation is opposite to the wind direction and exposed to the direct sun radiation most of the day-time, which in turn offers maximum heat gain from the sun with no air movement for cooling.

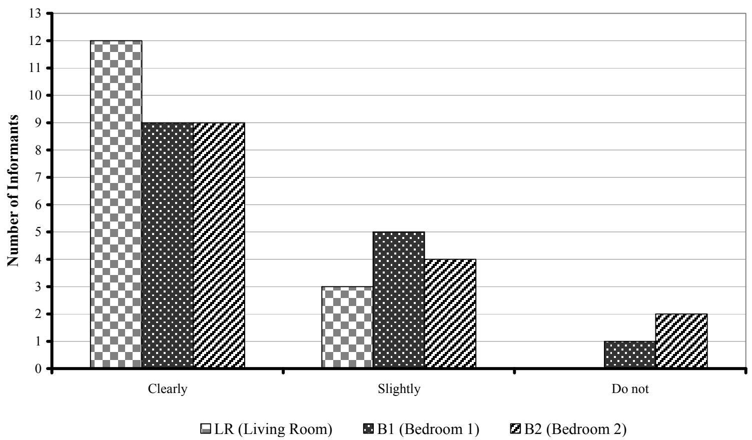


Figure 6-6: The informants' feeling with the positive effect of opening windows in reducing the space's temperature

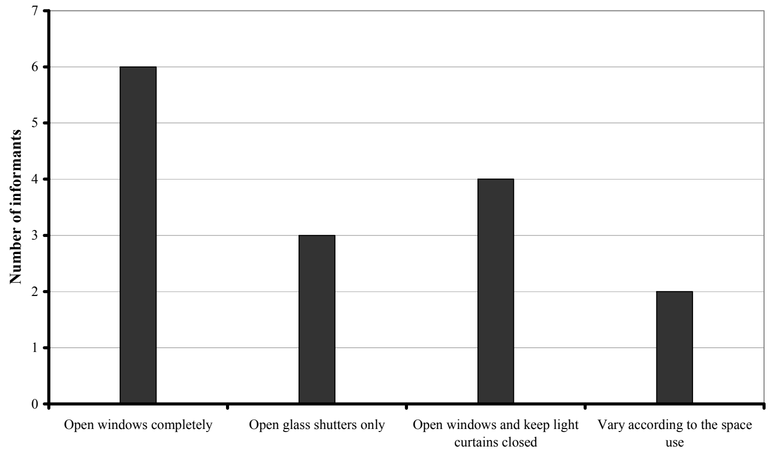


Figure 6-7: How the informants open the windows for ventilation purposes

The way by which the occupants normally open the windows greatly affects the natural ventilation performance in the dwellings. When the informants were asked about that, (*6 out of 15*) reported that they normally open the windows completely (*100% opening area*) (Figure 6-7). They said that they open the windows in that way in order to provide the maximum area for the air to flow into the spaces, as the weather is hot and the air is strongly needed for cooling. Four of the informants reported that they are used to opening the windows completely, but keep them covered by light curtain for privacy and protection from mosquitoes and insects (Figure 6-7). Only three of the informants said that they open the glass shutters only and keep the wooden Venetian shutters closed (Figure 6-7). This is to allow air to enter the space through the Venetian shutters holes and, meanwhile, to provide protection from sun radiation as well as dust. The remaining two informants reported that their behaviour in opening the windows varies according to the space use (Figure 6-7). Both of them stated that they used to open the living rooms' windows completely in order to renew the air in the dwellings for internal air quality purposes, as a low degree of privacy is required in the living rooms. However, they deal with bedrooms, where privacy is fully required, in a different manner. One of them reported that he only opens the glass shutters in both his bedrooms to avoid privacy breach. The other one said that he only opens the glass shutters in his master bedroom, while keep light curtains over the other bedroom's window, especially at day-time, to avoid heat from the sun.

The informants were asked "*When opening windows, do they feel with noticeable air movement around their bodies or feel that the air is still?*". (*13 out of 15*) reported that they clearly observe the air movement around them in all their dwelling spaces. However, (*2*) informants said that they always feel that the air is still either in all the space or in some of them. By looking into the spaces in which the informants said that they do not feel any air movement, it was found that their orientation was either south-west or south-east. These orientations are opposite to the prevailing wind and this result is expected.

Also, the result that most of informants feel with noticeable air movement is found to be contradicted by the airflow simulation results in the previous section. This can be justified with the different orientation of the simulated case study as distinct from the orientation of the blocks inhabited by the informants.

The informants were asked which of their dwellings' openings they open in order to create airflow current and to allow cross-ventilation across the flat. The informants' responses were analyzed with respect to the dwellings' opening orientations. Four different orientations of the informants' dwellings (*SW/SE, NW/SW, SE and NE*) were found in the block oriented in different way than the simulated block (Figure 6-8). Another two orientations (*SW and NW*) were found in a block that has the same orientation as the simulated block in the previous section. These two orientations are *SW and NW* flats that respectively match *flat (4)* and *flat (2)* in the simulated floor in Figure 5-35 and Figure 5-36.

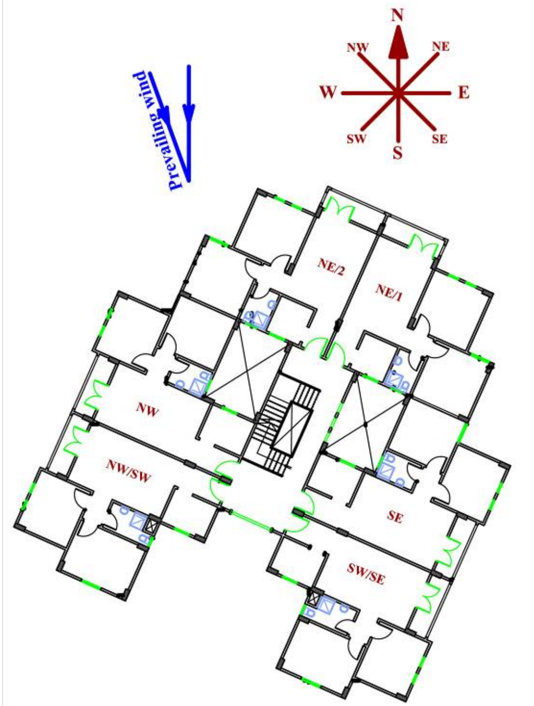


Figure 6-8: The flats' wind orientations in the informants' blocks

In the flats that are oriented (*SW/SE*), the majority of informants (*3 out of 4*) in these flats reported that the best way to allow cross ventilation is to open the living room balcony's door along with the flat's main door. However, one informant said that he opens all spaces' windows along with the flat main door in order to create the required cross-ventilation. In respect to the wind direction and the opened stair well, both scenarios could possibly achieve the required cross-ventilation.

In the flats that are oriented (*NW/SW*), all the informants reported that they mainly open the balcony's door in the living room, which faces the prevailing wind. None of them was found to rely on this opening only. This indicates the awareness of the informants to the necessity of adding an air outlet in order to create cross-ventilation. Two out of (*5*) were found to open the main door of the flat in addition to the balcony's door. One of those five was found to open the bedroom that faces *SW* in addition to the balcony's door. Another informant was found normally to open all other spaces windows, including the bathroom and the kitchen. The last informant of those five said that he only opens the window of the bedroom that faces *NW* in addition to the balcony's door. All these scenarios could create the required cross-ventilation as they have air inlet and air outlets except the last one, as the two opened components in the flat are believed both to be inlets.

Only one informant was found living in the flat with the *SE* orientation (Figure 6-8). He claimed that cross-ventilation can be created by opening the living room balcony's door along with the window in the farthest bedroom from the living room. This scenario could create the cross-ventilation, as the projection of the other bedroom in the flat acts as a wing wall and regulates the air pressure.

The four informants who were found to live in the flat with the *NE/1* orientation were, also, found mainly to open the living room balcony's door. One of them opens the flat's main door with the balcony's door to create cross-ventilation. In addition to the balcony's door, another one was found to create cross-ventilation by opening the windows of the kitchen and the bathroom. Also, one informant reported that he normally opens all openings in his flat for the cross-ventilation to be created. The last one stated that he only open the window of the bedroom nearest to the living room along with the living room balcony's door. All these scenarios could create the required cross-ventilation as they have air inlet and air outlets except the last one, as the two opened openings are believed both to be inlets.

The informant who lives in the flat that faces (*SW*) (*Flat 4*) in the same block as the simulated one reported that he opens the openings of the living room, kitchen and the farthest bedroom from the living room (*B2*). This combination of openings could not create strong cross-ventilation as could be seen from (*flat 4*) in Figure 5-35. However, the informant who lives in the flat (*flat 2*) that faces (*NW*) in the same block reported that he only opens the balcony door of the living room. By using this door only without any of the other spaces' openings, an air current could be created as only in the living room as shown in Figure 5-35.

From the discussion above and regardless of the efficiency of the cross-ventilation created by the informants, it can be argued that most have a basic awareness of how to create airflow inside the flats when needed. Although, most of the informants are normally acting by opening the flat main door, it can be argued that this action is a temporary action that results from the few occupants in the blocks. After the blocks become fully occupied, fewer occupants, if any, will open the flat door for ventilation and will prefer to close it for privacy.

Also, in all the above cross-ventilation scenarios, if the rooms doors are not kept opened, no cross-ventilation will be created. Therefore the informants were asked whether they keep them opened or not. (*14 out of 16*) answered "*yes, we do keep them opened*", while only (2) informants answered "*No, they do not*".

Moreover, four informants justified their non-use of the bathrooms and the kitchens' windows in creating cross-ventilation by:

- These windows are not effective in cooling by ventilation;
- The neighbour could easily breach their privacy through the courtyard, if these window are opened; and
- The undesired smells could be brought into the flat, if these windows are opened

This confirms the validity of describing kitchens and bathrooms' windows, when found to work as air inlets in the airflow simulation analysis, by poor design.

6.3.4. The use of mechanical ventilation

All the informants reported that they are using electric fans either in all spaces within their dwellings or in some spaces. None of them was found to use air conditioning at all. This is because the electric fans are significantly cheaper (*about 170 L.E*/ each) than air conditioning systems (*about 3000 L.E / each*) in the down payment and the electricity consumption. The electric fans used vary between the ceiling fan type and desk fan type. All ceiling fans have 5 ranges of speeds, while desk fans have 3 ranges of speeds. Each informant indicated his preferred operation speed for the fans he uses. The most frequent desired operating speed was calculated statistically for each type of fans by calculating the mode of the informants' answers. The calculations showed that the informants who use ceiling fans most likely prefer operating it on the middle speed (*3*), while those who use desk fans most likely prefer operating it, also, on the middle speed (*2*). The medium rotation speed for the ceiling fans could provide an output mean airspeed ranges between 1.265 to 1.595 m/s on a height of 1.5 m from the floor level and according to the profile shown in Figure 6-9 [230]. This range of airspeed can be set as the desired airspeed of the informants. Half the informants (*8*) reported that they use the fans during both day and night-times, while 6 and 2 of them reported that they use them during day-time only and night-time only respectively (Figure 6-10).

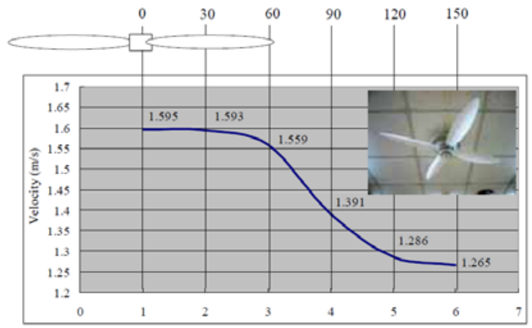


Figure 6-9: Profile of mean air velocity generated by the ceiling fan at height 150cm and at medium rotation speed, after Chiang et al[230]

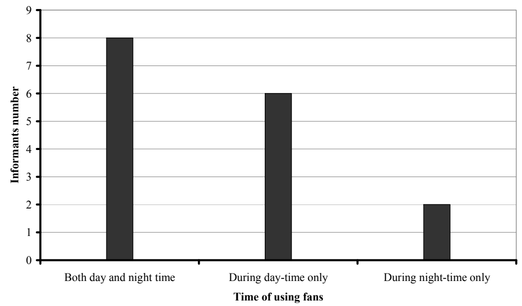


Figure 6-10: The preferred time in which the informants, most likely, use the fans

In terms of the reasons of using the fans, the following reasons took the same weight in the informants responses:

- Using them at day time only, when opening the window is not possible due to the high outside temperature;
- Using them all the day round due to the lack of airflow inside the dwelling; and
- Using them because the airspeed that comes from the window is not enough to provide comfortable conditions, so they increase its velocity by using the fans.

6.3.5. The residents' evaluation of the natural ventilation performance in their dwellings

In this section, the informants' satisfactions with natural ventilation in their dwellings and their awareness with the other passive measures for achieving thermal comfort were investigated. Also, their opinions as to how to improve natural ventilation in their dwellings were investigated.

When they were asked whether they were satisfied with natural ventilation or not, the majority of them (*14 out of 16*) reported that they are, in general, satisfied with natural ventilation performance. However, only two informants said that they are dissatisfied. Those who reported dissatisfaction referred that to the extremely hot weather and the weak airflow within their dwellings. However, those who answered (*satisfied*) gave some reasons such as:

- The airflow here (*they meant the city*) is fair enough and available;
- The city is located up hill and has good wind exposure;
- The air here (*they meant the city*) is fresh and clean;
- My flat is in the last floor and picks very good airflow; and
- My flat facing north (*predominant wind direction*).

When these reasons are looked at, it can be clearly seen that most of the informants gave these reasons based on their believe that the city has better wind flow than anywhere else, rather than based their opinion on their dwellings performance. Therefore, they believe that nothing will be better than what they have already. So, their response could not at all be connected with their dwellings' performance.

The informants were asked "*Do they see that providing suitable natural ventilation is the solution to provide thermal comfort during the summer time?"*. The majority of them (*13 out of 16*) answered "*Yes*" and only (*3*) informants answered "*No*". Those who answered "*No*" said that the extremely hot temperature hinders any possibility of effective natural ventilation and the use of mechanical ventilation is a must. They added that it will be better to provide shading devices along with mechanical ventilation equipments. However, those who answered "*Yes*" gave many reasonable reasons for their response such as:

- The availability of natural sources that creates good potential for using natural ventilation;
- Saving energy through decreasing the use of mechanical ventilation equipments; and
- Natural ventilation is healthier and better that mechanical ventilation.

When they asked about the alternatives that could achieve thermal comfort, more than half of them had no idea, while the rest stated the use of mechanical ventilation as the only alternative.

The informants were then consulted on how to improve natural ventilation performance through design parameters. They were given a list of modifications, which could possibly enhance natural ventilation performance, to choose from. In addition, they were given the opportunity to raise another alternative, if they would not find any alternative from the given list to do the job. This list of parameters was:

- Increasing the opening's size;
- Decreasing the opening's size;
- Change the location of the opening;
- Adding another opening in the room;
- Treating the opening's design in order to induce more air to enter the room;
- Providing openings above the rooms' doors in order to allow cross ventilation without opening the doors and hindering the privacy;
- Adding a wind catcher as the room is located on a downwind façade where no air enters;
- In general, the dwelling's design is a total failure and needs to be changed completely in order to achieve good air movement across it

By matching their answers with the rooms associated to these answers, none of them was found to give a valid choice and they chose some options from the list in haphazard manner. This indicates their unawareness of the effect of any of the options given to them. The full set of the questionnaire's data and its analysis can be found in the spreadsheet of (*Appendix G*).

6.4. Conclusions

To summarize, a subjective evaluation study was conducted with the case study's occupants by using a designed questionnaire in order to understand their subjective response toward using natural ventilation as a passive cooling strategy.

Although the number of questioned informants was not enough to generalize the results of the questionnaire, many useful indications could be understood from them, such as:

- The majority of informants are thermally uncomfortable either during summer or winter in their dwellings;
- Most of them respond to hot weather by opening windows for ventilation cooling;
- The main reasons for not opening the windows were found to be privacy, dust, insects, non-effective air movement and sometimes the tendency to using fans in bedrooms;
- The intuitive use of both; night purge ventilation and comfort ventilation strategies by the informants as a form of their adaptation to maintain thermal comfort;
- Most informants are found to be keen to create cross-ventilation throughout their dwellings by opening some windows and doors along with keeping room doors opened all the time.
- All the informants were found to use fans in all or some of their dwelling spaces either; to avoid opening windows during hot day-time, to improve the movement of their dwellings' still air or for enhancing the airspeed around their bodies;
- By comparing the preferred speed of the informants' fans with the known airspeed profile generated by the standard ceiling fan, it was found the informants prefer airspeed range of (*1.265 to 1.595 m/s*) around their bodies.
- The informants justified their satisfaction with natural ventilation by the availability of

such natural resources in their city, it decreases energy consumption and it is healthier than mechanical ventilation; and

- The informants were not aware of the effect of any of the design parameters that could actually enhance airflow.

All the problems in natural ventilation performance, which resulted from the evaluation study presented in the previous three chapters, were identified and need to be addressed. Formulating the design measures that could possibly introduce solutions for these problems and so could enhance the airflow for ventilation purposes inside the case study is the subject of the next part of the thesis (*The natural ventilation enhancement*).

Part 3:
Enhancing Natural ventilation performance in the case study

Chapter 7:
Formulating possible measures to enhance natural ventilation inside the case study

7.1. Chapter seven introduction

The work in this chapter aims to formulate the design measures and their parameters that could be used to enhance natural ventilation performance inside the case study. The chapter starts with drawing the design measures and their parameters, from the literature review in chapter three, that are believed to have positive effect on the air movement in and around the buildings and, in turn, positively affect natural ventilation performance. These measures are extracted in three main levels as classified in chapter 3; the macro design level, the intermediate design level and the micro design level. A list of possible measures for optimizing natural ventilation performance will be then formulated.

7.2. Possible measures that could be used for natural ventilation enhancement

Based on the literature review conducted in chapter three, many design measures and their parameters were found to have significant positive effect on natural ventilation performance on macro, intermediate and micro design levels. Taking into account the same classification of the reviewed design measures, the ventilation enhancement measures on macro, intermediate and micro design level could be extracted with reference to chapter three as in Table 7-1.

The huge list of measures summarized on all design levels (Table 7-1) could not be all applied to the case study enhancement.

Table 7-1: The studied ventilation measures and best configurations for ventilation enhancement within macro, intermediate and micro design levels.

Design level	Design measures		Studied parameter	Best practice	Notes
Macro-level	Site landform		- Flat site - Sloping site - Undulating site	Middle of the windward facing slope	Great attention has to be given to the local climate
	Availability of heat sinks (large water bodies and forests)		- Near them - Away from them	Build the building near to them to benefit from cold sea breeze	Risk of floods should be considered
	Urban form		- Compact form - Disperse form - Clustered form - Combined form	- Disperse form - Clustered form	- The disperse form can be used when ventilation has priority and clustered form when sun shading has priority. - Distance between buildings and site orientation should be considered.
	Street design	Streets wind orientation	- Normal - Oblique - Parallel to wind	20º to 30º oblique to wind direction	-
		Street canyon geometry	- H/W < 0.3 - 0.3 < H/W < 0.65 - H/W =1 - H/W = 1.5	H/W ratio of 0.5 to 0.44	Great attention has to be given to the local climate
Intermediate-level	Building adjacency		- Detached - Semi-detached - Rows lining single-loaded corridors - Rows lining double-loaded corridors	detached and rows lining single-loaded corridors for their ability to provide cross ventilation	Orientation and arrangement should be considered
	Buildings arrangement	Locating a building in a site	- Building location in the site - The distance between the building and adjacent buildings = 0.5, 1.0, 1.5 its height	- The building should be located for maximum exposure to the desired wind - The building aligned to the adjacent building with distance between them = approximately 1.5 their height	Orientation and wind profile in the site have significant effect and should be both considered
		Arranging small group of buildings	Different general arrangements of a group of four buildings maximum	arranging the buildings around a central space opened to wind direction	Unlimited arrangements are possible and should be designed according to the orientation and wind profile in the site
		Arranging a compound	- Aligned rows arrangement - Staggered arrangements	Staggered arrangement	Staggered arrangement was also rejected by many researchers
	Soft landscape	Vegetation profile	Many arrangements, locations, patterns and functions of the vegetation	Dependant on the design proposal	-
		Availability of fountains and ponds	As microclimate modifier	Trickle fountains are recommended for cooling air by evaporation	Not recommended in humid climates

Micro-level	Building mass			General configuration such as: - Plan aspect ratio (length/width) - Area density	- Narrow depth plan along wind direction - Low (length/width) ratio - Relatively wide and low buildings built on a site with low to medium area density	No literature was found to introduce an absolute aspect ratio for best airflow and ventilation performance in buildings.
	Building form and shape		Building form	- Atrium building form - Courtyard building form - Modern pavilion block building form	- Atrium: good for stack ventilation - Open courtyards are more energy efficient in smaller building heights, while, atrium buildings performed better at high building heights. - Courtyard aspect ratio (0.3 < H/W <1) and (H/W= 0.25) with gap. - Porous pavilion block with 50% voids	No absolute preference has been set
			Building shape	- Rectangular shape - U-shape - L-shape - T-shape - Square shape - Irregular or corrugated shapes	Irregular or corrugated shapes	No absolute preference has been set due to vast varieties
	Building orientation			- 30^{o} to 120^{o} - 45^{o}	45^{o}	Related to the street orientation
	Building envelope	Building roof shape		flat, single-slope, double-slope (Pitched), dome or vault	- No preference and dependant on orientation - Dome roof could enhance internal stack effect due to the difference in its surface temperature	No absolute preference has been set
		Opening design	Opening size	- 5 to 30% from the served floor area - Ao/Ai = 0.5, 1.5, 2.0, 3.0	-Air inlet area = 20% of the floor area, - Between 15% - 20% of façade area -Higher maximum internal airspeed was obtained when (Ao/Ai = 3) with oblique wind direction 45^{o}. -Higher average speeds and reasonable max. speed was when Ao/Ai = 1.5	- Local building regulation control the minimum size of openings for ventilation - Larger inlet or outlet was a debatable point between the researchers -Larger outlets than inlets are preferable in bedrooms, while larger inlets are preferable in living rooms. - Cross-ventilation should be provided to maximize the opening size effect
			Opening position	- Horizontal position - vertical position	- The air inlets and outlets should be located in the portion of façade that secures maximum pressure differential between them - The opening position should be close to the thermal exchange surfaces - The position of openings on lateral walls should be as far part as possible to avoid short circuits - The outlets should be always higher than the inlets	The height of the outlet has almost neglected effect in directing the airflow

		Opening number	- Provide single or more than one opening in different external walls - Provide single or more than one opening in the same external wall	-Providing at least one inlet and one outlet in different walls - Two openings as far apart as possible should be provided in the same wall	Oblique orientation to the wind direction should be provided
		Opening type	simple opening, vertical-vane opening and horizontal-vane opening	Side-hinged casement in the vertical-vane opening	Selecting window type is according to the designer proposal.
	Natural ventilation inducers	Building envelope projections	- Horizontal projection - Vertical projection	- Horizontal projection with gab between it and the façade wall - Vertical projection depth of the same window's width associated with 45° orientation	- Horizontal projections have their greatest effect in directing the airflow not in increasing its speed. - The depth of the wing wall, in multi-space buildings, should not more than one-half the distance between the wing wall of the first room's outlet and the beginning of the second room's inlet.
		Ventilation shafts	Different head opening number, orientation, cross-sections, height and dimensions	- Rectangular cross-section wind catcher with one opening directed to the wind. - It is enough to use wind catcher with height of (4m) and cross-section of (0.57m * 0.57m)	-
		Double skin façade	- Full height DSF - Floor to floor DSF - Natural ventilation system DSF	Vary according to the design proposal and climate nature	Its tendency to overheat and increase the cooling loads of the attached internal space with inefficient cost treatment
	Space height		- High heights - Low normal heights (2.5 to 2.7 m)	Found not to have any significant effect on the internal airflow pattern. It was found only that very high ceiling could have important role in allowing thermal stratification and improving stack ventilation	No other studies were found in the available literature concerned with the effect of ceiling height on airflow, airspeed and natural ventilation inside spaces.
	Internal spatial planning		- Horizontal distribution of spaces - Vertical distribution of spaces - Increasing internal spaces porosity	- Providing large connections between spaces and reducing the number of spaces through which the air has to pass -Locating the larger and longer rooms in the upwind side in order to avoid air stagnation - Locating kitchens and bathrooms with large outlets in leeward side - Creating connections between vertical spaces in order to enhance stack ventilation - Adding night ventilation opening over the doors and windows (transom windows) to enhance cross-ventilation between space at night, when spaces' doors and windows are kept closed for privacy	-

The nature of the case study and the less possible control over some listed measures hindered the use of them in the enhancement process. In addition, some measures could be only applied to new designs rather than already designed case study. Moreover, the nature of the research context forced some measures to be implemented in the enhancement process. Therefore, these measures should be discussed, filtered and modified in order to select the final list of measures that will be applied to the case study and their effect on natural ventilation will be quantified in the enhancement process.

7.3. Selected measures

In this section, all the design measures and their parameters that mentioned in Table 7-1 will be filtered in order to select the most appropriate measures to be used in the enhancement process. The filtering process will be conducted bearing in mind that the proposed measures will be applied to an already designed case study.

On the macro design level, the site landform and heat sinks measures will be excluded from the choice, as the architect does not have any control over their design parameters. In addition, their design parameters seem to be not applicable in the research context. The landform in most of the Egyptian deserts is almost flat and no large water bodies or forests could be found within these deserts.

The urban form measures seem to be more suitable to be applied to a newly designed housing prototype rather than to be applied to an already designed case study. The best natural ventilation measures that reported by pervious studies for this parameter are the disperse form [90, 95, 96] and the clustered form [85, 91]. The unlimited diversity of the clustered form configuration and designs prevent quantifying its effect. Moreover, the nature of the research case study design (*stand alone detached blocks*) encourage the use of the disperse form. However, great attention has to be given to the buildings arrangement and the distance between them. *The disperse form measure* is then selected among these design measures to be used in the enhancement process.

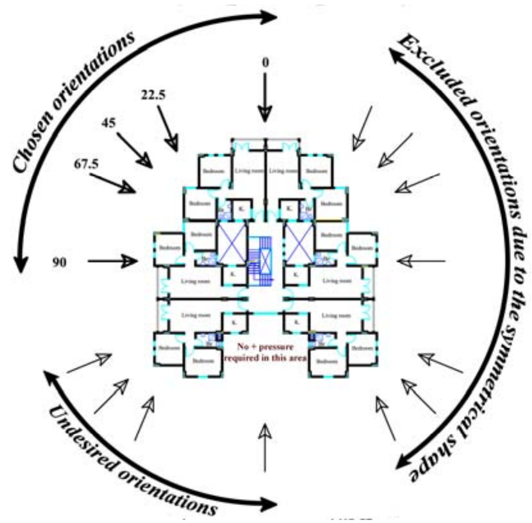


Figure 7-1: The orientation measures choice

In terms of street design, The street wind orientation is greatly connected to the building orientation design measure in the micro-level category. Previous studies [85, 99, 100] recommended orienting the street grid and buildings to be oblique to the wind direction and found the measures of an angle between 20^o and 30^o or 45^o would be the most suitable orientation for efficient ventilation. These measures could not be taken as absolutes, as most of them were extracted from studying simple single space models. The complex building design and the building arrangements on site could modify the wind direction, create local wind environment as well as exclude some orientations for specific reasons. By looking at the research case study, it can be seen that the case study was designed vertically in symmetrical shape (Figure 7-1). Therefore, it will be time consuming to study the effect of all orientation measures all around it and it is enough to study just the measures for one vertical half of the orientation's circle. According to that, one of the halves was excluded (Figure 7-1). The location of the bathrooms and kitchens in the lower part of the other half forced excluding this section from the choice. Applying these orientation measures will apply positive pressure on the lower area of the plan and maximize the possibility of the kitchens and bathrooms openings to be air inlets of their flats (Figure 7-1). Such an effect is not desired, as it was reported to be one of the ventilation problems in the evaluation study earlier in this work. According to this, the upper left quarter of the orientation’s circle was found to me the most suitable orientation range for the case study nature. Therefore, and by considering recommended orientation measures from previous studies, the orientations of 0^o, 22.5^o, 45^o, 67.5^o *and* 90^o were then chosen among the orientation measures to be tested in the enhancement process for both the street and building orientation.

The last design measure in this level (*macro-level*) is the street canyon geometry. The recommended parameters for this measure are H/W of 0.5 to 0.44 [95]. Giving the fact that the height of the case study is (*H=18m*), it requires a street width of (*W=36m or larger*) to achieve the recommended H/W ratio. Because of the hot arid nature of the Egyptian deserts climate, where the compact form is required, it was necessary to test the effect of larger ratios. Larger H/W ratios could possibly achieve good internal ventilation conditions in some spaces due to the turbulence that results from the adjacent blocks’ wakes. Therefore, it was necessary to include H/W ratios that represent the deep (*H/W=1.5*) and regular (*H/W=1*) canyon configuration. The regular canyon configuration in the case study requires street width of (*W=18m*) and the deep canyon requires street width of (*W=12m*). The H/W ratio of 1.5 is the upper limit allowed by the Egyptian buildings’ law. It will be useful also to include smaller H/W ratio, in order to quantify the effect of the isolated roughness flow (*IRF*), although this configuration is not recommended for the research context. A ratio of (*H/W=0.25*) was selected, where (*W =72m*) as it lies in the middle of the range at which the named above flow happens. According to the discussion above, the H/W ratios of (*1.5, 1.0, 0.5 and 0.25*) that give distances between buildings (*W= 12m, 18m, 36m and 72m*) respectively were then chosen among the canyon parameters to be tested in the enhancement process.

On the intermediate design level, the building adjacency design measure was excluded, as the case study is designed in detached blocks with no option given allowing attachment to each other. For the buildings' arrangement design measure under this level (Table 7-1), the previous studies raised a debate about the use of either aligned rows arrangement or staggered arrangement for efficient ventilation. This encourages this work to choose both arrangements' parameters; *the aligned rows and the staggered arrangements* to be tested in the enhancement process.

The last design measure in the intermediate level is the soft landscaping measures (Table 7-1). The huge diversity of the effect of the vegetation design measures and its parameters on the air movement and the time limitation for this research project prevent the implementation of such measure in the enhancement process. However, the positive effect of the vegetation profile and the availability of fountains and ponds design measures on the air properties and thermal comfort forces their existence in the site. Therefore, this work prefers to recommend their existence in the case study site rather than includes them in the air movement enhancement process. The summery of the proposed measures to be applied to the case study in the enhancement process within the macro and intermediate design levels can be listed as in Table 7-2.

Table 7-2: The proposed measures and their parameters for applying in ventilation enhancement within the macro and intermediate design levels.

Design level	Design measure	Proposed parameters
Macro-level	Street orientation	- Normal 0º, - Oblique 22.5º, - Oblique 45º, - Oblique 67.5º and - Perpendicular 90º.
	Street canyon geometry	- H/W = 1.5 (*Deep canyon with width of 12m*), - H/W = 1.0 (*Regular canyon with width of 18m*), - H/W = 0.5 (*Shallow canyon with width of 36m*) and - H/W = 0.25 (*Shallow canyon with width of 72m*).
Intermediate-level	Buildings arrangement	- Aligned rows arrangement - Staggered arrangement

On the micro design level, the building mass, building form and building shape measures will be excluded from the choice, as their design parameters are more suitable for designing a new housing prototype rather than being applied to an already designed and built prototypes. The research case study has its own fixed form, shape and mass configuration. As long as this work aims to enhance the case study as designed and as built, there is no point to study the effect of these measures. The building orientation design measure within this design level was dealt with earlier along with the street orientation measure.

The building envelope design measures including roof shape and opening design was dealt with as follows. Again, the case study is being enhanced as designed and has its own flat roof shape, which is not proposed to be changed. Therefore, the parameters of the building roof shape measure were excluded from the choice.

In terms of the building openings design measure, it was divided into four sub-measures; openings size, openings position, openings number and openings type (Table 7-1). Each sub-measure here has its own parameters. The openings size for best ventilation performance was reported by the previous studies [127, 128, 153] to be 20% of the served floor area. 20% of the floor area in such a hot climate can be large and unsuitable as well as occupying a large wall area that could prevent appropriate furnishing. Therefore, the 20% size was set as the upper limit for the selected parameters in this design measure. The minimum size of the openings was also determined by the Egyptian building low to be 8% from the residential spaces' floor area and 10% from the service spaces' floor area. Therefore, they were set to be the lower limit for the selected measures in this design parameter. In addition, a size of 15% was excluded from the choice as most of the base case opening size range between (*12.92% and 18.20%*) from the served area. According to this discussion, the ratios of (*8%, 10% and 20%*) from the served floor area were then chosen among the opening size measure's parameters to be tested in the enhancement process. The measures of the Ao/Ai ratio were excluded from the choice, as the main proposed outlets for the case study's flats are the kitchens and bathrooms' windows. Those windows are already small and the small areas of the kitchens and bathrooms do not allow them to be changed to larger size than inlets. So, they will be always smaller than inlets.

As for the opening position, the proposed outlets (*kitchens and bathrooms' windows*) in the case study are used to be located in higher levels than the rooms' windows (*proposed inlets*). However, this work will consider the horizontal position of the openings. Two parameters of openings position were selected to quantify their effect in the enhancement process. They are:

- *Locating the outlets and inlets in the same space in the portion of the façade that secures maximum pressure difference between them, and*
- *Positioning the openings in lateral walls, if found, far apart as possible to avoid short circuits.*

In terms of the opening number, and as recommended by the previous studies [33, 127, 168], the measure of *providing more than one opening in the same space in either the same wall or two different walls* was selected to be tested in the enhancement process.

The case study is already using the recommended parameter in terms of the opening type measure (*single-hinged casement opening*). Therefore, no measures will be added in the enhancement process and this design parameter was excluded from the choice.

In terms of the natural ventilation inducers, double skin façade option was excluded from the choice, as it was reported to be more suitable for cold climates rather than hot climates. However, where needed, the research chooses to use vertical projections *(wing walls) with the depth equal to half the opening width and full opening width* (Figure 7-2). *Another wing will be added to the best predicted performing case of them,* as shown in Figure 7-2, in order to

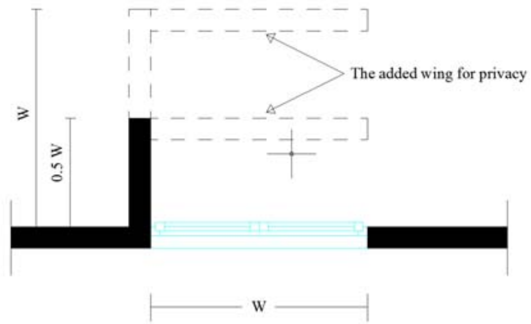


Figure 7-2: The proposed wing walls measures

provide privacy to the spaces that was indicated as a desirable measure in the evaluation study earlier in this work.

In terms of ventilation shafts that were used intensively in the traditional Egyptian architecture, the research chose to quantify the effect of two different wind catcher measures, where needed, in the enhancement process. The recommended measure [148] *(Square cross-section (0.57m*0.57m) wind catcher with one opening directed to the wind and with height of 4m) and double this cross section* (Figure 7-3).

Due to the lack of previous studies that investigate the effect of space height on airflow pattern and airspeed inside spaces, this parameter was chosen to be tested in enhancement process in order to bridge this gap in knowledge. The normal space height in the case study is 3.0 m. The proposed heights that were chosen to be tested are *3.25 m, 3.50 m and 3.75*.

As for the internal spatial planning measure, the distribution of the internal spaces either vertically or horizontally is not applicable for the research case study. However, the internal spaces porosity could be increased through creating cross-ventilation between spaces by *adding transom windows above the internal doors, providing lower louvered openings to the internal doors, or adding both of them* (Figure 7-4). The transom window above each door will be the same width of the door above which it will be added and with height of (*30 cm*). Limiting the height of the transom window to (*30 cm*) is necessary, as the clear floor height of 3.00 m is used in the case study. 2.20m is occupied by the door itself and 50 cm should be left under ceiling in order to allow a minimum drop of the concrete bearing beam (Figure 7-4).

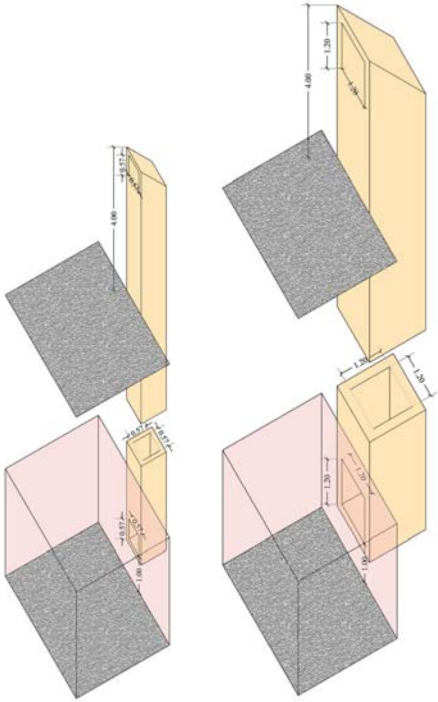


Figure 7-3: The proposed wind catcher parameters

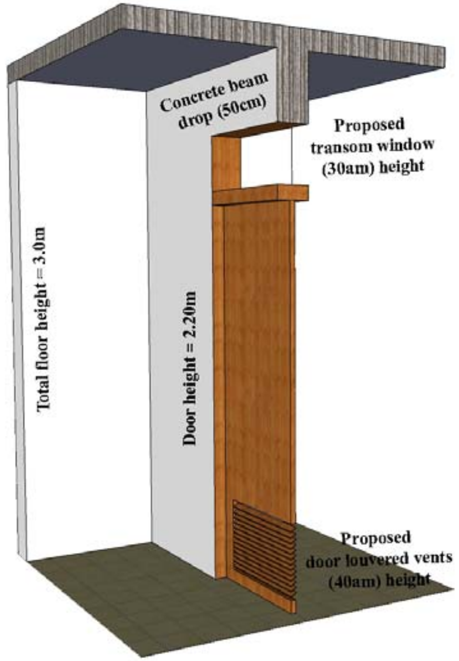


Figure 7-4: The proposed transom window and louvered vents to allow cross-ventilation and keep the privacy un-breached

These measures and their parameters were selected to be applied to the case study and quantify their effect. The summery of the proposed measures and their parameters to be applied to the case study in the enhancement process within the micro design level can be listed as in Table 7-3.

Table 7-3: The proposed measures for applying in ventilation enhancement within the micro design level.

Design level	Design measures		Proposed parameters
Micro-level	Opening design	Opening size	- 8% of served floor area, - 10% of served floor area, - 20% of served floor area,
		Opening position	- Locating the outlets and inlets in the same space in the portion of the façade that secures maximum pressure difference between them, and - Positioning the openings in lateral walls, if found, far apart as possible to avoid short circuits
		Opening number	- Providing more than one opening in the same space in either the same wall or two different walls.
	Natural ventilation inducers	Building envelope projections	- Wing wall with depth equal to half the opening width, - Wing wall with depth equal to full the opening width, - Adding wing for privacy to the best option of the first two measures.
		Ventilation shafts	- Square cross-section (0.57m*0.57m) wind catcher with one opening directed to the wind and with height of 4m, and - Square cross-section (1.2m*1.2m) wind catcher with one opening directed to the wind and with height of 4m
	Space height		- 3.25 m, - 3.50 m, and - 3.75 m.
	Internal spatial planning		- Adding transom windows above the internal doors, - Adding lower louvered opening to each internal door, and - Adding both of them

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

Chapter 8:
Enhancing natural ventilation performance in the case study

8.1. Chapter eight introduction

In this chapter, The detailed methodology of conducting the enhancement process will be explained. Then the results of the composed simulation cases for applying the selected measures in order to enhance natural ventilation performance in the case study are presented, analyzed and discussed. Firstly, the airflow performance in the original base case is explained. Then the performance of each set of the selected measures within macro, intermediate and micro design levels are introduced in order to reach the final overall enhanced case.

8.2. The enhancement detailed methodology

The natural ventilation enhancement part of this work will be conducted using *FloVent* computational fluid dynamics (*CFD*) simulation software. The effectiveness of the proposed design measures will be quantified through conducting parametric analysis, in which each measure will be applied to a base case. The effectiveness of each parameter of these measures will be judged in terms of both; the average volumetric airspeed across the internal spaces and the quality of the air movement pattern. Enhancing the volumetric airspeed inside a space maximizes the use of comfort ventilation strategy, while enhancing the air movement pattern inside a space secures good exposure of the building fabric to the night airflow and maximizes the cooling effect of night ventilation. The details of conducting this study, in terms of the determination of the base case and the procedures of conducting the parametric analysis, are explained below.

8.2.1. The base case

When the natural ventilation performance in the case study was evaluated in the previous part of this research, the evaluated block was chosen in location that provides the maximum potential for natural ventilation. However, when working on the enhancement, it was decided to choose a block with the most prevailing surrounding conditions. Therefore, a block in the middle of the compound with the most prevailing wind orientation and adjacency's status was chosen to be the base case in this study (Figure 8-1). Also, a middle floor within the block was modelled in detail to study the effect of each measure on the ventilation performance in each space. The cross-ventilation between internal spaces was prevented by modelling the internal doors as closed doors. Locating the detailed block in the middle of the compound with preventing cross-ventilation by closing internal doors could provide the worst possible case in airflow performance. Therefore, it was employed in the enhancement process.

Figure 8-1: The proposed block to be the base case in the enhancement process

A model for the base case was constructed in *FloVent* with the same settings and grid configuration as the site model in the evaluation study (*For more information, refer to chapter 5*). The same boundary layer settings were attached to the model's solution domain.

The results of the airflow patterns and airspeed in and around the base case will then be extracted and analyzed as follows:

- The airflow quality, sources, paths, and distribution inside the detailed floor will be analyzed; and

- The airspeed will be volumetrically averaged within the main living spaces (*living rooms and bedrooms*) in each flat in the detailed floor and expressed as a percentage from the prevailing wind speed observed at the weather station (*5.6 m/s*) using the equation:

$$[V_{i\text{-}avg} / V_w] \times 100 \qquad \text{(Eq: 8-1)}$$

Where:
Vi-avg = average volumetric internal airspeed
Vw = Observed wind speed at weather station that attached to the model (5.6m/s)

These results will form the datum line that the enhancement process results will be compared to. This is in order to quantify the effect of applying the proposed measures in enhancing airflow performance in the case study. It should be noted here that this base case will be called (*The original base case*) herein after.

8.2.2. Quantifying the effect of the selected measures

The research case study could be in one of four different stages. It could be:

- Built, finalized and handed over to people;
- Built but still under government control;
- Concrete skeleton built only; or
- Not built yet.

Each stage from the above four stages creates limitations that control the range of interventions that could be apply to the case study. For example, the case study blocks that have already built and handed over to people allow no intervention and no enhancement measures could be applied. This is because any decision of applying change to the design should be taken individually, as no one can force the residents to apply any changes they refuse for individual or financial reasons. The possibility of applying the proposed design interventions increases for the other stages to reach its maximum in the (*not built yet*) stage.

In order to maximize the benefit from this work and cast a practical nature to its results, the research chose to work on the (*not built yet*) stage. This stage gives the opportunity to apply all the proposed enhancement measures, providing by such the maximum possible intervention to the case study without changing its design. By doing so, the research presents a spectrum of solutions that the responsible of each stage either, individuals, authority or the government can choose from according to their affordability.

To begin with, the enhancement process will deal with the selected measures in the macro and intermediate design levels (Table 7-2). This will be done in a designed virtual site to facilitate changing the blocks arrangement, canyon width and orientation. Because the orientation, street canyon configuration and building arrangement are all connected and have a combined effect, it was decided to quantify this combined effect rather than dealing individually with each measure. Accordingly, virtual sites with the same number of blocks in the case study's site (*64 blocks*) were designed. Each site consists of (*8 x 8 blocks*) and the detailed block was located at the middle of each site. In theses virtual sites, the two selected arrangements (*Aligned rows and staggered arrangement*) are combined with the selected four parameters of street width (*12m, 18m, 36m and 72m*) introducing by such eight different sites. These eight different combined cases will be modelled in *FloVent* and tested against the proposed five orientations (0^o, 22.5^o, 45^o, 67.5^o and 90^o) (Figure 8-2). These combinations create 40 simulation cases, as described in Table 8-1.

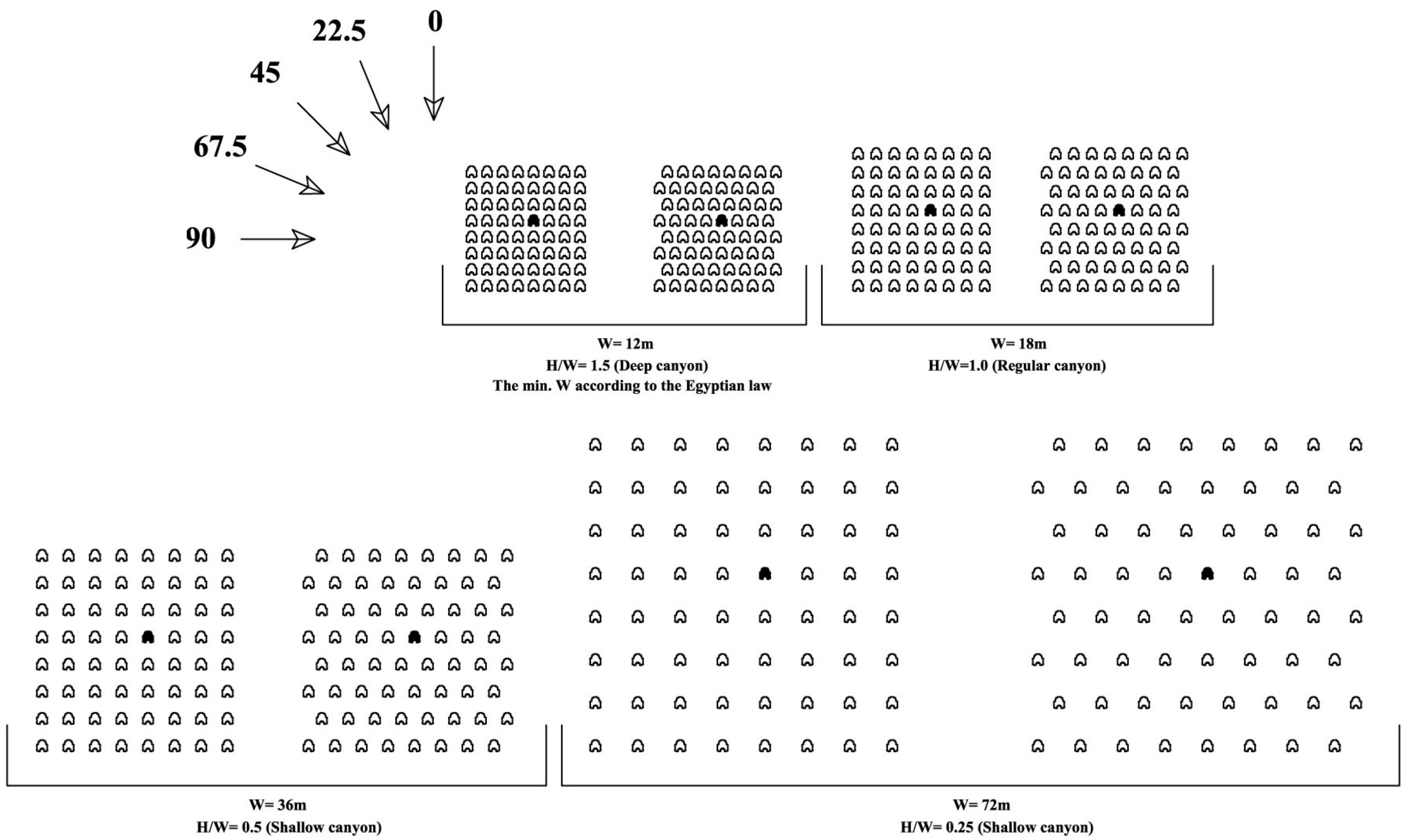


Figure 8-2: Different site configurations that are proposed to be tested in the microclimate level enhancement with the detailed block indicated

Table 8-1: The simulation cases for quantifying the combined effect of the selected macro and intermediate design levels' measures.

Simulation case	Description	Simulation case	Description	Proposed measures to be quantified	Base case to be compared to	Results case
Case (1)	Aligned rows / W= 12 / 0º wind	Case (21)	Staggered / W= 12 / 0º wind	Quantifying the combined effect of building arrangements, orientation and canyon geometry	The original base case	Optimum (1) [OP01]
Case (2)	Aligned rows / W= 18 / 0º wind	Case (22)	Staggered / W= 18 / 0º wind			
Case (3)	Aligned rows / W= 36 / 0º wind	Case (23)	Staggered / W= 36 / 0º wind			
Case (4)	Aligned rows / W= 72 / 0º wind	Case (24)	Staggered / W= 72 / 0º wind			
Case (5)	Aligned rows / W= 12 / 22.5º wind	Case (25)	Staggered / W= 12 / 22.5º wind			
Case (6)	Aligned rows / W= 18 / 22.5º wind	Case (26)	Staggered / W= 18 / 22.5º wind			
Case (7)	Aligned rows / W= 36 / 22.5º wind	Case (27)	Staggered / W= 36 / 22.5º wind			
Case (8)	Aligned rows / W= 72 / 22.5º wind	Case (28)	Staggered / W= 72 / 22.5º wind			
Case (9)	Aligned rows / W= 12 / 45º wind	Case (29)	Staggered / W= 12 / 45º wind			
Case (10)	Aligned rows / W= 18 / 45º wind	Case (30)	Staggered / W= 18 / 45º wind			
Case (11)	Aligned rows / W= 36 / 45º wind	Case (31)	Staggered / W= 36 / 45º wind			
Case (12)	Aligned rows / W= 72 / 45º wind	Case (32)	Staggered / W= 72 / 45º wind			
Case (13)	Aligned rows / W= 12 / 67.5º wind	Case (33)	Staggered / W= 12 / 67.5º wind			
Case (14)	Aligned rows / W= 18 / 67.5º wind	Case (34)	Staggered / W= 18 / 67.5º wind			
Case (15)	Aligned rows / W= 36 / 67.5º wind	Case (35)	Staggered / W= 36 / 67.5º wind			
Case (16)	Aligned rows / W= 72 / 67.5º wind	Case (36)	Staggered / W= 72 / 67.5º wind			
Case (17)	Aligned rows / W= 12 / 90º wind	Case (37)	Staggered / W= 12 / 90º wind			
Case (18)	Aligned rows / W= 18 / 90º wind	Case (38)	Staggered / W= 18 / 90º wind			
Case (19)	Aligned rows / W= 36 / 90º wind	Case (39)	Staggered / W= 36 / 90º wind			
Case (20)	Aligned rows / W= 72 / 90º wind	Case (40)	Staggered / W= 72 / 90º wind			

The results of the macro and intermediate design levels' 40 cases will be analysed as follows:

- The airflow quality, sources, paths, and distribution inside the detailed floor will be analyzed; and
- The airspeed will be volumetrically averaged within the main living spaces (*living rooms and bedrooms*) in each flat in the detailed floor and expressed as a percentage from the speed of the prevailing wind attached to the models (*5.6 m/s*) using equation (Eq: 8-1) as in the original base case analysis methodology explained in section 8.2.1.

This analysis method will be applied to all enhancement cases. The case that will achieve the higher average volumetric airspeed and higher quality airflow pattern in most of the detailed floor spaces will be chosen as the best cases. The results of this best case will be compared to the original base case in order to quantify the enhancing effect of its tested measures. It should be mentioned here that the research is proposing to reach the final enhanced optimum case using an accumulative manner. In other words, the optimum case that achieves the best results in any of the tested measures' set will be used as the base case in quantifying the effect of the next set of measures. Accordingly, the best case from the first 40 simulation cases will be denoted as optimum case (1) *[OP01]* and will be used as the base case in quantifying the effect of the next set measures (*Wing wall measure*).

In terms of quantifying the effect of the selected measures in the micro design level, the proposed measures within this level were applied in different order than that of Table 7-3. This was to facilitate creating airflow inside the case study spaces that are not exposed to airflow and have still air inside. For example, there is no point in increasing or decreasing window size at a space that is not exposed to the prevailing wind; it will have still air inside unless its envelope is treated to induce airflow through it. In addition, some of these measures (Table 7-3) do not take their significant effect until the cross-ventilation is provided, such as opening's size. In general, the proposal here is to create the own ventilation system for each space in the case study before allowing cross-ventilation between spaces in each flat.

The building design enhancement process starts with treating the building envelope first in order to serve this proposal. This is through adding vertical projections' measures and ventilation shaft's measures, where needed and suitable. Three simulation cases (*Case 41, 42 and 43*) are created in order to quantify the effect of different wing walls' parameters. In each case, one wing wall parameter is applied to optimum case (1), where needed. The results of the three cases will be then analyzed in terms of the airflow quality and the average volumetric airspeed within the spaces that the measure is applied to. The best case in its performance among them will be chosen as the optimum case (2) *[OP02]* (Table 8-2).

In order to quantify the effect of the two wind catchers' selected parameters (Table 7-3 and Figure 7-3), each parameter will be add to the spaces in the negative pressure area in the optimum case (2). The best case among those two cases will be selected as the optimum case (3) *[OP03]* (Table 8-2).

In order to enhance the individual ventilation system for each space, a combined simulation case (*Case 46*) will be created through applying the openings' position and the openings' number measures (Table 7-3) to the optimum case (3) (Table 8-2). The pressure profile around the detailed block will be investigated and, where possible, the windows area in the spaces with single window will be divided into two windows to be located in the locations that secure maximum pressure difference between them. The combined effect of applying these measures to optimum case (3) will be quantified and the result simulation case (Optimum case (4) *[OP04]*) is then taken as a base case for the next set of measures.

In the next step, the effect of different space height parameters will be quantified through applying each parameter to the optimum case (4). This creates three simulation cases (*Case 47, 48 and 49*) that employ space heights of (*3.25m, 3.50m and 3.75m*) respectively (Table 8-2). The best case of these three cases will be chosen as optimum case (5) *[OP05]* and then employed as base case for the next set of measures.

At this point of the investigation, it is necessary to allow cross ventilation between spaces before applying the opening's size parameters in order to get the maximum effectiveness from them. This is done through applying the selected parameters in the internal spatial planning design measure that creates cross-ventilation and increases the internal porosity of the optimum case (5). Three different simulation cases will be created (*Case 50, 51 and 52*) as in Table 8-2. In the first case (*case 50*) a transom window above each door will be added.

In the second case (*case 51*), a louvered vent is provided to each door at the lower level (*10 cm above the floor level*) with height of 40 cm and width of (*the door width – 20 cm*) as shown in Figure 7-4. The third case (*Case 52*) includes both; transom windows and louvered vents. The best case that provides the best airflow quality and the higher average airspeed inside spaces among these three cases will be chosen as optimum case (6) *[OP06]*.

The last set of parameters proposed to be tested in the enhancement is the opening size parameters' set. This set of parameters has four different parameters that will be individually applied to the optimum case (6) in order to quantify the effect of the windows' size measure.

Table 8-2: The simulation cases for quantifying the enhancement effect of the selected micro design level's measures and their parameters.

Simulation case	Description	Proposed measures to be quantified	Base case	Result case
Case (41)	OP01 + Wing wall with depth = half the opening width (where needed)	Quantifying the effect of different wing walls parameters	Optimum (1) OP01	Optimum (2) OP02
Case (42)	OP01 + Wing wall with depth = the same opening width (where needed)			
Case (43)	OP01 + Added wing for privacy to the best measure from the last two			
Case (44)	OP02 + Square cross-section (0.57m*0.57m) wind catcher with height of 4m (where needed)	Quantifying the effect of different wind catcher parameters	Optimum (2) OP02	Optimum (3) OP03
Case (45)	OP02 + Square cross-section (1.20m*1.20m) wind catcher with height of 4m (where needed)			
Case (46)	OP03 + Adding another window to the space, where possible + positioning the openings in locations that secures maximum pressure difference, where possible	Quantifying the effect of opening number and position	Optimum (3) OP03	Optimum (4) OP04
Case (47)	OP04 + space height 3.25m	Quantifying the effect of ceiling height	Optimum (4) OP04	Optimum (5) OP05
Case (48)	OP04 + space height 3.50m			
Case (49)	OP04 + space height 3.75m			

Simulation case	Description	Proposed measures to be quantified	Base case	Result case
Case (50)	OP05 + Adding transom windows above the internal doors	Quantifying the effect of creating cross-ventilation through increasing internal porosity	Optimum (5) OP05	Optimum (6) OP06
Case (51)	OP05 + Adding lower louvered opening to each internal door			
Case (52)	OP05 + Adding lower louvered openings + transom windows			
Case (53)	OP06 + windows area (8% of served floor area)	Quantifying the effect of windows size	Optimum (6) OP06	The final enhanced case (FEC) to be compared to the original base case
Case (54)	OP06 + windows area (10% of served floor area)			
Case (55)	OP06 + windows area (20% of served floor area)			

Three simulation cases will be tested (*Case 53, 54 and 55*) in order to quantify the effect of the window's size of 8%, 10% and 20% of the space floor area respectively. The openings size will be changed in width while keeping the heights constant, except for the spaces that do not allow that. In this case, the opening height will be changed with keeping the sill height constant.

The best case of this set will contain the best performing parameters among all the tested parameters and it will be the final enhanced case *[FEC]* that represents the final output of this research work. The performance of this final case will be compared to the performance of the original base case in order to quantify the amount of enhancement applied to the case study.

Figure 8-3 illustrates the methodological flow and stages of the enhancement process as explained above.

8.3. CFD results, analysis and discussion

The results of airflow enhancement process and their discussion, according to the methodology that was explained above, are introduced in details in the next section. For the full set of simulation results and data, refer to *Appendix H*.

8.3.1. The original base case performance

The simulation results of the airflow quality and the average volumetric airspeed in the original base case's spaces are shown and discussed below.

The simulation results of the original base case showed a poor air movement within the detailed floor of the block under investigation as shown in Figure 8-4. It can be clearly seen from the figure that the air has no access to most of the floor spaces. The main air stream that accesses the whole floor comes from the windows of both kitchens (*K1 and K6*) and the

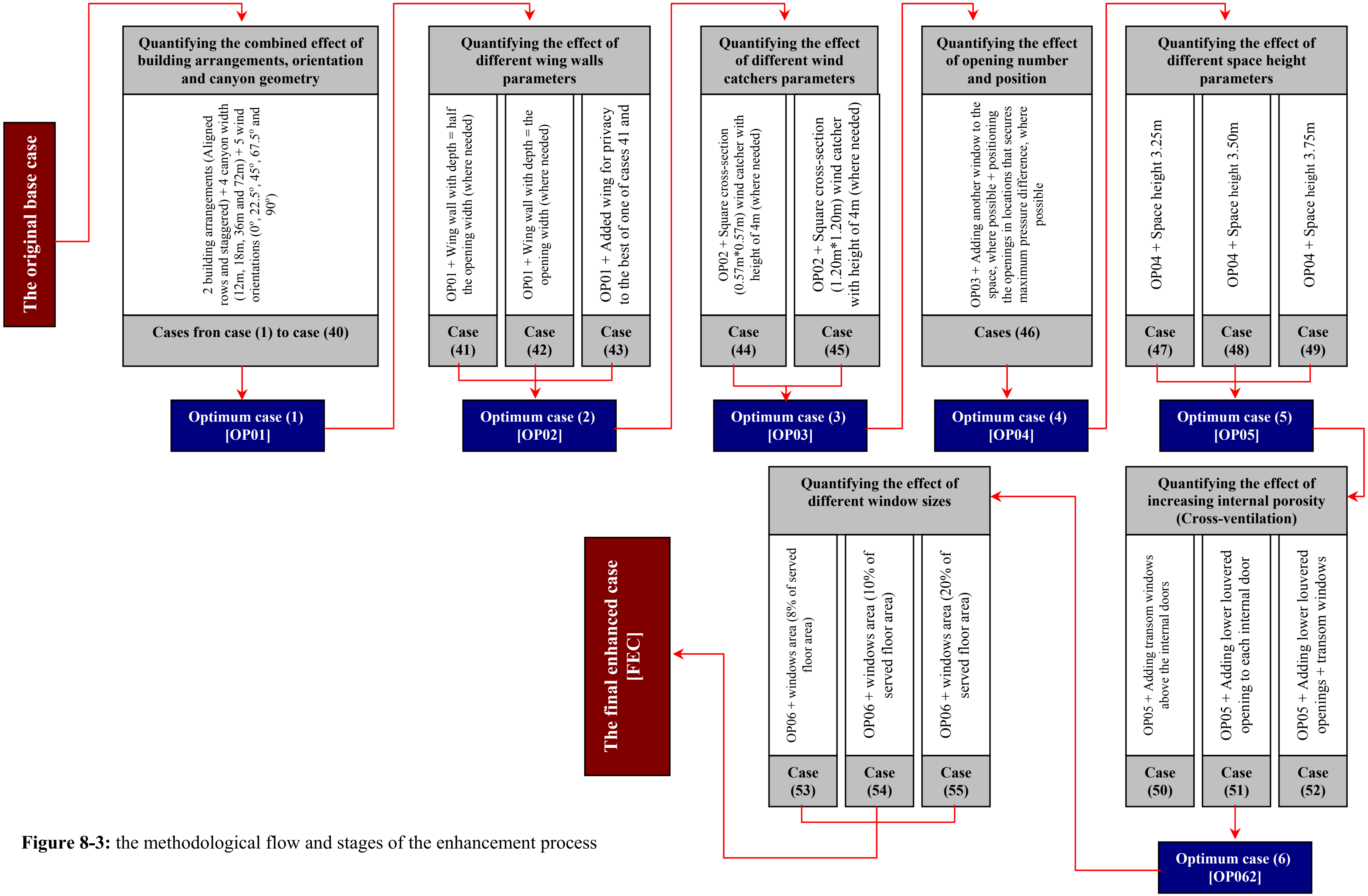


Figure 8-3: the methodological flow and stages of the enhancement process

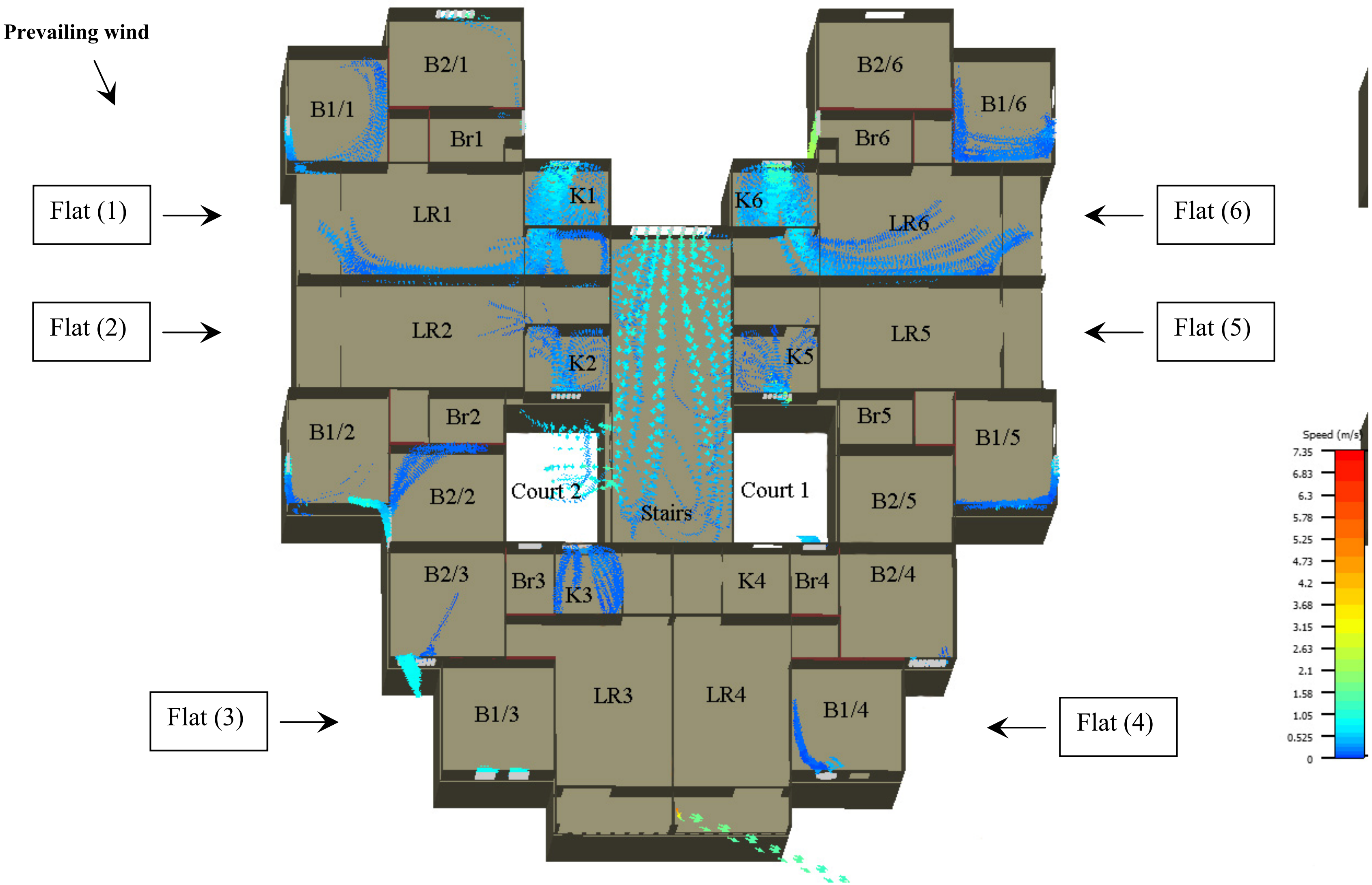


Figure 8-4: The airflow pattern inside the detailed floor of the original base case

Stairwell's window. The weak airflow enters from (*K1 and K6*) flows slowly toward (*LR1 and LR6*) respectively before leaves from their balconies' doors. Weaker air stream are provided to (*K2 and K3*) through (*Court 2*) by the airflow that comes from the stairwell. This flow struggles to exit from (*K2 and K3*) due to its weakness. Some other weak airflow is also found in some spaces such as (*B1/1, B2/2, B1/4, B1/5 and B1/6*). The performance of airflow within this selected base case showed a huge difference than that of the monitored block analyzed before in chapter 5. This was expected due to the deliberately prevented cross-ventilation through closing the rooms' doors and the intermediate location of the block between other blocks in the site that reflected negative pressure zone around most of the block mass.

The airspeed was averaged over the whole volume of each living space (*living rooms and bedrooms*) within the detailed modelled floor of the base case. Table 8-3 shows the average volumetric airspeed in each main living space within the base case expressed as a percentage of the provided wind speed (*5.6 m/s*). From the table, it can be clearly seen that the air over most of the spaces is almost still air with maximum average speed of 0.135 m/ s (*2.42% from wind speed*) achieved in *B1/1* that faces the prevailing wind. These results form the datum lines by which the enhancement effect of the selected measures will be quantified.

Table 8-3: The volumetric average airspeed inside the main living spaces of the flats in the original base case

	Flat (1)			Flat (2)			Flat (3)			Flat (4)			Flat (5)			Flat (6)		
	LR1	**B1/1**	**B2/1**	**LR2**	**B1/2**	**B2/2**	**LR3**	**B1/3**	**B2/3**	**LR4**	**B1/4**	**B2/4**	**LR5**	**B1/5**	**B2/5**	**LR6**	**B1/6**	**B2/6**
Average internal airspeed (m/s)	0.115	0.135	0.160	0.044	0.070	0.048	0.012	0.055	0.030	0.012	0.042	0.040	0.029	0.082	0.044	0.124	0.091	0.148
Percentage from wind speed (%)	2.06	2.42	2.85	0.78	1.25	0.87	0.22	0.99	0.54	0.21	0.75	0.71	0.52	1.46	0.79	2.22	1.63	2.64

8.3.2. The combined effect of orientation, building arrangements and canyon geometry

In this section, the results of the first 40 cases (Table 8-1), which include the combination between building arrangement, orientation and canyon geometry, are discussed. This is in order to extract optimum case (1) *[OP01]*.

In order to facilitate comparison, the annotations of the spaces inside the detailed floor were kept the same as in the original base case regardless of the orientation of the block. Figure 8-5 illustrates the spaces' annotations and the different tested orientations. Table 8-4 shows the *CFD* results of the volumetric average airspeed inside the main living spaces of the flats in the macro and intermediate design level cases (*case 1 to 40*) expressed as percentage from the provided wind speed. From the table, some general conclusions could be drawn as follows:

- In the same orientation and the same building arrangement (*each set of 4 cases in order*), the average airspeed over the whole floor slightly increases as the distance between buildings increases (Figure 8-6). In most of orientations, the maximum was reached, when *W= 72m*. However in some orientations, the cases of *W=36m* achieved higher average airspeed than the cases of *W=72* (Figure 8-6). This can be justified by the turbulence in the leeward side of the building that caused by the interference of the adjacent buildings' flow wake. This turbulence induces more air to enter the spaces in the negative pressure side of the building and in turn increases the overall average airspeed in the floor. This could not happen in the W=72m cases, as the airflow there is a free stream flow.

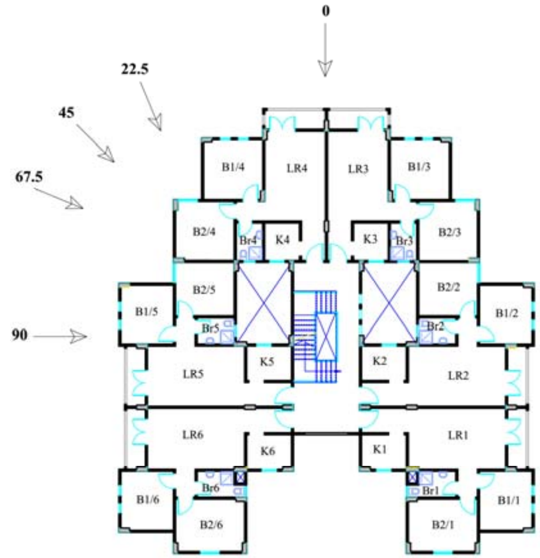


Figure 8-5: The spaces annotations in the enhancement cases with the tested orientations indicated

- In the cases that have the same orientation along with the same canyon width, different building arrangements achieved different total average airspeed over the detailed floor (Figure 8-7). In the majority of the cases, the aligned rows arrangement achieved higher total average airspeed than the staggered arrangement (Figure 8-7). This, in general, supports the opinion of some researchers [90, 122, 123] that the staggered arrangement is blocking the air rather than allowing access for it. This could not be taken as an absolute and it is only valid for this case study design with its current opening position. In addition, it is greatly affected by the wind direction and the distance between buildings.

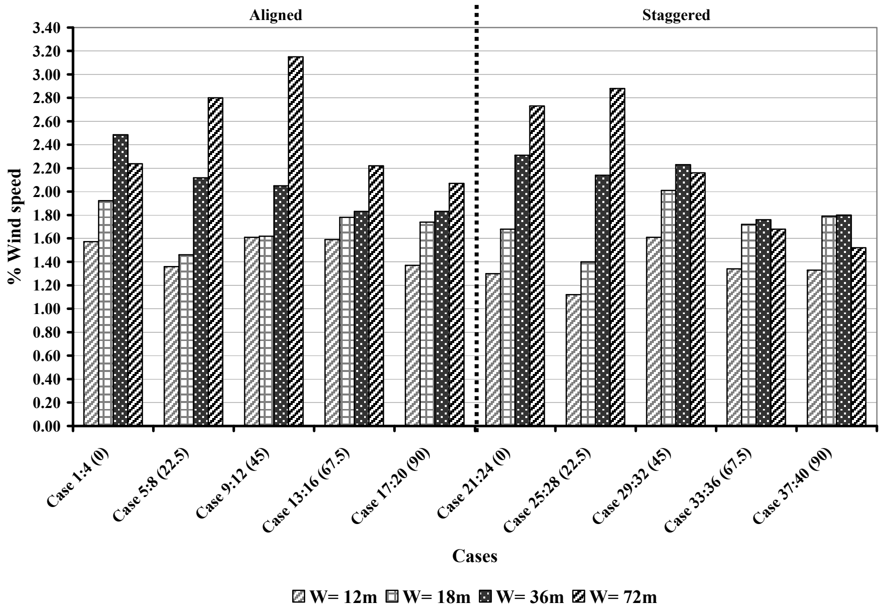


Figure 8-6: The total average airspeed (% wind speed) over the detailed floor at the same orientation and building arrangements with different canyon width

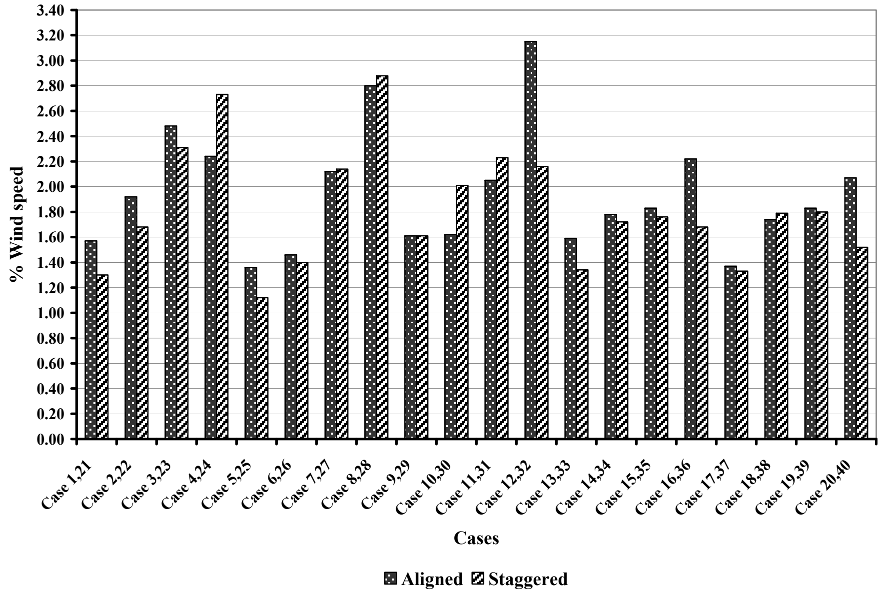


Figure 8-7: The total average airspeed (% wind speed) over the detailed floor at the same orientation and canyon width with different arrangements

Table 8-4: The volumetric average airspeed inside the main living spaces of the flats in cases from case (1) to case (40) (% wind speed) with the spaces achieved airspeed higher than the overall average (1.88%) highlighted in light gray and the highest two speeds in the spaces that did not achieve the overall average highlighted in dark gray

Case	description	Flat (1)			Flat (2)			Flat (3)			Flat (4)			Flat (5)			Flat (6)			Total Ave	No. of spaces
		LR1	B1/1	B2/1	LR2	B1/2	B2/2	LR3	B1/3	B2/3	B2/6	B1/4	B2/4	LR5	B1/5	B2/5	LR6	B1/6	B2/6		
1	**Aligned / W= 12 / 0°**	0.73	0.46	0.30	**1.98**	1.00	**4.30**	0.70	**2.84**	**3.75**	**2.55**	1.17	**2.12**	1.53	0.52	**2.31**	0.30	0.64	1.11	1.57	7
2	**Aligned / W= 18 / 0°**	1.16	0.86	1.74	**2.47**	1.12	**3.56**	1.73	**1.89**	**3.83**	**2.63**	1.51	**3.50**	1.80	0.74	**3.43**	0.48	0.39	1.75	1.92	7
3	**Aligned / W= 36 / 0°**	1.23	0.55	0.33	**2.82**	1.39	**3.78**	**4.13**	**2.69**	**5.12**	**3.87**	**2.47**	**5.05**	**3.02**	1.44	**4.77**	1.28	0.47	0.31	2.48	10**
4	**Aligned / W= 72 / 0°**	1.15	0.59	0.30	**2.76**	1.48	**3.44**	**5.36**	**2.32**	**2.41**	**5.03**	**2.30**	**3.33**	**2.79**	1.44	**3.61**	1.10	0.60	0.26	2.24	10**
5	**Aligned / W= 12 / 22.5°**	1.36	**1.59**	0.84	1.32	0.54	1.80	**1.98**	1.02	1.51	1.32	1.05	**2.78**	1.40	0.59	**2.92**	0.42	0.67	1.34	1.36	4
6	**Aligned / W= 18 / 22.5°**	0.22	1.21	1.18	1.29	0.49	1.53	**2.49**	1.33	1.39	**1.96**	**2.22**	**4.06**	1.49	0.74	**3.83**	0.27	0.43	0.16	1.46	5
7	**Aligned / W= 36 / 22.5°**	0.46	1.09	0.30	1.07	0.44	0.67	**3.98**	**2.16**	0.46	**5.06**	**3.87**	**6.12**	1.75	1.21	**5.30**	**2.31**	1.37	0.50	2.12	7
8	**Aligned / W= 72 / 22.5°**	1.10	0.56	0.38	1.71	1.06	0.41	**8.18**	**2.94**	1.58	**8.62**	**3.71**	**5.71**	1.22	1.25	**5.22**	**3.94**	**2.23**	0.66	2.80	8
9	**Aligned / W= 12 / 45°**	0.76	**1.60**	1.00	1.05	1.84	0.77	**2.10**	**2.02**	1.26	1.10	1.59	**2.97**	0.97	**2.52**	**2.41**	1.64	1.82	1.51	1.61	6
10	**Aligned / W= 18 / 45°**	0.18	1.50	0.37	0.97	0.98	0.32	**2.76**	**2.33**	0.31	**2.60**	**2.21**	**3.85**	**1.97**	**2.10**	**3.15**	**2.20**	0.98	0.38	1.62	9
11	**Aligned / W= 36 / 45°**	0.12	0.36	0.15	0.83	0.42	0.19	**3.12**	**2.14**	0.45	**4.02**	**2.97**	**4.57**	**3.06**	**3.68**	**3.79**	**3.90**	**2.82**	0.31	2.05	10**
12	**Aligned / W= 72 / 45°**	0.85	0.32	0.45	1.58	0.80	0.89	**5.68**	**2.09**	1.67	**6.29**	**3.05**	**5.81**	**5.26**	**5.20**	**4.93**	**6.34**	**4.58**	0.90	3.15	10**
13	**Aligned / W= 12 / 67.5°**	0.30	0.74	1.46	0.43	1.16	1.10	0.91	**2.58**	1.51	1.54	1.29	**2.51**	**1.92**	1.83	**2.48**	**2.95**	**2.76**	1.11	1.59	6
14	**Aligned / W= 18 / 67.5°**	0.42	0.52	1.34	0.72	0.16	0.35	1.60	0.97	0.71	**2.26**	1.82	**4.77**	**2.71**	**2.93**	**4.51**	**3.68**	**2.28**	0.34	1.78	7
15	**Aligned / W= 36 / 67.5°**	0.06	0.62	1.02	0.35	0.51	0.18	1.56	**2.52**	0.39	1.60	**2.41**	**3.56**	**3.24**	**3.35**	**3.37**	**3.81**	**2.99**	1.33	1.83	8
16	**Aligned / W= 72 / 67.5°**	0.22	0.15	0.18	0.60	0.27	0.47	1.15	1.24	0.95	1.64	**2.27**	**4.46**	**5.45**	**5.13**	**4.35**	**6.11**	**4.58**	0.75	2.22	7
17	**Aligned / W= 12 / 90°**	0.28	0.97	1.36	0.26	0.24	0.96	1.21	**2.43**	0.94	**2.03**	1.55	**3.00**	1.52	1.40	**2.37**	**1.88**	0.61	1.65	1.37	5
18	**Aligned / W= 18 / 90°**	0.89	1.16	1.11	0.26	0.72	0.64	**2.02**	**2.18**	0.25	**2.99**	**2.03**	**3.93**	**3.01**	0.78	**2.95**	**3.68**	1.13	1.63	1.74	8
19	**Aligned / W= 36 /90°**	0.79	0.66	0.94	0.59	0.58	0.23	**2.15**	1.48	0.21	**3.45**	**2.06**	**3.63**	**3.24**	**2.70**	**2.68**	**3.32**	**3.32**	0.83	1.83	9
20	**Aligned / W= 72 / 90°**	0.77	0.34	0.93	0.55	0.19	0.15	**2.23**	0.73	0.23	**3.40**	1.17	**4.01**	**4.66**	**4.52**	**3.54**	**4.88**	**4.36**	0.61	2.07	8
21	**Staggered / W= 12 / 0°**	0.67	1.37	1.32	0.53	1.59	1.29	**3.45**	1.38	0.84	**3.22**	1.22	0.49	0.64	1.69	0.54	0.50	1.41	1.32	1.30	2
22	**Staggered / W= 18 / 0°**	0.57	0.28	0.18	1.79	0.80	**2.17**	**6.44**	**3.78**	0.45	**5.53**	**2.49**	1.69	1.71	0.50	0.63	0.30	0.26	0.62	1.68	5
23	**Staggered / W= 36 / 0°**	0.64	0.31	0.16	1.46	1.01	**3.83**	**6.65**	**3.29**	0.54	**6.11**	**3.19**	**3.61**	**3.06**	1.40	**3.98**	1.61	0.51	0.16	2.31	8
24	**Staggered / W= 72 / 0°**	**2.24**	0.66	0.36	**3.10**	1.66	**4.90**	**8.03**	**3.52**	0.56	**7.40**	**3.38**	0.50	**3.13**	1.63	**4.86**	**2.26**	0.65	0.32	2.73	10**

25	**Staggered / W= 12 / 22.5°**	0.08	1.11	1.16	0.65	1.24	0.57	**2.02**	0.85	0.24	**2.06**	0.66	**2.21**	0.55	**1.89**	**2.08**	0.97	0.80	1.04	1.12	5
26	**Staggered / W= 18 / 22.5°**	0.24	0.88	0.29	1.37	0.40	1.59	**4.22**	1.85	0.41	**4.12**	1.80	**2.75**	0.71	0.43	**2.07**	1.47	0.54	0.14	1.40	4
27	**Staggered / W= 36 / 22.5°**	0.82	0.82	0.17	1.51	0.78	**1.91**	**6.06**	**2.41**	0.93	**5.91**	**2.87**	**4.63**	**2.00**	1.06	**3.82**	1.27	1.30	0.28	2.14	8
28	**Staggered / W= 72 / 22.5°**	**3.23**	0.73	0.35	**3.43**	**2.07**	0.54	**8.98**	**3.47**	**2.45**	**8.75**	**3.94**	**2.04**	**1.99**	1.11	**5.95**	1.36	0.79	0.60	2.88	11*
29	**Staggered / W= 12 / 45°**	0.23	1.19	1.26	0.80	1.41	0.96	**2.23**	1.47	1.80	**1.98**	0.87	**2.63**	1.61	**2.01**	**2.19**	**2.62**	**2.43**	1.32	1.61	7
30	**Staggered / W= 18 / 45°**	0.13	1.32	0.78	1.32	1.24	**2.11**	**3.77**	**2.12**	0.38	**3.99**	1.64	**3.15**	**2.85**	**2.75**	**2.88**	**3.01**	**2.12**	0.55	2.01	10**
31	**Staggered / W= 36 / 45°**	0.13	0.72	0.32	0.95	1.14	**2.01**	**4.05**	**2.57**	0.51	**4.53**	1.81	**3.98**	**2.94**	**3.52**	**3.59**	**3.96**	**3.11**	0.22	2.23	10**
32	**Staggered / W= 72 / 45°**	0.53	0.32	0.31	0.74	0.42	0.60	**3.97**	1.11	1.47	**4.53**	**2.91**	**2.15**	**3.23**	**4.53**	**5.15**	**3.83**	**2.33**	0.70	2.16	9
33	**Staggered / W= 12 / 67.5°**	0.28	0.40	1.08	0.22	1.10	0.90	1.29	**2.73**	1.45	**2.03**	1.30	**2.34**	1.29	1.21	1.61	1.55	**2.13**	1.26	1.34	4
34	**Staggered / W= 18 / 67.5°**	0.13	0.90	0.60	0.60	0.39	0.31	**2.87**	1.33	1.07	**1.98**	1.58	**4.14**	**2.97**	**3.06**	**3.14**	**2.96**	**2.25**	0.71	1.72	8
35	**Staggered / W= 36 / 67.5°**	0.42	0.48	0.73	0.31	0.95	1.11	**1.96**	**2.58**	1.87	1.36	1.33	**3.05**	**2.50**	**2.89**	**2.90**	**2.89**	**2.51**	**1.94**	1.76	9
36	**Staggered / W= 72 / 67.5°**	0.79	0.35	0.60	0.47	0.73	0.25	**2.43**	**2.56**	0.56	0.86	1.44	0.66	**3.44**	**3.29**	**3.55**	**3.34**	**3.78**	1.09	1.68	7
37	**Staggered / W= 12 / 90°**	0.36	1.05	1.28	0.41	0.25	0.95	1.58	**2.26**	0.46	**2.21**	1.55	**2.81**	**2.11**	0.65	1.57	**2.19**	1.03	1.23	1.33	5
38	**Staggered / W= 18 / 90°**	0.95	1.02	1.24	0.41	0.51	0.75	**2.17**	1.30	0.29	**3.19**	**2.36**	**4.11**	**3.43**	1.82	**2.08**	**3.18**	**2.94**	0.50	1.79	8
39	**Staggered / W= 36 / 90°**	0.78	1.50	**2.31**	0.61	0.62	0.62	1.62	**2.51**	0.71	**2.77**	1.45	**3.04**	**2.45**	**1.96**	**2.37**	**2.75**	**2.44**	**1.89**	1.80	10**
40	**Staggered / W= 72 / 90°**	0.75	1.48	**2.01**	0.51	0.71	0.15	1.63	0.72	0.13	**2.61**	0.77	1.00	**2.91**	1.45	**3.10**	**2.97**	**3.26**	1.19	1.52	6

* First case in rank, ** Second cases in rank

- When the arrangements and canyon width are constant, the effect of orientation could be measured. In general, the lowest total average airspeed was found, when the wind incident angle was 67.5^{o} and 90^{o} (Figure 8-8). It can be seen from Figure 8-8 that the wind angle of 0^{o} achieved the higher total average airspeed in most cases, when the building arranged in aligned rows except for the canyon width cases of 72m (*cases 4,8,12,16,20*), where the angle of 45^{o} took the lead. However, when the buildings arranged in staggered manner, the wind angle of 45^{o} achieved the higher total average airspeed at canyon widths of 12m and 18m. The wind angle of 0^{o} was the higher W=

36m, while the wind angle of 22.5^o showed better performance at W= 72m.

From these conclusions, it can be concluded that the best combination between these measures for this particular case study would be the canyon width of 72 or 36 + the aligned rows arrangement + 0^o wind angle. Because of the hot dry nature of the case study's context, where the use of compact pattern is recommended, the *72m* canyon width can be excluded as it is a very wide distance that could be hardly treated against sun access. Therefore, the best combination could be altered to include the canyon width of *36m* instead. 36m canyon width can be easily treated in terms of sun access by using the landscape design elements and furniture.

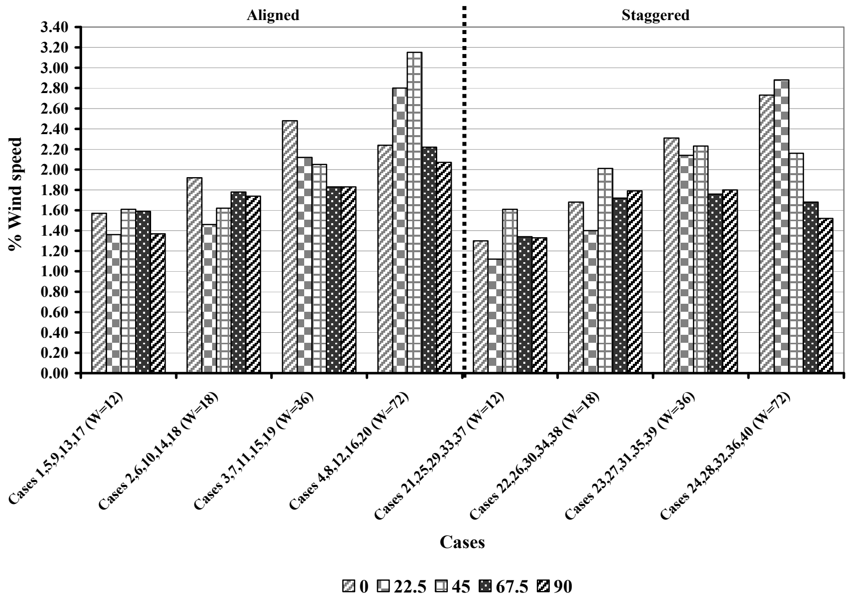


Figure 8-8: The total average airspeed (% wind speed) over the detailed floor at the same building arrangements and canyon width with different orientation

However, this best case only expresses a general indicator as the combined effect of these measures have to be considered, and thus the all cases (*from 1 to 40*) should be analyzed together in order to obtain the best case. The total average airspeed over all floor spaces in each case can not be used as a reliable indication of the best case performance. Some cases' configuration could introduce a huge airspeed in few spaces that faces the wind while decrease it in the other spaces. This in total gives high average total airspeed while most of the spaces have low internal airspeed. The best case should achieve higher airspeed in each space with the highest possible balance in airspeed distribution over all spaces.

Another possible method of extracting the best case among the simulated 40 cases is to determine the highest airspeed under each space in Table 8-4 and then selecting the case that achieves these highest airspeeds in higher number of spaces. Analyzing the cases in such a manner was found to be unfair as there are speed values under each space that could be slightly lower than the highest value. The same problem was found also, when considering the highest two values in each space.

Therefore, it was found that the best method to analyze these cases is to calculate the overall average airspeed that is achieved by all cases at all spaces (*1.88% from wind speed*) and select the spaces in front of each case in Table 8-4 that achieved higher airspeed than this value (*highlighted in light gray in Table* 8-4). For the spaces that found to not achieve any higher values than this overall average at any of the cases (*B1/1*), the highest achieved two speed values were considered (*highlighted in dark gray in Table* 8-4). The number of spaces achieved these criteria in each case was then counted and the cases was ranked according to a dissenting order. See the last column in Table 8-4 for the number of spaces with higher speeds and their rank. Using this method in analyzing the 40 cases can ensure a balanced distribution of airspeed over all the spaces in the proposed optimum case.

According to this way of analysis, only one case (*Case 28*) was found to achieve average internal airspeed higher than the calculated overall average in the high number of its spaces (*11 out of 18*) (Table 8-4). In addition, 8 cases (*Case 3, 4, 11, 12, 24, 30, 31 and 39*) came in the second order with the average internal airspeed higher than the calculated overall average in (*10 out of 18*) spaces. By excluding the cases with canyon width of *72m* (*Case 28, 4, 12 and 24*) for their unsuitability of the local climate, the selection of optimum case (1) was restricted to only 5 cases (Case 3, 11, 30, 31 and 39) to select from (Table 8-5).

Table 8-5: The internal average airspeed of the five best adaptable with climate cases (% wind speed) to choose the optimum (1) case among them

Case No.	Description (arrangement + canyon width + wind angle)	Flat (1)			Flat (2)			Flat (3)			Flat (4)			Flat (5)			Flat (6)			Total average
		LR1	B1/1	B2/1	LR2	B1/2	B2/2	LR3	B1/3	B2/3	B2/6	B1/4	B2/4	LR5	B1/5	B2/5	LR6	B1/6	B2/6	
Case 03	**Aligned + 36m + 0**	1.23	0.55	0.33	2.82	1.39	3.78	4.13	2.69	5.12	3.87	2.47	5.05	3.02	1.44	4.77	1.28	0.47	0.31	2.48
Case 11	**Aligned + 36m + 45**	0.12	0.36	0.15	0.83	0.42	0.19	3.12	2.14	0.45	4.02	2.97	4.57	3.06	3.68	3.79	3.90	2.82	0.31	2.05
Case 30	**Staggered + 18m + 45**	0.13	1.32	0.78	1.32	1.24	2.11	3.77	2.12	0.38	3.99	1.64	3.15	2.85	2.75	2.88	3.01	2.12	0.55	2.01
Case 31	**Staggered + 36m + 45**	0.13	0.72	0.32	0.95	1.14	2.01	4.05	2.57	0.51	4.53	1.81	3.98	2.94	3.52	3.59	3.96	3.11	0.22	2.23
Case 39	**Staggered + 36m + 90**	0.78	1.50	2.31	0.61	0.62	0.62	1.62	2.51	0.71	2.77	1.45	3.04	2.45	1.96	2.37	2.75	2.44	1.89	1.80

At this point of analysis, the total average value of each case is meaningful, as all the five selected cases have now balanced airspeed distribution over their spaces. The highest total average in a case indicates the highest airspeed achieved inside spaces within this case. According to this, Case 03 could be selected as the best case among them (*Optimum case (1)*). This confirmed the preliminary choice according to the recommended combination between measures that was stated before. However, a very important factor should be considered in this choice, which is the airflow quality over the detailed floor. The airflow pattern inside the highest 4 cases in total average airspeed (*Case03,11, 30 and 31*) was investigated as shown in Figure 8-9, Figure 8-10, Figure 8-11 and Figure 8-12 respectively.

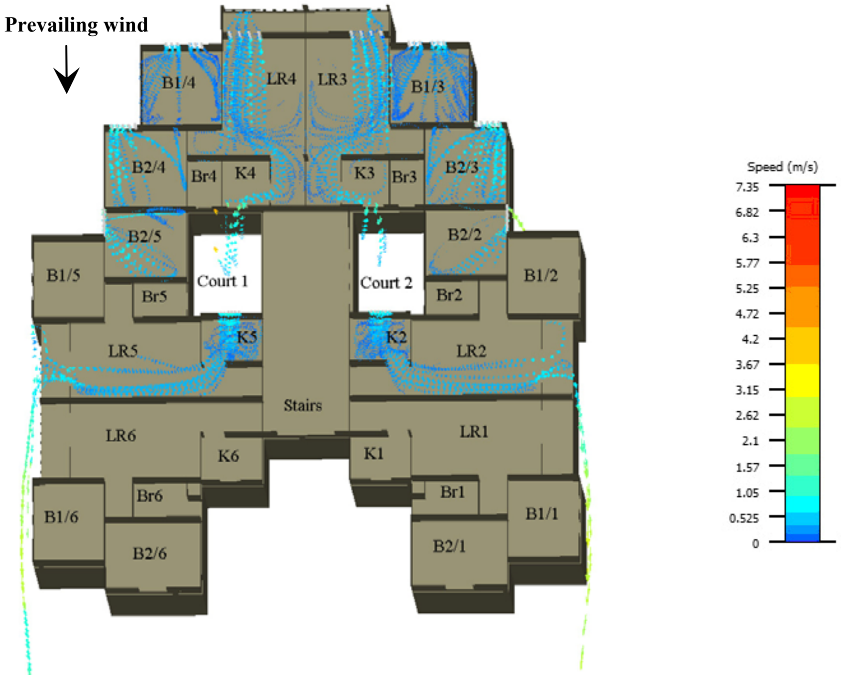


Figure 8-9: The airflow pattern throughout spaces of case (3)

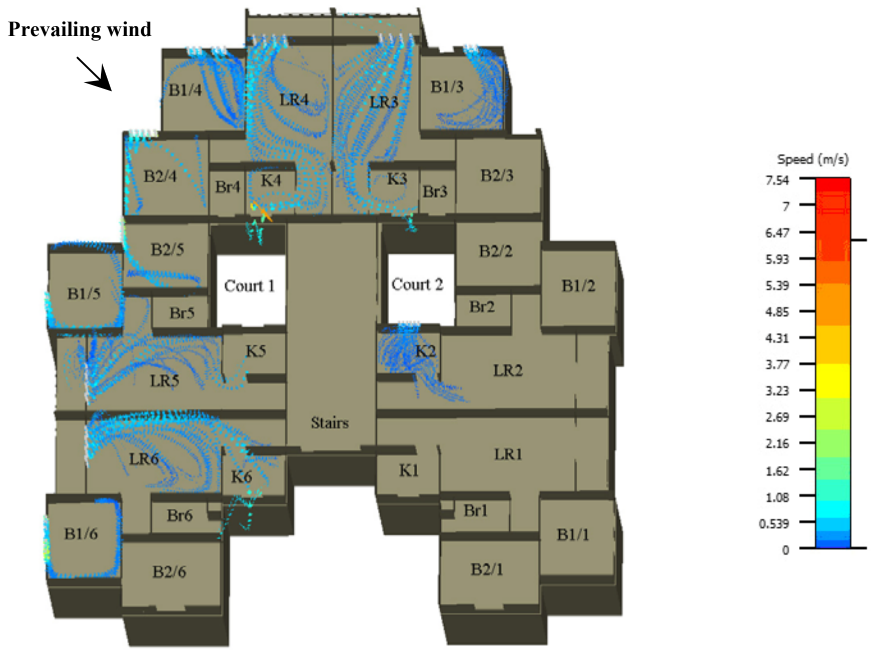


Figure 8-10: The airflow pattern throughout spaces of case (11)

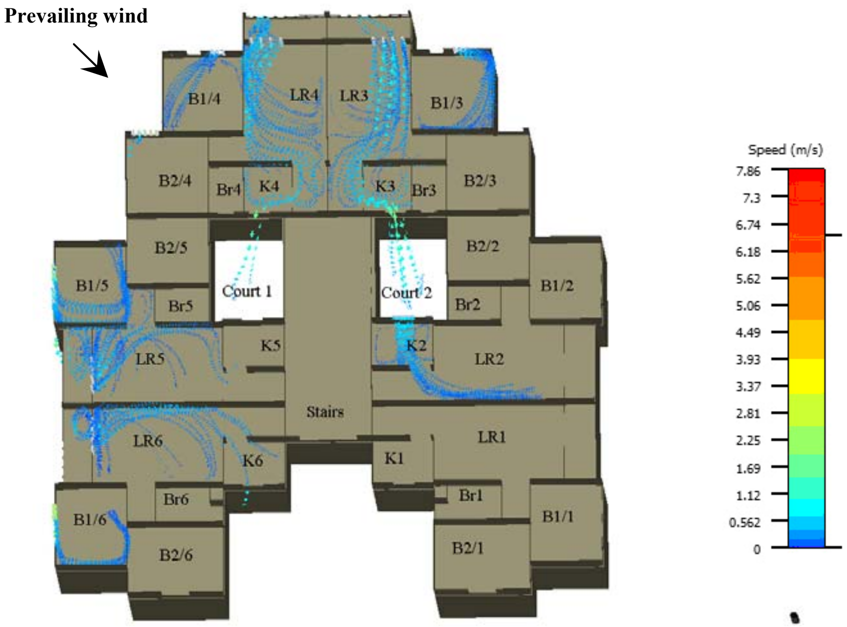


Figure 8-11: The airflow pattern throughout spaces of case (30)

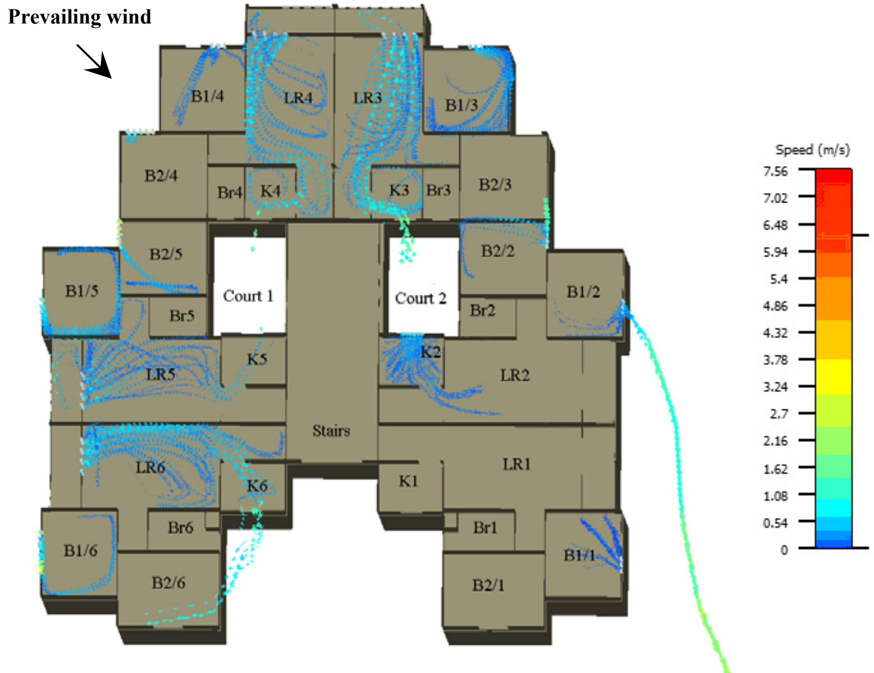


Figure 8-12: The airflow pattern throughout spaces of case (31)

It can be clearly seen from the figures that the best airflow pattern over most of the spaces is achieved in cases 3 and 11. However, there are some factors that support the choice of case (3) over case (11) as OP01. Those are:

- Bearing in mind that the most frequent wind in the case study context blows from the north, the corrugated northern façade's design of the block in case (3) could cast larger area of shadow on façades than that of case 11 during the heat stress time at the midday, when the sun comes from the south. This in turn helps natural ventilation to give maximum cooling effect when provided at night as the walls have minimum heat absorption during daytime.

- By considering the limitation of the *FloVent* in modelling the rotated objects and the need to model the wind catchers that directed normal to the wind direction in the following proposed measures, it can be argued that case (3) with its normal wind orientation is the best choice.

According to the above discussion, Case (3) was chosen to be the Optimum case (1) that introduces the best airflow performance due to the application of the combination between building arrangement, orientation and canyon geometry. In order to quantify the enhancement effect of this combination of measures, the results of optimum case (1) *[OP01]* were compared to the results of the original base case. From Table 8-6, it can be clearly seen that optimum case (1) has achieved enhancement in the internal airspeed in most of the spaces (*11 out of 18*) in comparison to the original base case with an overall increase on average of 1.21% from the provided wind speed. The average internal speeds (*as percentage of the provided wind speed*) were increased within these spaces with values ranged between 0.14 % (*B1/2*) to 4.58 % (*B2/3*). The difference in wind direction between the OP01 and the original base case causes the reduction in the internal average speed of some spaces especially, in flats (1) and (6). This enhancement could be realized in the quality of the airflow pattern inside the spaces by comparing Figure 8-9 and Figure 8-4.

Optimum case (1) *[OP01]* works as the base case for testing the effectiveness of next set of measures.

Table 8-6: The results comparison between optimum case (1) and the original base case *(all values are average internal speeds expressed in % from wind speed)*

	Flat (1)			Flat (2)			Flat (3)			Flat (4)			Flat (5)			Flat (6)			Total average
	LR1	**B1/1**	**B2/1**	**LR2**	**B1/2**	**B2/2**	**LR3**	**B1/3**	**B2/3**	**B2/6**	**B1/4**	**B2/4**	**LR5**	**B1/5**	**B2/5**	**LR6**	**B1/6**	**B2/6**	
Original base case	2.06	2.42	2.85	0.78	1.25	0.87	0.22	0.99	0.54	0.21	0.75	0.71	0.52	1.46	0.79	2.22	1.63	2.64	1.27
Case 03 [OP01]	1.23	0.55	0.33	2.82	1.39	3.78	4.13	2.69	5.12	3.87	2.47	5.05	3.02	1.44	4.77	1.28	0.47	0.31	2.48
The difference	**- 0.83**	**- 1.87**	**- 2.52**	**2.04**	**0.14**	**2.97**	**3.91**	**1.7**	**4.58**	**3.66**	**1.72**	**4.34**	**2.5**	**- 0.02**	**3.98**	**- 0.94**	**- 1.16**	**- 2.33**	**1.21**

In the following sections, the *CFD* results of the cases from (*41 to 55*) (Table 8-2), which include the selected design measures on the micro design level, are analyzed and discussed. This is in order to extract the cases from optimum case (2) to the final enhanced case. This is in an accumulative manner, as explained in the detailed methodology.

8.3.3. The effect of different wing walls parameters

The airflow around the case [*OP01*] was investigated in order to determine the spaces that are valid to apply the wing wall parameters to. See Figure 8-13. From the figure, it can be clearly seen that due to the corrugated design of the building, many spaces' walls work as wing walls for the other spaces. However, at the sides of the block, where the airstreams flow parallel to some spaces' windows, there are some spaces that can benefit from adding wing walls to their windows (Figure 8-13). Adding wing walls to the windows of spaces (*B1/1, B1/2, B1/5 and B1/6*) can trap the air and force it to enter the space.

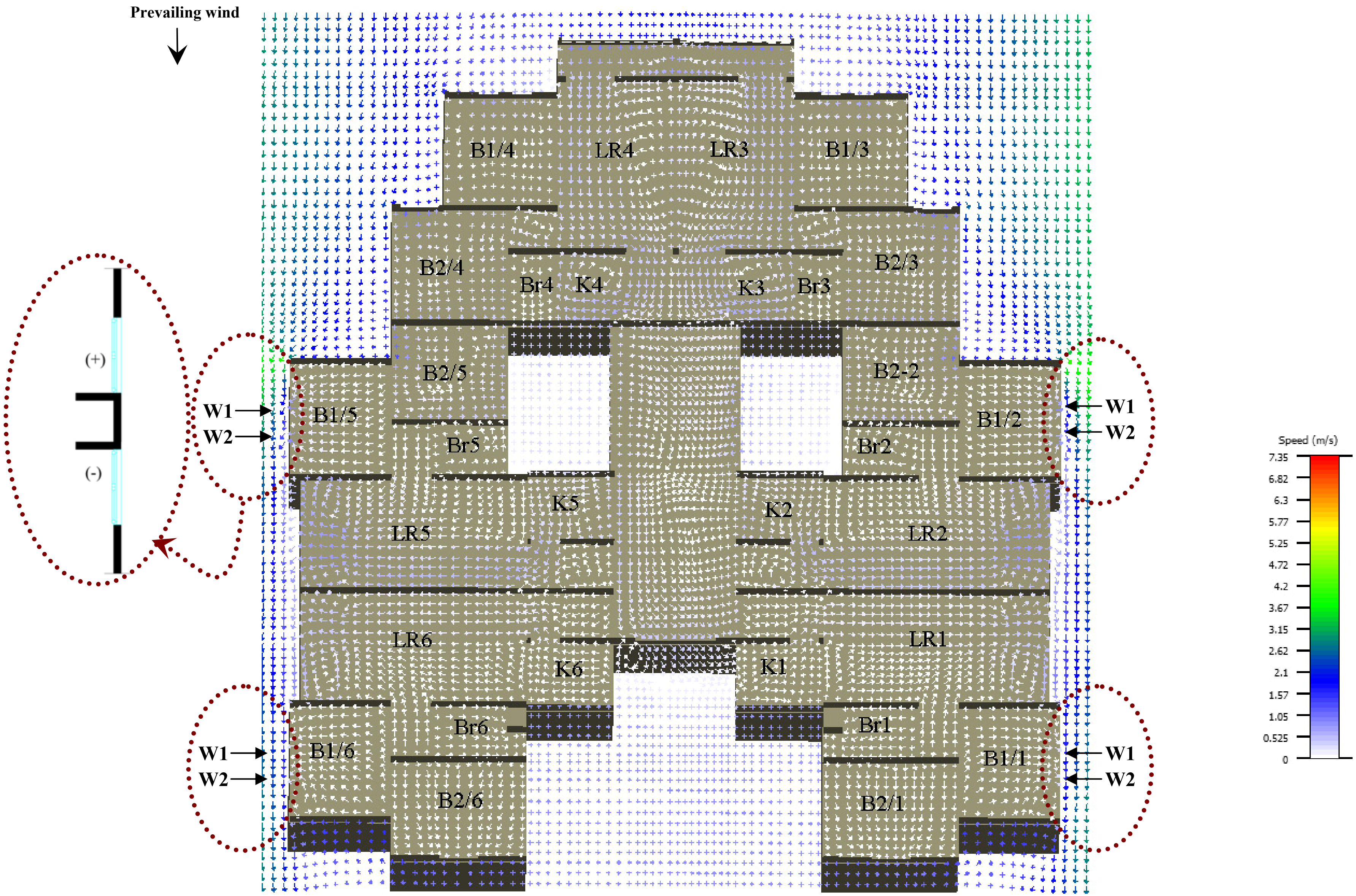


Figure 8-13: The airflow vectors' pattern around optimum case (1) at the middle of windows height (*7.5 m AGL*) with the proposed wing wall places indicated

Because these spaces have two windows each, it was decided to apply the wing wall to each window in a reverse way as shown in Figure 8-13. By applying the wing wall measures in such a way, a positive pressure area in front of one window and a negative pressure area in front of the other are expected to be formed. This was in order to employ one of them as an inlet and the other as an outlet and create the own ventilation system within these spaces as proposed by the methodology.

Firstly, the first two parameters of the wing wall (*Case 41 and 42*) were applied to the selected spaces in the case study in order to obtain the best case. Secondly, the third parameter of the wing wall (*privacy wing*) was then applied to the resultant best case of the last two and called (*Case 43*). Table 8-7 shows the results of cases (*41, 42 and 43*) expressed as a percentage from the wind speed along with the airspeed values within the same spaces in the case (*OP01*). From the table, it can be clearly seen that applying the wing wall measures generally improved the average internal airspeed in the spaces that they were installed in. It was found, also, that installing wing walls with depth equal to the full width of the window (*Case 42*) introduced better improvement to the average internal airspeed than that of (Case 41), especially in (*B1/1 and B1/6*). However, in the spaces of (*B1/2 and B1/5*), both cases (*41 and 42*) showed either a slight improvement or reduction in the internal average speeds in comparison to the case (*OP01*) (Table 8-7). This was found to happen due to the deflection of the wind around the corners of those spaces that deflect the air stream at a distance more than the wing wall depth (Figure 8-14). The air stream was found to be relived before reaching (*B1/1 and B1/6*). This justifies the pattern of the results in Table 8-7.

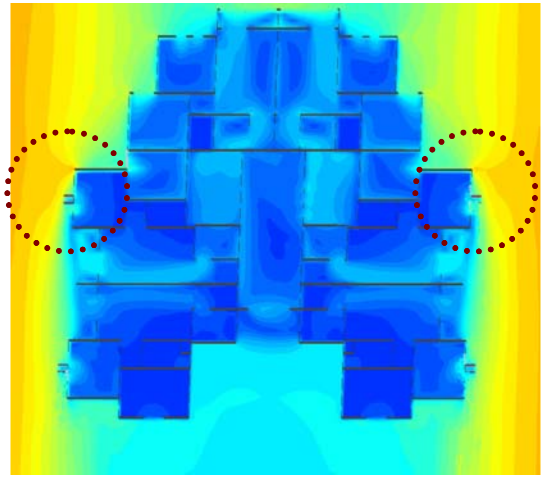


Figure 8-14: The airflow pattern around the block in cases (41, 42) with air deflection around B1/2 and B1/5 corners indicated

Table 8-7: The internal average airspeed of the wing wall cases (% wind speed) along with the airspeed percentage in the case (Optimum 1) within the same spaces

Case No.	Description	Space with a simulated wing wall			
		B1/1	B1/2	B1/5	B1/6
Case OP01	Without wing walls	0.55	1.39	1.44	0.31
Case 41	Optimal (1) + Wing wall with depth = half the opening width	1.15	1.37	1.46	0.86
Case 42	Optimal (1) + Wing wall with depth = the same opening width	2.37	1.37	1.41	2.46
Case 43	Optimal (1) + Added wing for privacy to the best measure from 41 and 42	3.14	1.97	2.61	3.31

In general, case (42) gave better results than case (41). When the privacy wings were added to case (42) and represented in (*Case 43*), a significant improvement in the internal average airspeed was observed within all spaces (Table 8-7). This was justified as the privacy walls maximized the pressure difference between the outlets and inlets in the spaces that they installed in. Based on these results, it can be argued that case (43) was the best case among these set of cases. Therefore, it was chosen as the Optimum case 2 *[OP02]*. By comparing the results of (*OP02*) to their counterparts in (*OP01*) (Table 8-8)., it can be seen that applying wing walls in the designated way that includes privacy wings to these spaces improved significantly the internal average volumetric airspeed. These improvements introduced an increase in the internal airspeed that ranged between 0.58 % from wind speed to 3.00% from wind speed (Table 8-8).

In terms of the airflow pattern inside the spaces that the wing wall's measures were applied to, Figure 8-15, Figure 8-16 and Figure 8-17 illustrate this airflow pattern. From the figures, it can be clearly seen that the spaces (*B1/1, B1/2, B1/5 and B1/6*) in case (43) has the greatest air

Table 8-8: The results comparison between optimum case (2) [OP02] and [OP01] *(all values are average internal speeds expressed in % from wind speed)*

Case No.	Description	Space with a simulated wing wall			
		B1/1	**B1/2**	**B1/5**	**B1/6**
OP01	**Without wing walls**	0.55	1.39	1.44	0.31
Case 43 [OP02]	**Optimal (1) + Added wing for privacy to the wing wall depth = full window's width**	3.14	1.97	2.61	3.31
The difference		**2.59**	**0.58**	**1.17**	**3.00**

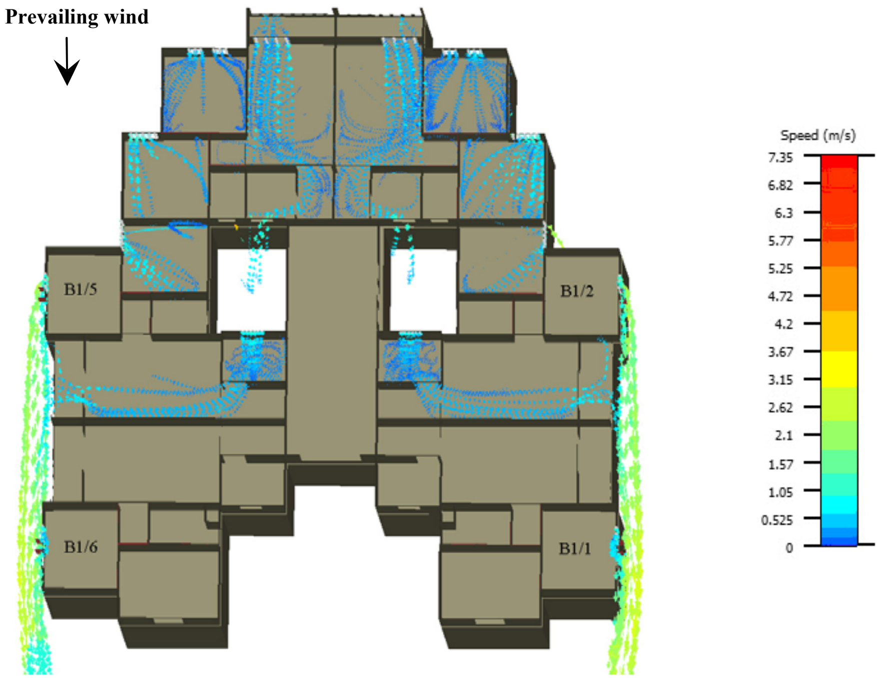


Figure 8-15: The airflow pattern inside the spaces of case (41) with the spaces with wing walls indicated

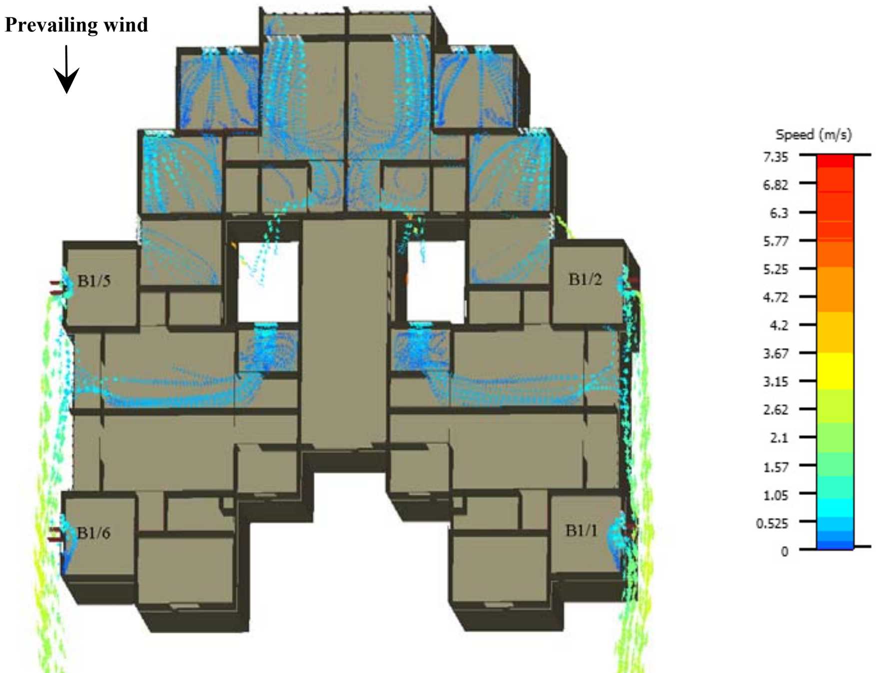


Figure 8-16: The airflow pattern inside the spaces of case (42) with the spaces with wing walls indicated

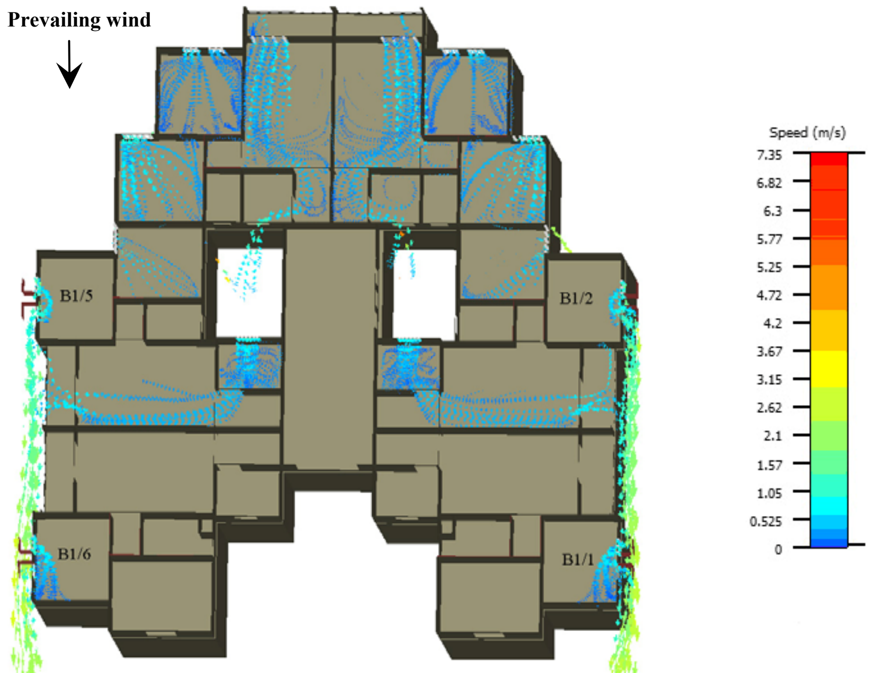


Figure 8-17: The airflow pattern inside the spaces of case (43) with the spaces with wing walls indicated

access among the all cases. In case (41), almost no air access was observed in spaces (*B1/2 and B1/5*) (Figure 8-15). In addition, due to the small distance between all windows, to which the wing walls were applied, short circuits were observed in the spaces of these windows (*B1/1, B1/2, B1/5 and B1/6*) in cases (42 and 43). This problem is proposed to be solved in the coming parts of the enhancement process later in this chapter. To summarize, the results of installing different wing wall's measures, where needed, showed that case (43) is the best among the tested cases. Therefore, it was chosen to be (*OP02*) case in order to be used as the base case in testing the effect of the next set of measures.

8.3.4. The effect of wind catchers

In order to determine the spaces that wind catcher's measures could be installed in, it was necessary to look into the airflow profile in (*OP02*) case. By looking into the airflow pattern inside (*OP02)* case (Figure 8-17), it can be spotted that the spaces (*B2/1, B2/6, LR1 and LR6*) have no air access to them. Equipping these spaces with wind catchers could possibly allow air access to them and establish ventilation systems through theses spaces. Also, the airflow in spaces (*LR2 and LR5*) was found coming from the kitchens of these flats, which is a problem that proposed to be solved. It was thought that if these living rooms are equipped with wind catchers, the airflow will be reversed due to the negative pressure at kitchens' windows and balconies' doors within these spaces.

In order to locate the wind catchers on the selected spaces envelope, the air pressure profile around these spaces was investigated (Figure 8-18). In spaces (*B2/1 and B2/6*), the higher pressure areas were chosen to locate the wind catchers on it (Figure 8-18). This location allows locating the proposed outlets (*Windows of the spaces*) in the lowest pressure area, which in turn expected to enhance the airflow inside those spaces. In terms of the spaces (*LR1, LR2, LR5 and LR6*), locating wind catchers on their envelope was a bit perplexing. The only places that could locate the wind catcher on, within theses spaces, are the walls of their balconies. However, the pressure on front of these walls is found always less than the pressure at kitchens' windows (Figure 8-18). This in turn is expected to employ the balconies' doors as

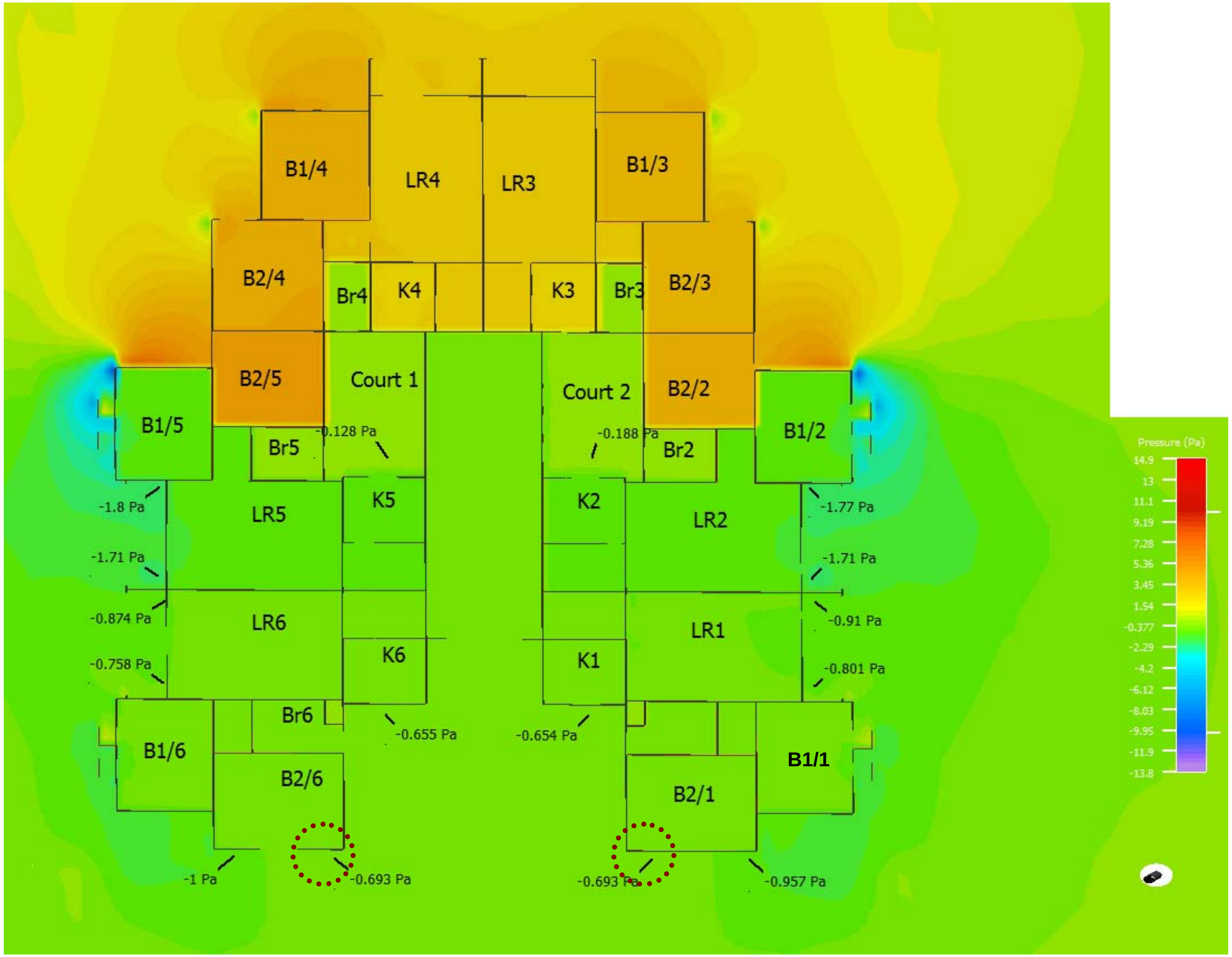


Figure 8-18: The air pressure profile in and around optimum case (2) in front of the middle of windows height with proposed locations of wind catchers indicated

outlets with short circuits airflow rather than flows towards the kitchens. Because of the short length of the balconies walls, locating the catchers' inlets and the balconies' doors (*the outlets*) far apart from each other will not be possible. This airflow problem will be hard to be treated due to the current design of the case study. Therefore, it was proposed to install the wind catchers only within (*B2/1 and B2/6*) and leave (*LR1, LR2, LR5 and LR6*) to the other proposed measures that might treat the airflow problems in them.

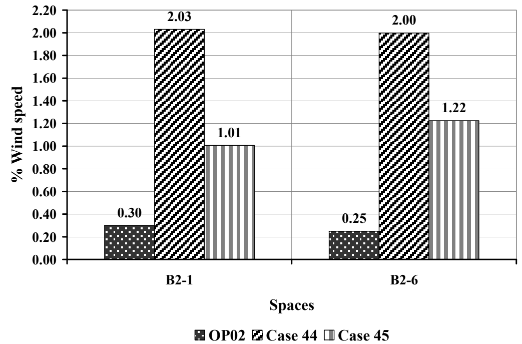


Figure 8-19: The average airspeed (% wind speed) over the spaces before (OP02) and after (Cases 44,45) installing the wind catchers measure to them

Two wind catchers' measures (*Case 44 and 45*) were applied to optimum case (2) in the way illustrated in chapter seven and the locations explained above. The wind catchers were modelled in full height with only opening in the detailed floor level. Figure 8-19 shows the volumetric average airspeed over spaces (*B2/1 and B2/6*) before (*Optimum case 2[OP02]*) and after installing wind catchers to them (*Case 44 and 45*). It can be seen from the figure that installing wind catchers to the spaces, in general, increases the average internal airspeed significantly over these spaces. However, installing wind catcher with cross-section of (*0.57m * 0.57m*) (*Case 44*) introduced almost double the increase of installing wind catcher with cross-section of (*1.20m * 1.20m*) (*Case 45*). This indicates the direct proportion between the internal average airspeed and the area of wind catcher's cross-section. The small area of the wind catcher's blows the air inside the space by larger airspeed and the airspeed results from a wind catcher is double that of another wind catcher with double cross-section area. In addition, This supports the results from Khan et al [148] that advised the use of wind catcher's measures with the same parameters used in (*Case 44*) as showed in chapter 3.

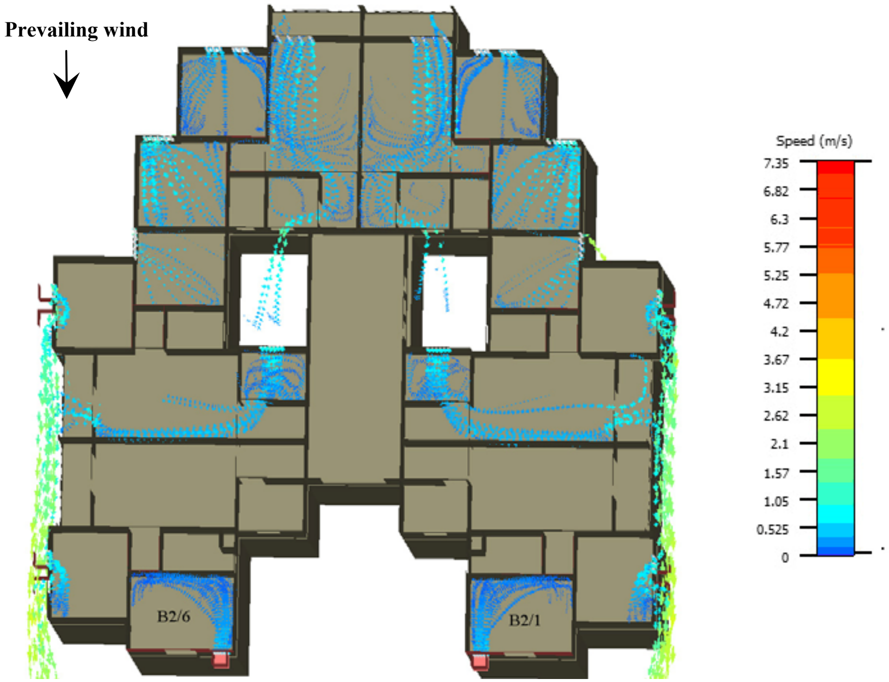


Figure 8-20: The airflow pattern inside the spaces of case (44) with the spaces with wind catchers indicated

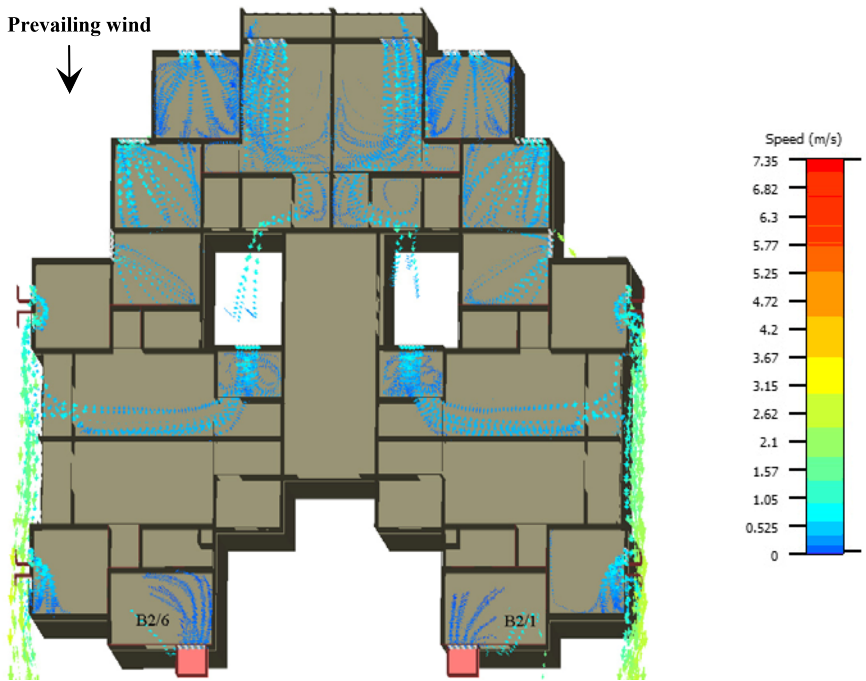


Figure 8-21: The airflow pattern inside the spaces of case (45) with the spaces with wind catchers indicated

Table 8-9: The results comparison between optimum case (3) [OP03] and [OP02] case *(all values are average internal speeds expressed in % from wind speed)*

Case No.	Description	Space with a simulated wind catcher	
		B2/1	B2/2
OP02	**Without wind catcher**	0.3	0.25
Case 44 [OP03]	**Optimal (2) + Added wind catcher with square cross-section (0.57*0.57 m) and height of 4m above the roof level**	2.03	2.00
The difference		**1.73**	**1.75**

In terms of airflow pattern inside the spaces (*B2/1, B2/6*) that were equipped with wind catchers, case 44 with the smaller cross-section area, also, showed a far better airflow pattern in comparison with case 45 (Figure 8-20 and Figure 8-21). According to these results, case 44 was chosen to be optimum case 3*[OP03]* (Table 8-9). By comparing its results with the result of optimal 2 case, it can be clearly seen that using a proper wind catcher parameters can significantly increase the internal average airspeed by about 1.73% and 1.75% from the provided wind speed within spaces (B2/1 and B2/6) respectively (Table 8-9). Optimum case (3) *[OP03]* will be considered as the base case in testing the effect of the next set of measures.

8.3.5. The effect of the right positioning and number of openings

The proposal here is to provide each space with its own ventilation system through dividing each space's window in two windows, where possible, and positioning them in the places that ensure maximum pressure difference in front of them. Therefore, the air pressure profile around the optimum case 3 was investigated and the maximum and minimum pressure points around the envelope of each space were identified (Figure 8-22). The air pressure in front of the only external wall of all living rooms (*LR1, LR2, LR3, LR4, LR5 and LR6*) is the same at almost all points (Figure 8-22). Therefore, there was no need to change the location of their openings. For the spaces that contain wing walls installed over their both windows (*B1/1, B1/2, B1/5 and B1/6*), it was chosen to locate the windows of each space far apart from each other at the edges of the wall that contains them with distance of 25cm from the edge. As for example, locating the inlets of *B1/2* and *B1/5* in the high pressure area of their low Z direction (Figure 8-22) could possibly reduce the amount of air that enters *B2/2* and *B2/5* respectively.

Prevailing wind

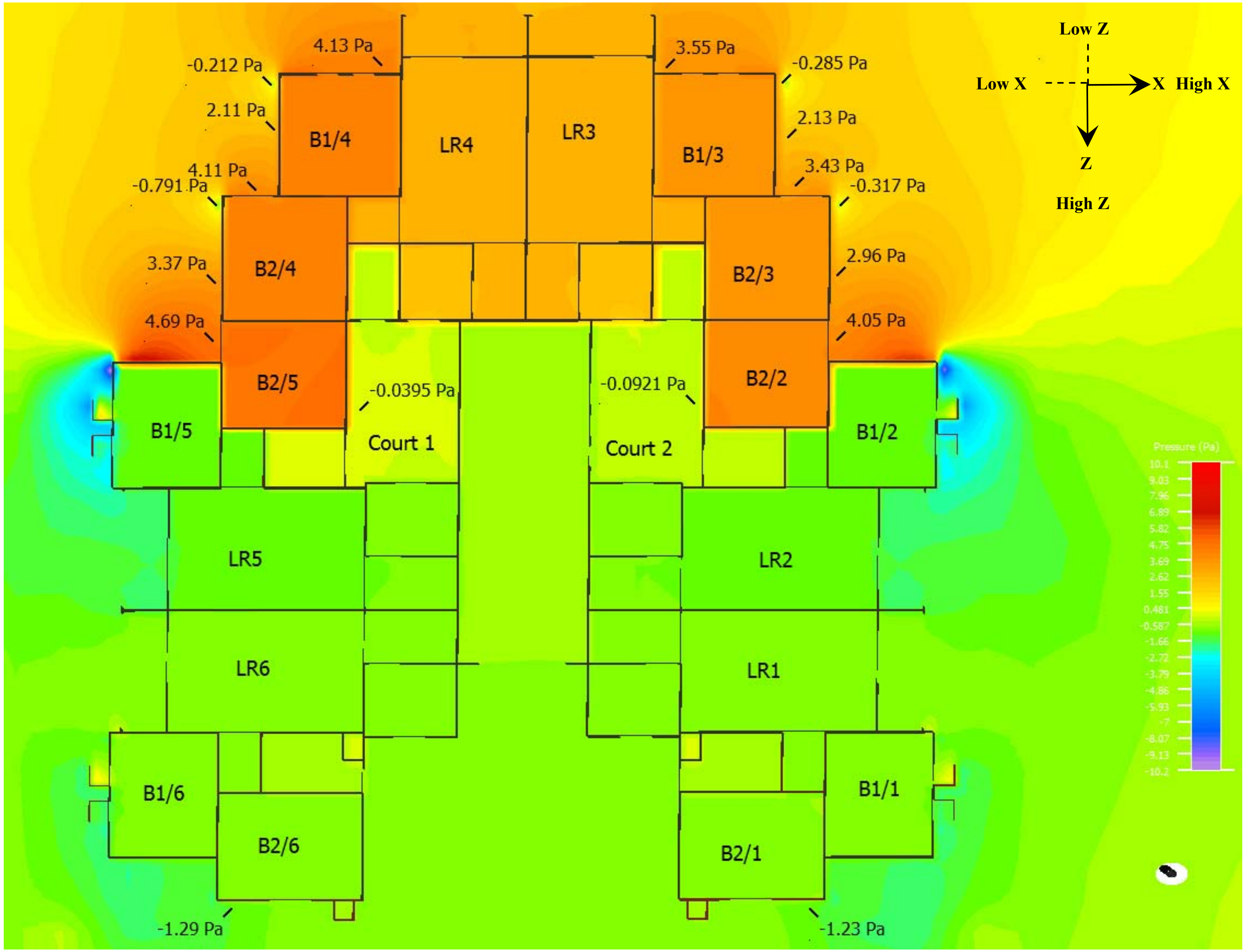


Figure 8-22: The air pressure profile in and around optimum case (3) in front of the middle of windows height with air pressure min. and max. values around each space indicated

In the spaces (*B2/2 and B2/5*), there is no chance to add another window in them as they both have only small external envelope that can only include one window. Another window can be added to them in the wall that faces the negative pressure areas in the (*Court 1 and Court 2*) that attached to (*B2/5 and B2/2*) respectively. However, adding windows on service courts for such kind of rooms is prohibited by the Egyptian building law [231]. Therefore, no change will be applied to these rooms' openings. For spaces (*B1/3 and B1/4*), the highest pressure area was found on the low X corner of the low Z wall (*3.55 Pa*) and the high X corner of the low Z wall (*4.13 Pa*) respectively (Figure 8-22). Therefore, they were considered to locate one of the two windows within each of theses spaces as an inlet of it with distance of 25cm from the corner. In the space (*B1/3*), the best location of the other window as outlet is the negative pressure area (*-0.285 Pa*) at the low Z corner of its high X wall. However, this location could provide short circuit airflow between the outlet and inlet and thus poor ventilation scenario. The solution was to locate this outlet far down in this wall to avoid the expected short circuit. Therefore, the outlet location was chosen to be located on the middle of the high X wall of the space, where the first lower pressure value (*2.13 Pa*) than that of the proposed inlet area (*3.55 Pa*) was found. Space (*B1/4*) was treated in the same manner with proposed inlet location at the high X corner of the low Z wall (*pressure = 4.13 Pa*) and outlet location at the middle of the low X wall (*pressure = 2.11 Pa*) (Figure 8-22). Also, the same problem was found in spaces (*B2/3 and B2/4*). The windows in these spaces were divided into two windows each (*0.60 * 1.30 m*). One of them was located as an inlet in the high pressure area of (*3.34 Pa and 4.11 Pa*) of spaces (*B2/3 and B2/4*) respectively and 25cm from internal wall corner (Figure

8-22). The outlets were located 1.00m away from the high Z corner of the high and low X walls of spaces (*B2/3 and B2/4*) respectively with pressures less than that of proposed locations of inlets (*2.96 Pa and 3.37 Pa respectively*) as seen in Figure 8-22. Finally, the windows of spaces (*B2/1 and B2/6*) was decided to be located in the far outer end of their high Z walls to be as far apart from the wind catchers' inlets. According to the intervention that explained above, the interventions and measures related to the openings position and number were applied to the spaces of (*B1/1, B2/1, B1/2, B1/3, B2/3, B1/4, B2/4, B1/5, B1/6 and B2/6*).

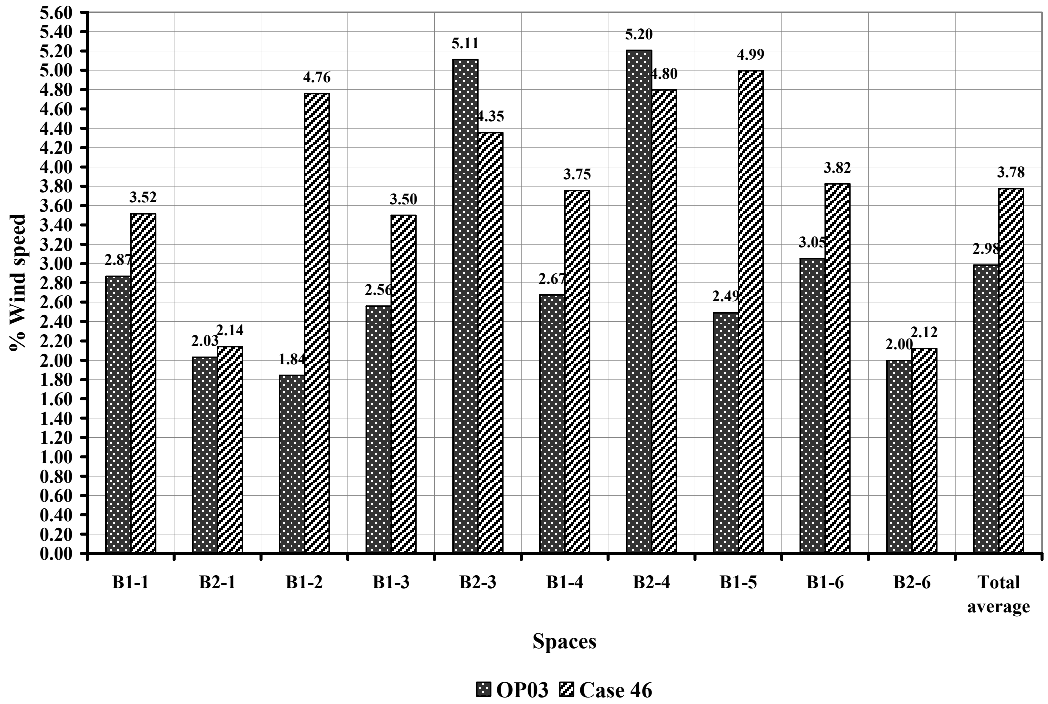


Figure 8-23: The average airspeed (% wind speed) over the spaces before (OP03) and after (Cases 46) applying the combined openings position and number measures

The simulation results of this case (*Case 46*) showed an increase in total average over all spaces of (*0.80% of wind speed*) in comparison to the OP03 case (Figure 8-23). In terms of the performance in each modified space, modifying the openings position and number showed and increase in the internal average airspeed within most of these spaces that ranged from 0.11% of wind speed in (*B2/1*) to 2.92% in (*B1/2*) (Figure 8-23). A reduction in the average airspeed was observed within (*B2/3 and B2/4*) (Figure 8-23). This can be caused by the small difference between the air pressure at the proposed locations of inlets and outlets.

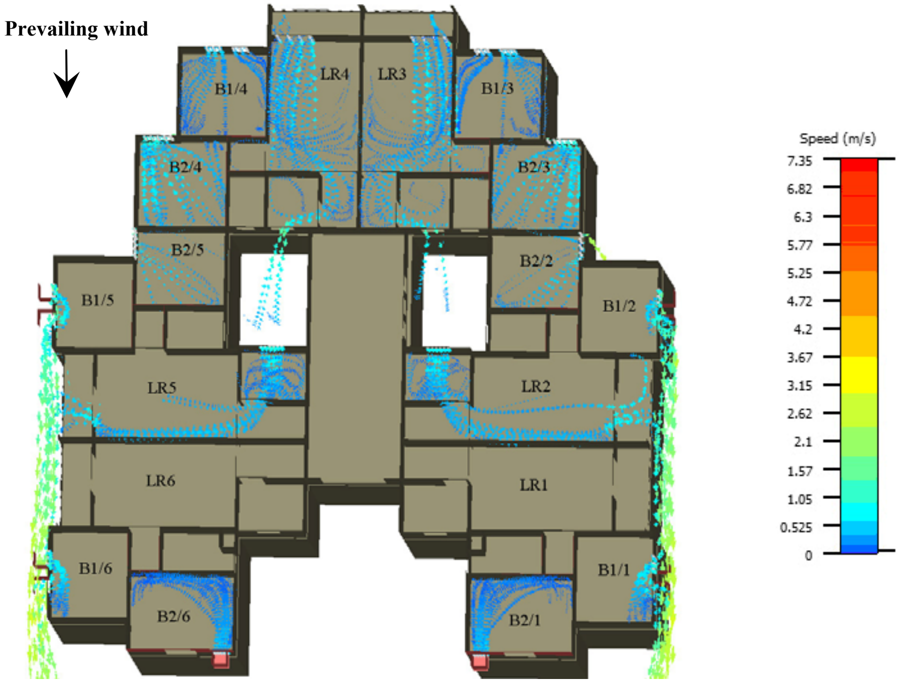


Figure 8-24: The airflow pattern inside the spaces of optimum case 3 [OP03]

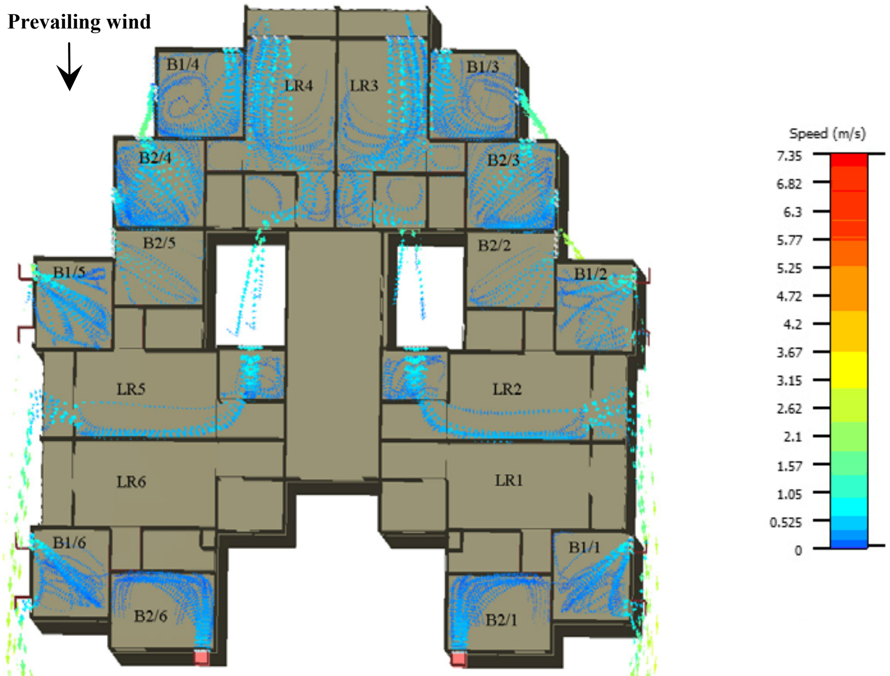


Figure 8-25: The airflow pattern inside the spaces of case (46)

By comparing the airflow pattern within the spaces, where the number and positioning measures were applied, it was found that the proper positioning and number of openings introduced significant improvement within all spaces than that of optimum case 3 (Figure 8-24 and Figure 8-25). This improvement even included the spaces, where a reduction in the average airspeed occurred (*B2/3 and B2/4*). The reason of this reduction was that the proposed outlets of these spaces has not worked as outlets but worked as inlets due to the small pressure difference, which in turn reduced the average speed but increased the flow dispersion over the spaces. Therefore, case (*46*) has been chosen as the Optimum case 4 *[OP04]* and considered as the base case to quantify the effect of the next set of measures.

8.3.6. The effect of different internal space heights

Three measures of the space height were applied to the optimum case 4 *[OP04]*. They are *3.25m, 3.50m and 3.75m* in cases (*Case 47, 48and 49*) respectively. Figure 8-26 shows the internal volumetric average airspeed in the case study's spaces after applying the proposed Space heights. In general, it can be seen from the figure that the space height only has a slight effect on increasing or decreasing the internal average airspeed, but no general pattern of this effect was observed. The average airspeed was found to increase with increasing the space height in some spaces that directly face the prevailing wind (*LR3, B1/3, LR4 and B1/4*) with slight difference between cases (*48 and49*) (Figure 8-26). The average airspeed in some spaces that do not face directly the free prevailing wind (*LR2, LR5, B1/5*) recorded slight decrease in the internal average airspeed with increasing the space height (Figure 8-26). The rest of the spaces showed non-regular patterns of the ceiling height effect.

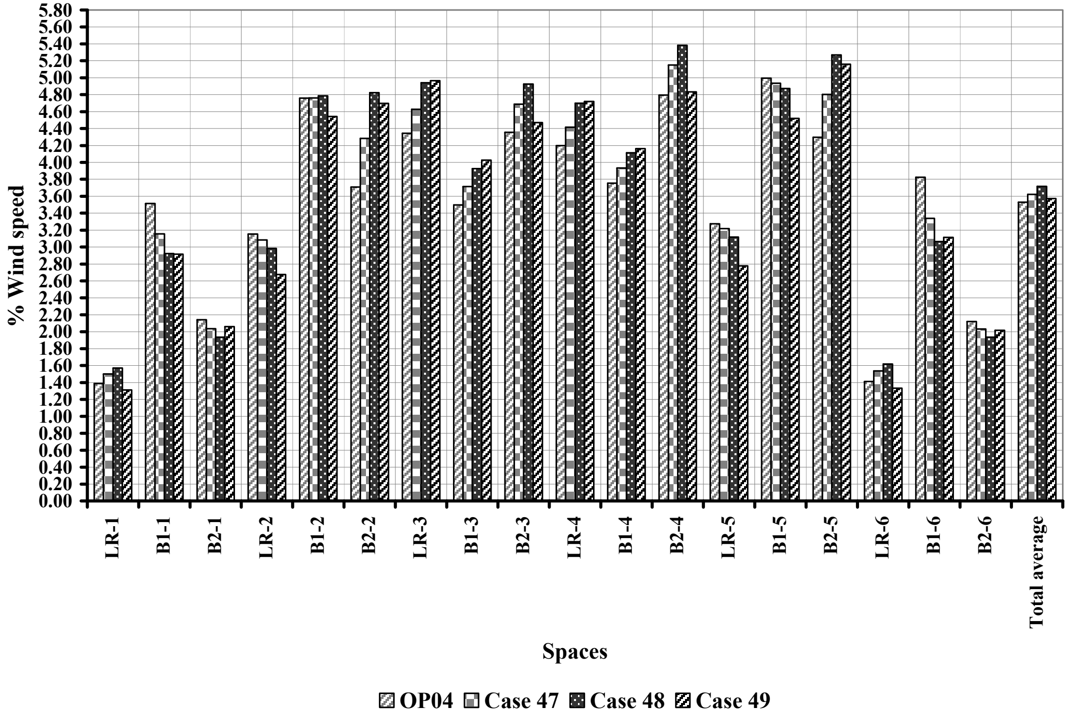


Figure 8-26: The average airspeed (% wind speed) over the spaces before (OP04) and after (Cases 47,48,49) applying different spaces heights

Further study for air pressure change with the height is needed to justify this pattern. When compared to the optimum case 4 *[OP04]*, the ceiling height of 3.50 m (*Case 48*) achieved an increase in the average speed in 11 spaces out of 18 spaces in comparison to 10 spaces and 8 spaces in case 47 and 49 respectively (Figure 8-26). Case 48 was also achieved the highest increase in the total average over all the space with difference of only (*0.19% of wind speed*) compared to 0.09% and 0.04% in case 47 and 49 respectively.

In terms of the airflow pattern, the space height showed almost no difference in all cases comparing to the optimum case 4 *[OP04]* case except at space height of 3.75m (*Case 49*), where he airflow pattern was negatively affected in some of its spaces (Figure 8-27, Figure 8-28, Figure 8-29 and Figure 8-30). From the above results, case 48 was chosen as the optimum case 5 *[OP05]* case that will be used as the base case in testing the next set of measures.

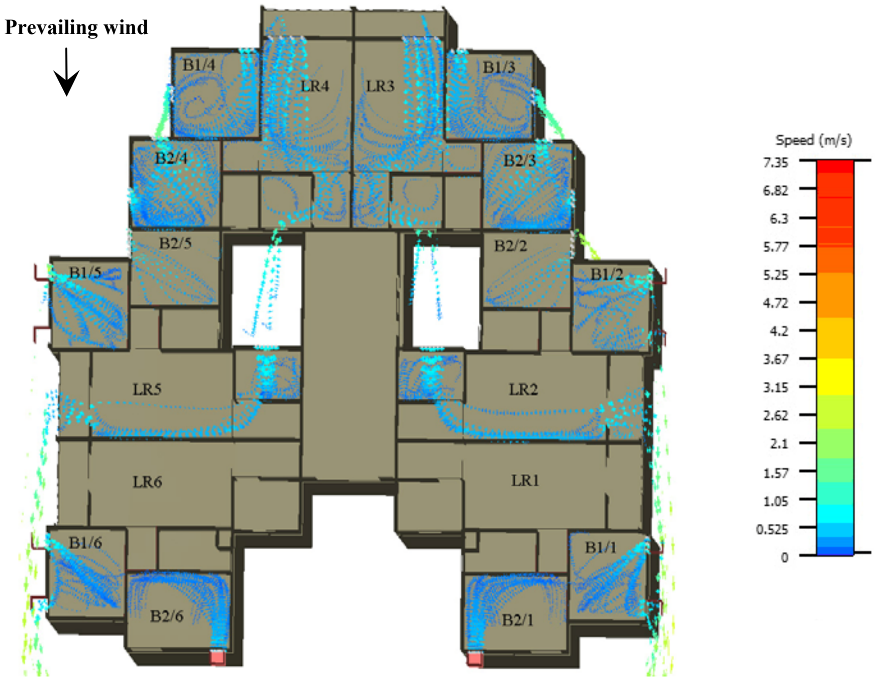


Figure 8-27: The airflow pattern inside the spaces of OP04 case

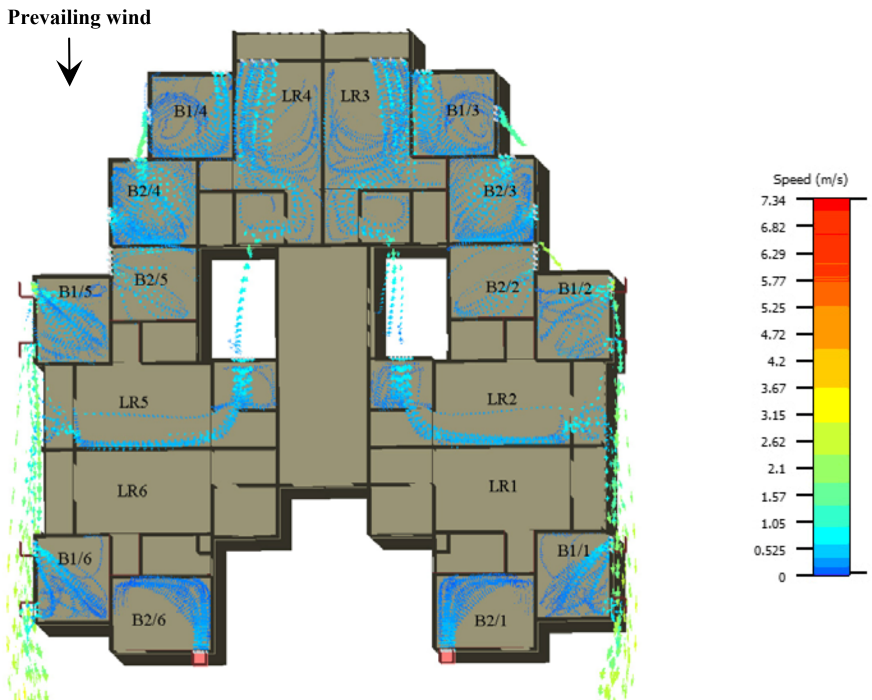


Figure 8-28: The airflow pattern inside the spaces of case (47)

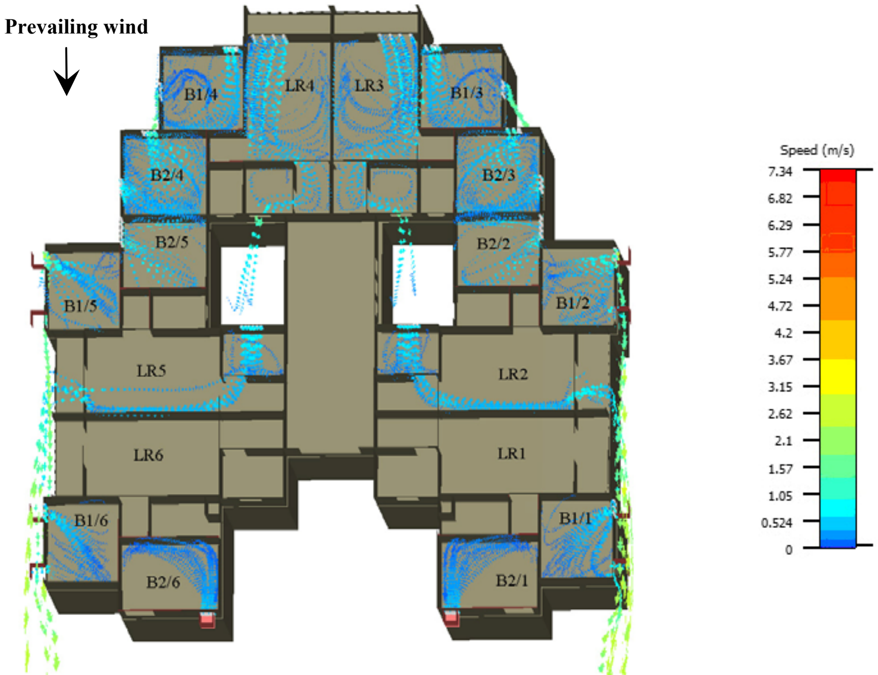


Figure 8-29: The airflow pattern inside the spaces of case (48)

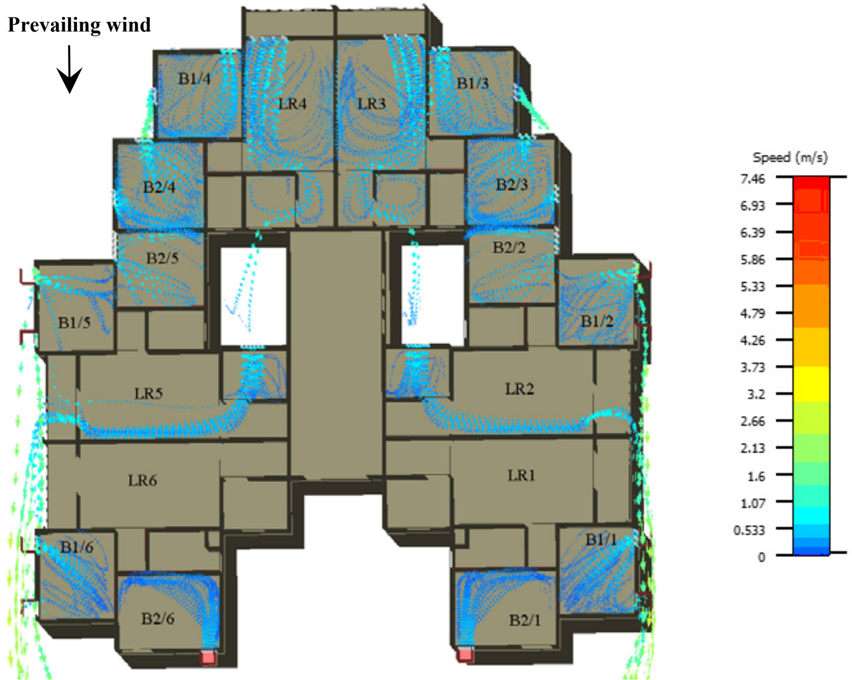


Figure 8-30: The airflow pattern inside the spaces of case (49)

8.3.7. The effect of creating cross-ventilation through increasing internal porosity

Three different measures where applied to (*OP05*) case in order to increase the internal porosity between the spaces and provide cross-ventilation without breaching the privacy in each space as explained in chapter7. Adding transom windows above the internal doors, adding lower louvered vents in the internal doors and adding both of them were tested in (*Case 50, 51 and 52*) respectively. The results showed that the cross-ventilation measures, overall has almost no effect on the total average internal airspeed over all spaces (Figure 8-31)

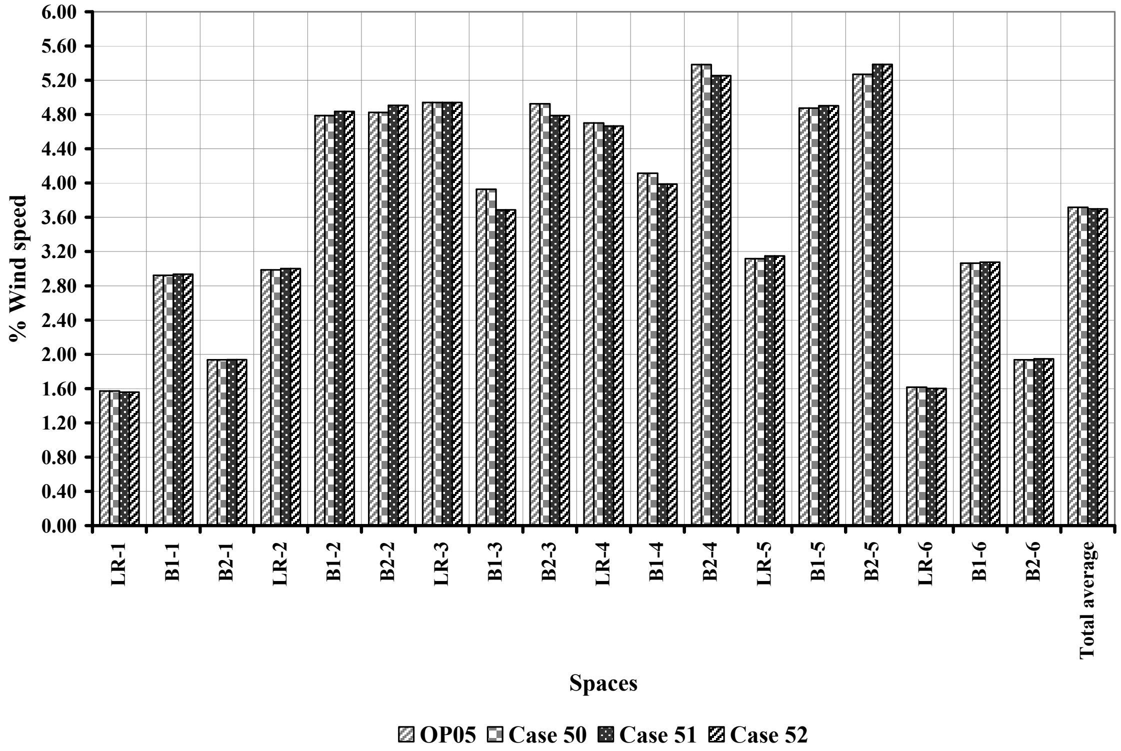


Figure 8-31: The average airspeed (% wind speed) over the spaces before (OP05) and after (Cases 50,51,52) applying the porosity measures

Even a slight decrease in the overall average was observed in cases (*51 and 52*). This possibly occurred because the individual ventilation system created within each space has the lead in driving the airflow over the cross-ventilation devices added in these cases. Also, the magnitude of the airflow within the spaces possibly were not directed to high level or low level of them, where the cross-ventilation devices where installed. This was found true, as a trial simulation case was conducted by opening the internal door, in which the air flowed between most of the spaces and achieved a significant increase in the internal airspeed.

However, this case was decided to be deferred in order to be applied on the final enhanced case. In terms of airflow pattern, increasing the internal porosity showed no significant difference between the airflow pattern of (*OP05*) case and any of the tested cases (*Case 50, 51 and 52*) (Figure 8-32, Figure 8-33, Figure 8-34 and Figure 8-35). Only some vortex was observed in the corridors between the rooms of flat 3 and flat 4 in all cases. However, a slight improvement in the airflow pattern was observed in cases (*50 and 52*) within the spaces (*LR3, LR4, B2/1 and B2/6*) (Figure 8-33 and Figure 8-35).

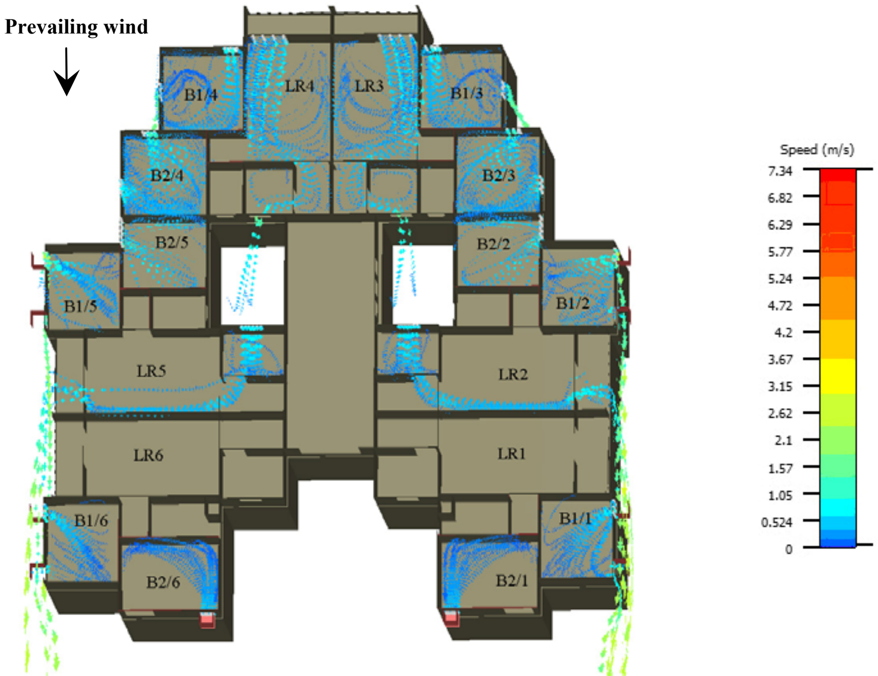


Figure 8-32: The airflow pattern inside the spaces of OP05 case

Figure 8-33: The airflow pattern inside the spaces of case (50)

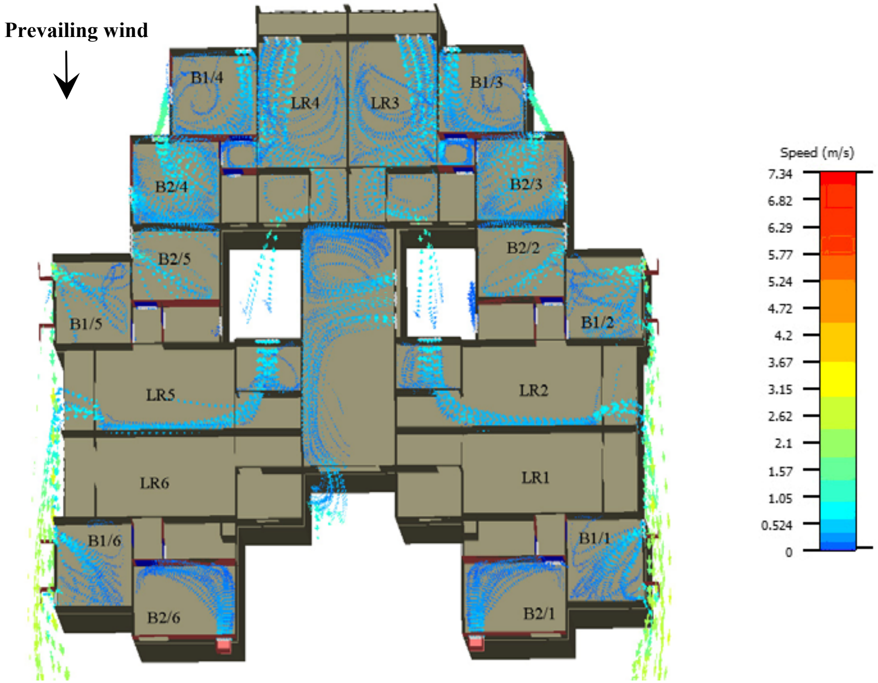


Figure 8-34: The airflow pattern inside the spaces of case (51)

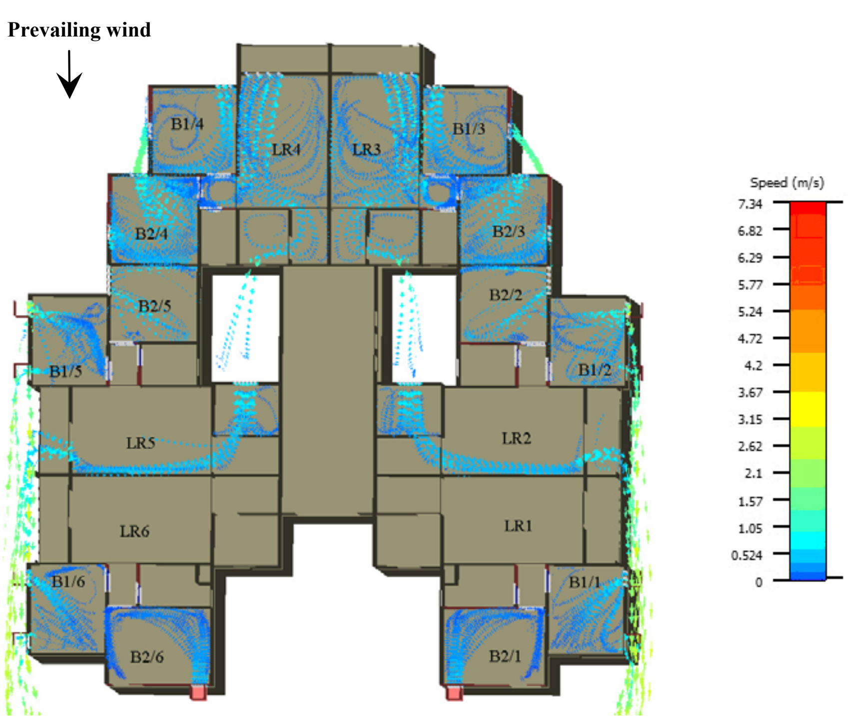


Figure 8-35: The airflow pattern inside the spaces of case (52)

According to the above results, case (50) was chosen as the optimum case 6 *[OP06]*. This was just to keep the slight improvement of the airflow pattern resulted from adding transom windows in some spaces. In addition, for keeping the possibility of creating cross-ventilation through these transom windows by thermal buoyancy, which is not studied in this work. Case 50 (*OP06*) was considered as the base case for quantifying the effect of the next set of measures.

8.3.8. The effect of changing window size

Three measures of the openings' size were applied to the optimum case 6 (*with openings' size range between 12.92% and 18.20% from the served area*). They are (*8%, 10% and 20% from space's area*) in cases (*Case 53, 54and 55*) respectively. Figure 8-36 shows the internal volumetric average airspeed in the case study's spaces after applying the proposed openings size parameters.

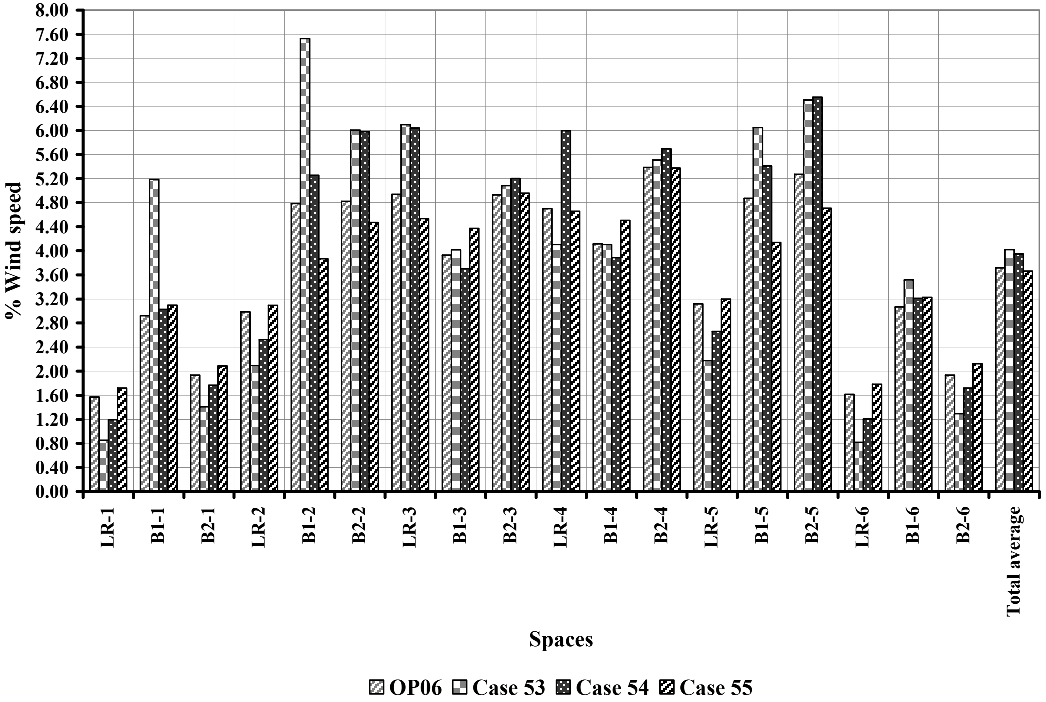


Figure 8-36: The average airspeed (% wind speed) over the spaces before (OP06) and after (Cases 53,54,55) applying the openings size parameters

In general, the total average over the whole floor' spaces was found to decrease with increasing the openings' size with the highest total average of (*4.02% from wind speed*) achieved when (*8%*) openings size was applied (*Case 53*) (Figure 8-36). The average airspeed was found to increase with increasing the opening size in some spaces that have no direct access to the prevailing wind (*LR1, B2/1, LR2, LR5, LR6 and B2/6*) (Figure 8-26). Increasing the opening's size in (*B2/1 and B2/6*) increases the outlet area in relation to the inlet area of the wind catcher's opening. This in turn accelerates the airspeed at the wind catcher inlet and increases the average airspeed within the space enclosure. In the spaces (*LR2 and LR5*), where the air inlets are the kitchens' windows, a similar conclusion can be drawn. However, in (*LR1 and LR6*), where no visible air movement can be observed, increasing the opening size provides more air volume into them that appears here as a slight increase in the average airspeed (Figure 8-36).

The average airspeed in some spaces that employ the wing wall features (*B1/1, B1/2, B1/5 and B1/6*) recorded significant increase in the internal average airspeed with decreasing the opening size (Figure 8-36). This indicates that wing wall feature work better with smaller opening size. The same air flux is induced by them into the smaller opening size increasing the air acceleration through the opening and increases the average airspeed of the enclosure. The similar performance was found in spaces (*B2/2 and B2/5*) as they found to perform better with smaller openings, but with neglected difference between 8% (*Case 53*) and 10% case (*Case 54*) (Figure 8-36). In (*B2/3 and B2/4*) the average airspeed inside them increased with increasing the openings size and reached its peak at size of (*10%*) then dropped for the opening size larger than that (Figure 8-36). A slight difference was observed in all cases within these spaces. In spaces (*B1/3 and B1/4*) the situation was reversed and achieved the peak at size 20% (*Case 55*), but again with slight difference between all cases (Figure 8-36). This might be a result of changing the air pressure difference between the openings in each space that change with changing the openings size. In (*LR3*), the average airspeed decreased with increasing the opening size with almost no difference between 8 and 10% sizes (Figure 8-36). The size of 10% (*Case 54*) achieved the maximum average speed in (*LR4*).

From the discussion above and apart from the wing walled spaces, it can be clearly seen that each space has different circumstances and has to deal with separately in determining its openings area. In order to choose the optimum case between these cases, they were compared to the (*OP06*) case. When compared to the optimum case 6 [*OP06*], the opening size of 20% (*Case 55*) achieved an increase in the average speed in 11 spaces out of 18 spaces in comparison to 10 spaces in both; case 53 and 54 (Figure 8-36). Although that, Case 55 achieved a reduction in the total average over all spaces of (-0.05 % of wind speed). Meanwhile, Case 53 achieved the highest increase in the total average over all the space with difference of only (*0.30% of wind speed*) when compared to OP06 case.

In terms of the airflow pattern, the openings' size measures showed better air dispersion within most of the spaces and better air contact with the building fabric, when decreasing the openings' size (Figure 8-37, Figure 8-38, Figure 8-39 and Figure 8-40). Cases (*53 and 54*) showed significant improvements in most of spaces that have airflow into. Within these spaces, the vertical vortexes occurred in the [OP06] case converted into horizontal vortex that skims over the space fabric and introduce maximum benefit from night purge ventilation strategy. From the results discussed above, case 53 was chosen as the Final enhanced case *[FEC]*.

Figure 8-37: The airflow pattern inside the spaces of OP06 case

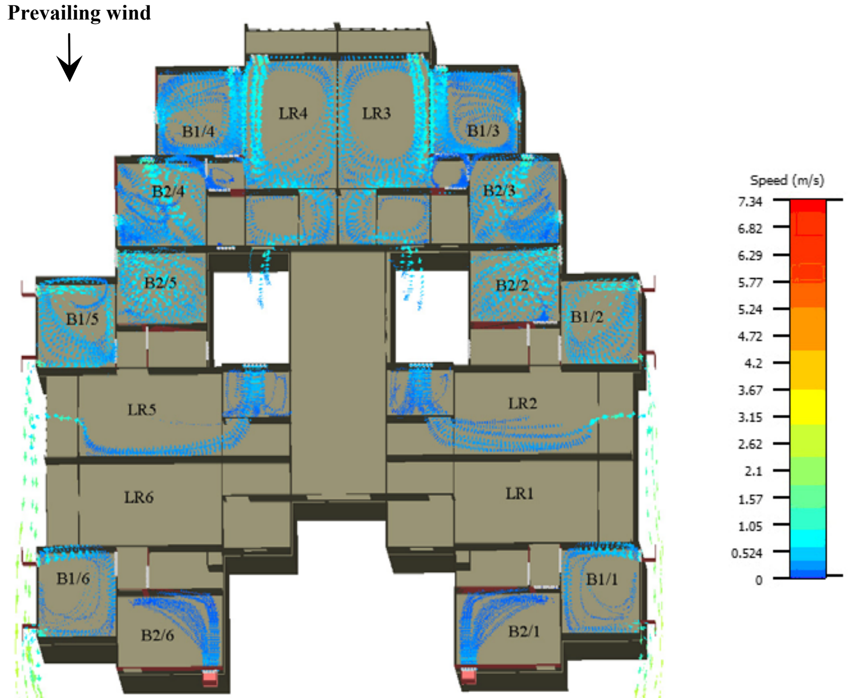


Figure 8-38: The airflow pattern inside the spaces of case (53)

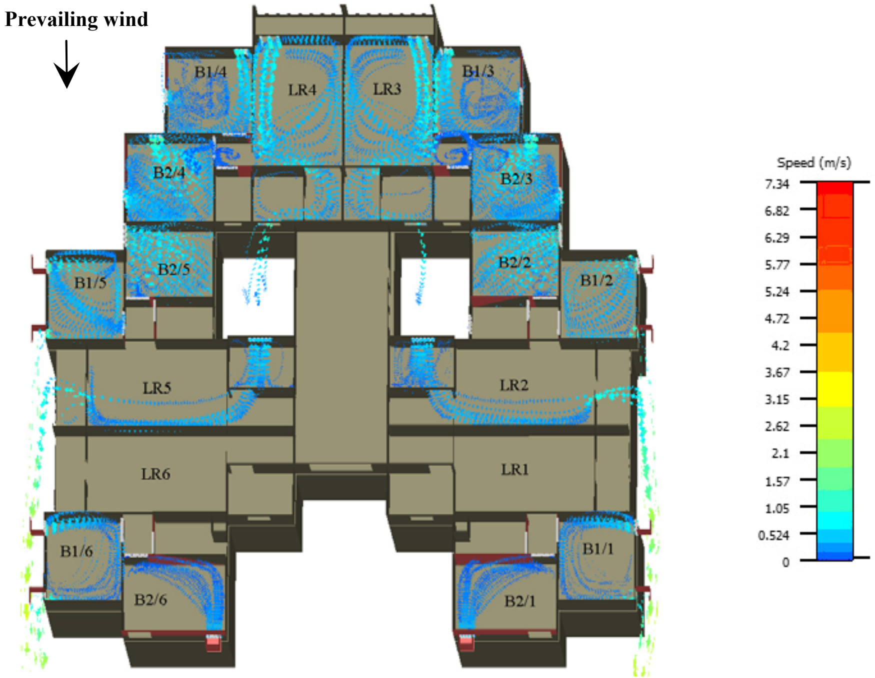


Figure 8-39: The airflow pattern inside the spaces of case (54)

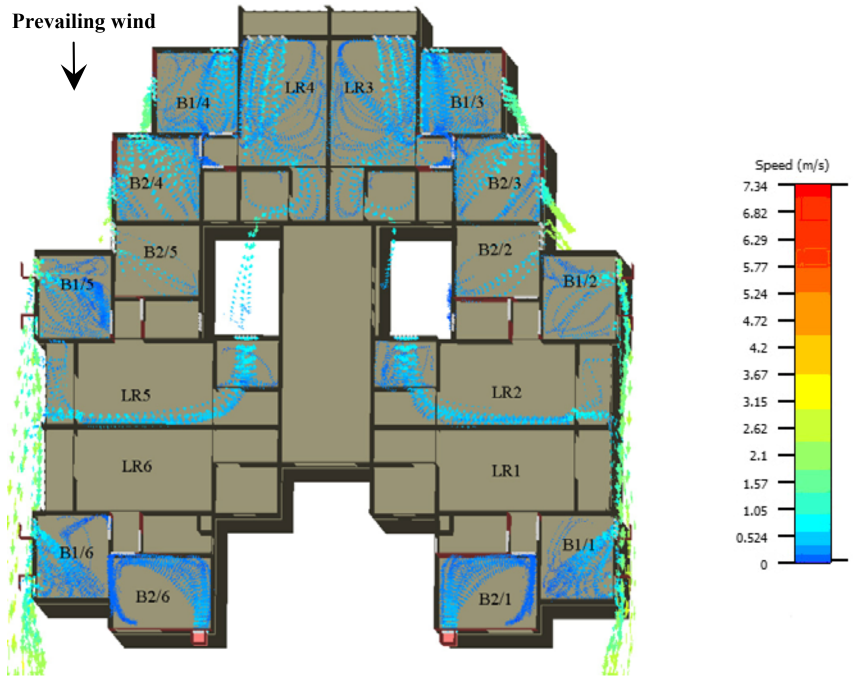


Figure 8-40: The airflow pattern inside the spaces of case (55)

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

The final overall enhanced case that resulted from the enhancement process that conducted above was also simulated with its doors opened and then both were compared to the original base case. This in order to quantify the combined effect of the best parameters of the tested design measures on enhancing the airflow performance for ventilation purposes inside

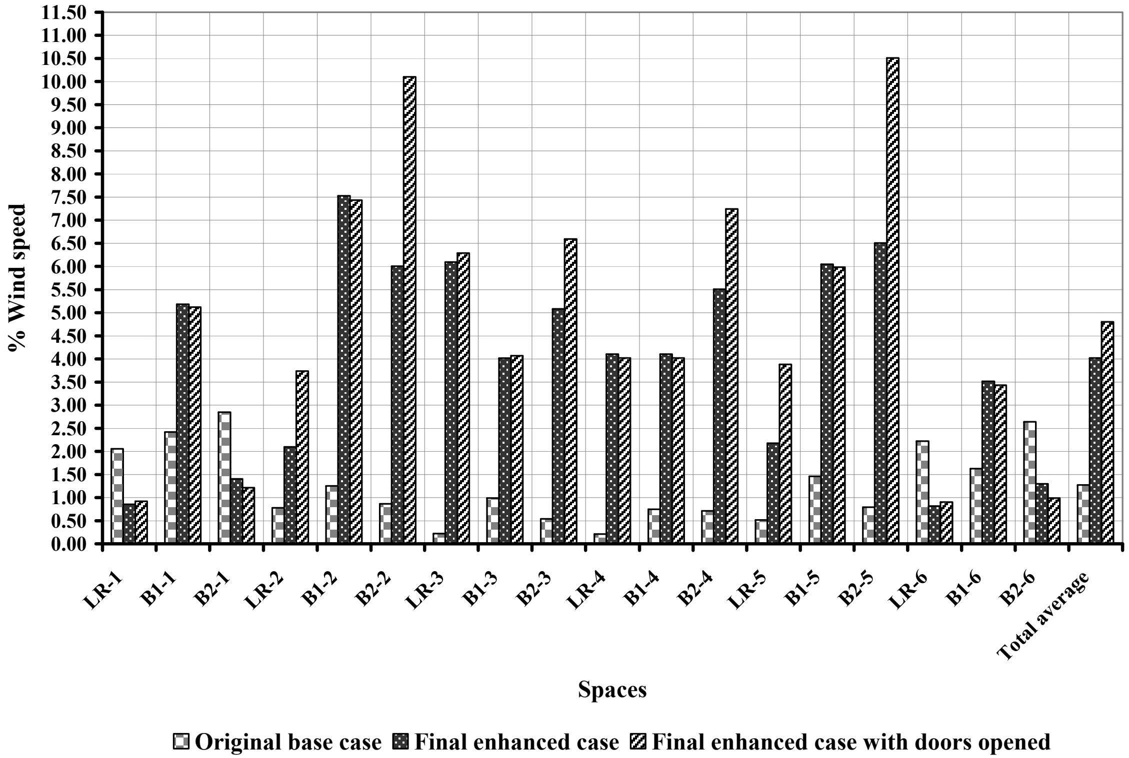


Figure 8-41: The average airspeed (% wind speed) over the spaces in the original base case and the final enhanced case with and without opening the internal doors

Table 8-10: The results comparison between the final enhanced case and the original base case *(all values are average internal speeds expressed in % from wind speed)*

	Flat (1)			Flat (2)			Flat (3)			Flat (4)			Flat (5)			Flat (6)			Total average
	LR1	B1/1	B2/1	LR2	B1/2	B2/2	LR3	B1/3	B2/3	B2/6	B1/4	B2/4	LR5	B1/5	B2/5	LR6	B1/6	B2/6	
Original base case	2.06	2.42	2.85	0.78	1.25	0.87	0.22	0.99	0.54	0.21	0.75	0.71	0.52	1.46	0.79	2.22	1.63	2.64	1.27
Final enhanced case (FEC)	0.85	5.19	1.41	2.10	7.53	6.01	6.10	4.02	5.08	4.10	4.10	5.51	2.18	6.05	6.51	0.82	3.52	1.29	4.02
The difference	**-1.21**	**2.77**	**-1.44**	**1.32**	**6.28**	**5.14**	**5.23**	**3.03**	**4.54**	**3.89**	**3.35**	**4.80**	**1.66**	**4.59**	**5.72**	**-1.4**	**1.89**	**-1.35**	**2.75**

Table 8-11: The results comparison between the final enhanced case with internal doors opened and the original base case *(all values are average internal speeds expressed in % from wind speed)*

	Flat (1)			Flat (2)			Flat (3)			Flat (4)			Flat (5)			Flat (6)			Total average
	LR1	**B1/1**	**B2/1**	**LR2**	**B1/2**	**B2/2**	**LR3**	**B1/3**	**B2/3**	**B2/6**	**B1/4**	**B2/4**	**LR5**	**B1/5**	**B2/5**	**LR6**	**B1/6**	**B2/6**	
Original base case	2.06	2.42	2.85	0.78	1.25	0.87	0.22	0.99	0.54	0.21	0.75	0.71	0.52	1.46	0.79	2.22	1.63	2.64	1.27
FEC with internal doors opened	0.92	5.12	1.22	3.74	7.44	10.10	6.29	4.07	6.59	4.02	4.02	7.24	3.88	5.98	10.51	0.90	3.43	0.99	4.80
The difference	**-1.14**	**2.70**	**-1.63**	**2.96**	**6.18**	**9.24**	**6.07**	**3.08**	**6.06**	**3.80**	**3.27**	**6.53**	**3.37**	**4.52**	**9.72**	**-1.32**	**1.81**	**-1.65**	**3.53**

the case study. Figure 8-41, Table 8-10 and Table 8-11 show the comparison between the volumetric average airspeed inside the spaces in the original case and the final enhanced case with and without opening the internal doors. It can be clearly seen from Figure 8-41, Table 8-10 and Table 8-11 that applying the selected measures to the case study has significantly improved the average airspeed within the majority of the spaces (Figure 8-41). This improvement even became better when the internal doors were opened and maximum internal porosity was provided (Figure 8-41 and Table 8-11). The reduction in the internal airspeed in some spaces (*LR1, B2/1, LR6 and B2/6*) occurred as a result of changing the block orientation in regard to the prevailing wind. This reduction was a slight reduction that ranged between 1.21% and 1.44% of wind speed within the final enhanced case (Table 8-10) and between 1.14% and 1.65% within the final enhanced case with the doors opened (Table 8-11). In general, applying the best selected measures to the block's design elements showed an increase in the total average of 2.75% of the wind speed in the final enhanced case over that of the original case (Table 8-10). This means that the total average speed over the whole spaces was almost tripled after the enhancement. This enhancement could be increased to reach 3.53% of wind speed by opening the internal doors. The enhancement in the average airspeed throughout each space was found to range between 1.32% (*LR2*) to 6.28% (*B1/2*) in the final enhancement case (Table 8-10). However, it ranged between 1.81% (*B1/6*) to 9.72% (*B2/5*), when the internal doors were opened (Table 8-11). In terms of the airflow pattern, Figure 8-42 and Figure 8-43 illustrate the airflow pattern within the original base case and within the final enhanced case with and without opening the internal doors.

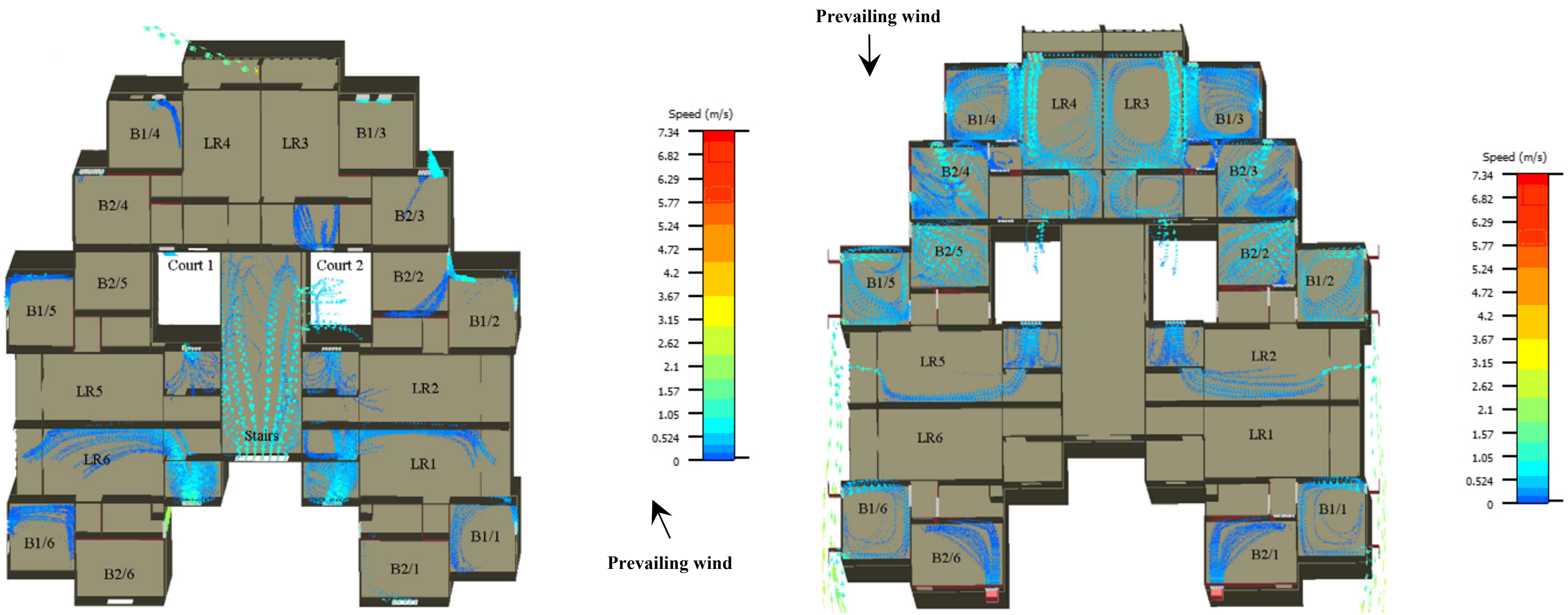


Figure 8-42: Comparison between the airflow pattern inside the original base case (left) and the final enhanced case (right)

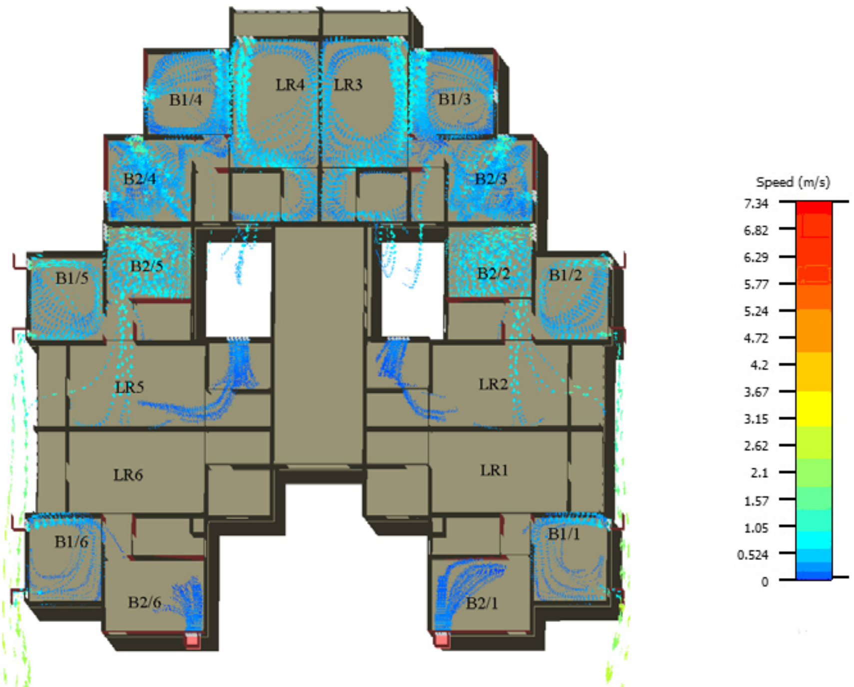


Figure 8-43: The airflow pattern inside the final enhanced case with the internal doors opened

It can be clearly seen from the figures that the airflow inside most of the spaces within the case study was significantly enhanced after applying the proposed measures. Larger building fabric became exposed to the flowing air, which support the use of night purge ventilation and maximize its benefit. The only spaces that could not be treated are (*LR1 and LR6*). None of the applied measures could induce the air to enter them due to the negative pressure around their external envelope. In addition, the problem of the kitchens being the air inlet could only be treated in 4 flats (*F1, F3, F4 and F6*) out of 6. This is due to the air pressure profile around the block forced by its design. For watching movies of the airflow inside these cases, please see (*Appendix I*).

8.4. Conclusions

In the enhancement process, the effectiveness of several passive measures in terms of airflow for natural ventilation purposes was quantified. Although, the quantification of the use of these measures did not achieve satisfactory results near those of previous work, it emphasized the importance of using such measures when designing for natural ventilation. This difference caused by the difference in the studied cases, as most of the previous work used a simplified models (*one space without surroundings*) to get their results, while this work used a multi-space case within its full context. The enhancement process was conducted in accumulative manner using the *FloVent* CFD software. In general, the results showed that the overall average airspeed inside the case study was more than tripled after the enhancement.

The combined effect of the building arrangement, orientation and canyon geometry measures showed the highest improvement (*95.3%*) among the used measures (Figure 8-44). The space height introduced the min. enhancements to its base case. Opening the doors in the final enhanced case provided (*19.5%*) more to the average airspeed, while no enhancement was provided when the internal porosity was increased through providing transom windows and louvered lower door parts (Figure 8-44). This indicates that most of the air flux flow within the middle height of the spaces rather than the higher or lower part of it.

This case treatment can be claimed to maximize the potential of using both ventilation passive strategies. By improving the airspeed inside the spaces, the potential of using comfort

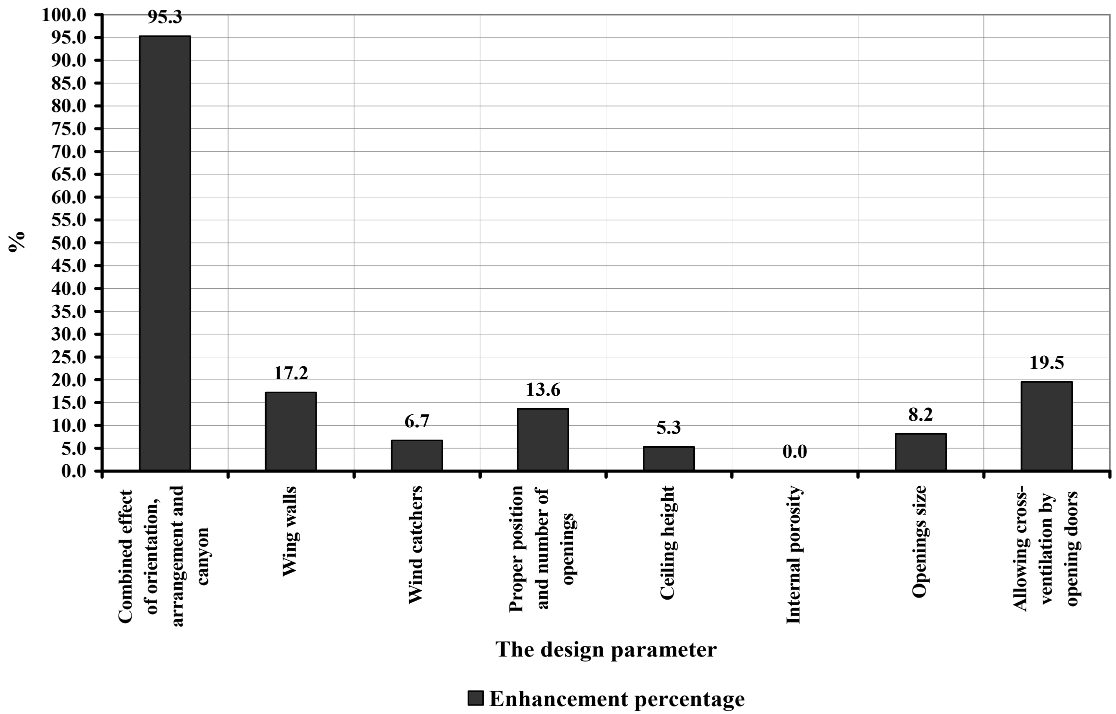


Figure 8-44: The overall enhancement percentage after applying the enhancement measures to their base cases

ventilation, when the external climatic conditions allow doing that, was maximized. In addition, by improving the airflow quality and the exposure of the building fabric to the flowing air maximizes the potential of using the night ventilation to cool down the building fabric. These enhancements that applied to the case study considered, to some extent, the privacy requirements of the residents resulted from the evaluation study. However, all the applied measures could not reach the preferred airspeed (*1.265 to 1.595 m/s = 22.6% to 28.5% of the prevailing wind*) that resulted from the evaluation study at any of the case study spaces. The results the FEC with doors opened also did not achieve the acceptable airspeed range inside naturally ventilated residential buildings (1-2m/s) identified by Givoni [38] (Figure 8-45). In addition, they did not achieve the range of internal airspeed (35%-50% of wind speed) stated by Givoni [19] for effective comfort ventilation (Figure 8-46).With the current design of the housing blocks this speed can not be achieved without the use of the mechanical assisted ventilation.

In general, it seems very difficult to optimize the airspeed within all spaces in a very dense multi-space design like this case study. A new design that considers natural ventilation and its drivers has to be introduced.

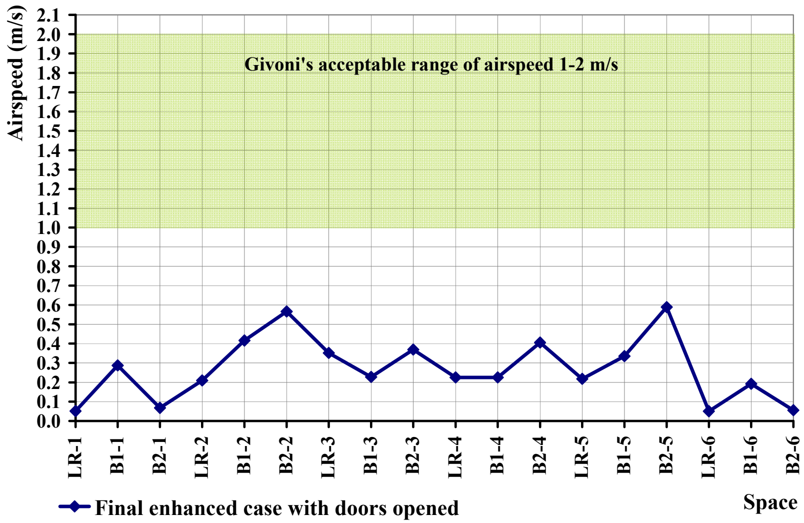


Figure 8-45: The final enhanced case with doors opened in contrast to Givoni's acceptable indoor airspeed (m/s) in naturally ventilated buildings

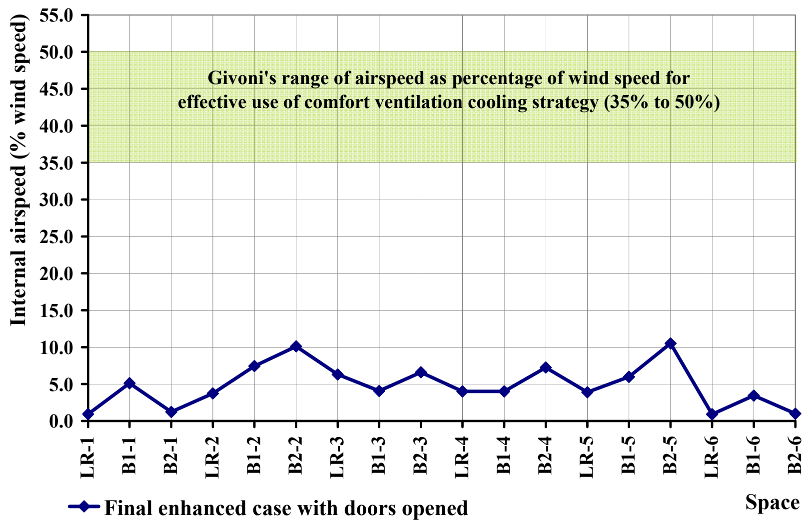


Figure 8-46: The final enhanced case with doors opened in contrast to Givoni's advised indoor airspeed for effective use of comfort ventilation

Chapter 9:
Conclusions and further work

9.1. Summery of conclusions

This problem of the reduced capabilities of natural ventilation passive cooling strategies in achieving thermal comfort, due to the poor airflow in dwellings as well as the poor exposure of their thermal mass to the airflow, within the walk-up public housing blocks in the Egyptian deserts had been identified. None of the available literature attempted to test the cooling capability of ventilation strategies in real terms. Moreover, none of them investigated the quality of airflow at any of their case studies. This gap in the body of knowledge was identified and was approached in this research. The current work was carried out in order investigate the possibility of enhancing the use of natural ventilation as a passive cooling strategy in walk-up public housing blocks in the Egyptian desert climatic design region. This main aim was achieved through fulfilling three objectives as follow:

1- Quantitatively and qualitatively evaluating the natural ventilation performance of the walk-up public housing blocks in desert region;
2- Formulating design measures that could enhance the natural ventilation performance of the walk-up public housing blocks; and
3- Quantifying the effect of the different design measures on enhancing the natural ventilation performance of the case study.

The main conclusions of the research could be drawn in the light of the both main studies implemented in these objectives; the evaluation study and the enhancement study

9.1.1. Evaluating natural ventilation performance in the walk-up public housing blocks

A representative case study was chosen to be used as a test vehicle in which the study can be conducted. The results of the case study analysis showed that there is no natural ventilation system designed for this case study at any of the given design levels. In addition, the internal design of the case study prevents cross-ventilation and only offers a separate single-side ventilation technique via each space, through its window. The natural ventilation performance and use in the case study was then evaluated quantitatively and qualitatively through objective and subjective assessment respectively..

In the objective assessment, the thermal effect of different natural ventilation scenarios (*S1=24 hours ventilated, S2=24 hours unventilated and S3=ventilated during night only*) was monitored, the cooling capabilities of the recommended ventilation strategy in the research context (*night purge ventilation*) in all the case study flats were monitored and the airflow in and around the case study was investigated using the *CFD* simulation tool (*FloVent*). The following conclusions could be drawn from this objective assessment:

- Although, all applied ventilation scenarios were found to be significantly higher than the comfort temperature, the monitoring of the thermal performance of the case study under the application of those ventilation scenarios confirmed the suggestion of the passive strategies analysis that indicated the use of night purge ventilation scenario as the most effective strategy in achieving thermal comfort. Night purge ventilation achieved the only observed cooling effect between all ventilation scenarios, the nearest average internal temperature to comfort temperature and the lowest degree of variation in temperature between both scenarios, in which the ventilation was allowed.

- The monitoring results of the temperature inside different flats under only the application of night purge ventilation scenario showed that the thermal performance of the monitored spaces has the same profile in each space. However, some significant discrepancies were observed between the different flats, especially at early and late night times. This was justified by the different thermal properties of the finishing materials of the surroundings and the duration of the solar radiation exposure. The performance of the monitored spaces was then evaluated using different evaluation methods. None of the spaces, which ventilated at night was found to satisfy any of these methods. The results indicated that poor cooling using night ventilation was achieved. This was referred to the poor thermal mass' design combined with insufficient exposure to cool night airflow. It can be concluded that the ventilation design of the monitored case study is not currently suitable for night time and thermal mass cooling.

- The airflow analysis over the case study's site showed a poor airflow pattern across it in all the tested heights. In addition, the analysis indicated the poor blocks' arrangements and orientations which could possibly undermine the possibility of the use of the available airflow ventilating internal spaces.

- The airflow quality pattern resulted from the CFD simulation of the monitored floor of the case study could apparently hinder the potential of cooling down the thermal mass by night purge ventilation. Moreover, all the average airspeeds that were achieved inside the main living spaces of the flats were found not to meet both, the acceptable airspeed inside the naturally ventilated residential buildings and the human sensation with the air movement. This in turn undermines the potential of cooling by comfort ventilation. From the results of the objective assessment outlined above, it became obvious that the current situation in the case study is not suitable for using natural ventilation with its both main cooling strategies.

In the subjective assessment, a purpose-designed questionnaire was conducted with the case study's occupants in order to understand their subjective response towards using natural ventilation as a passive cooling strategy. Although the number of questioned informants was not enough to generalize the results of the questionnaire, many useful indications could be understood from them, such as:

- The majority of informants were thermally uncomfortable during summer and winter in their dwellings;
- Most of them were found to respond to the hot internal weather by unconsciously opening windows for ventilation cooling. However, those, who do not open the windows, justified that in the breach of their privacy, dust, insects, non-effective air movement and sometimes the tendency to use fans, especially in bedrooms;
- The intuitive use of both; night purge ventilation and comfort ventilation strategies by the informants as a form of their adaptation to maintain thermal comfort were confirmed;
- Most informants were found to be keen to create cross-ventilation throughout their dwellings by opening some windows and doors

along with keeping room doors opened all the time.

- All the informants were found to use fans in all or some of their dwelling spaces either; to avoid opening windows during hot day-time, to improve the movement of their dwellings' still air or for enhancing the airspeed around their bodies;
- By comparing the preferred speed of the informants' fans with the known airspeed profile generated by the standard ceiling fan, it was found that the informants prefer airspeed range of (*1.265 to 1.595 m/s*) around their bodies.

All the problems in natural ventilation performance that had risen from the evaluation study with its two parts were consequently addressed and steps towards introducing solutions for them were taken in the enhancement study.

9.1.2. Enhancing natural ventilation performance in walk-up public housing blocks

The effectiveness of the carefully selected design measures and their parameters was quantified in order to reach the enhanced overall case for the case study under investigation. The enhancement process was conducted in accumulative manner using the *FloVent* CFD software. Although, the quantification of the use of these measures did not give results near to those of previous work, it emphasized the importance of using such measures when designing for natural ventilation. The quantification process showed that the following measures introduced the best potential to facilitate natural ventilation use as a passive cooling strategy for this specific case study:

- Aligned rows building arrangement associated with 0^o wind orientation and 36m canyon width;
- Designed wing walls with a privacy wing provided they were installed in the right place;
- A wind catcher installed, where needed, with a square cross-section (57cm * 57cm) and with a height of 4m above the roof level;
- Positioning the spaces' openings in the right place to secure the maximum air pressure difference between the inlets and outlets with providing 2 openings in each room, if possible;
- Considering the ceiling height of 3.50 m in residential building could contribute not only to improving the wind driven ventilation, but

also expected to improve the thermal buoyancy driven ventilation;

- Providing an increase in the internal porosity in the right place that takes account of the direction and level of the air stream flow;
- Stuck to opening size of 8% from the space's area that advised as a minimum by the Egyptian building regulations, in the spaces that have direct wind access or equipped with wing walls, while increasing this to 20% in those spaces that do not have direct wind access.

Some general conclusions also could be drawn from the enhancement study such as:

- In general, the use of the above measures showed that the overall average airspeed inside the case study was more than tripled after the enhancement.
- The combined effect of the building arrangement, orientation and canyon width showed the highest improvement (*95.3%*) to the base case among the measures used,
- The ceiling height introduced a minimum enhancement to its base case.
- These treatments can be claimed to maximize the potential of using both ventilation passive strategies. As by improving the airspeed inside the spaces, the potential of using comfort ventilation, when the external climatic conditions allow doing that, was maximized. In addition, by improving the airflow quality and the exposure of the building fabric to the airflow maximizes the potential of using night ventilation to cool down the building fabric.
- These design measures as applied to the case study presented the maximum intervention that could be applied to the case study without changing its design. In addition, it provides a range of solutions to be applied to the case study at any construction stage from the (*not built yet*) case to the (*finished and handed over to occupants*) case.
- In order to maximize the effectiveness of the introduced treatment of the case study in this work, the use of vegetation and trickle fountains in the case study site so to alter the air properties and to cool it down to be suitable for comfort ventilation in high heat stress conditions at mid-summer's day is recommended.

- The results confirmed the use of some measures as advised by other researchers, for example such as, wind catcher measure and its parameters.
- They were found, also, to reject other measures, such as the opinion that advised on absolute the use of opening size of 20%.
- The results, also, showed the performance of some newly applied measures such as; wing walls with a privacy wing, increasing internal porosity measures and different ceiling height measures.
- All the applied measures could not achieve neither an acceptable airspeed at any of the case study spaces nor a good airflow circulation at some of its spaces. It can be concluded that the current design of the case study can not achieve quality airflow without the use of the mechanical assisted ventilation. In general, it seems very difficult to optimize the air velocity within all spaces in a very dense multi-space design like this case study. A new design that considers natural ventilation and its drivers has to be introduced.

9.2. List of contributions

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

- Introducing a methodology to identify the research problem through conducting pilot investigations rather than putting up hypotheses based on literature and testing their validity;
- Introducing a comprehensive classification for the design measures and their parameters that have impact on natural ventilation performance, as well as assisting in the practical revision of such theories still remiss in the field of natural ventilation and its relation to building design that can help in other countries.
- Identifying quantitatively and qualitatively the natural ventilation performance in the Egyptian walk-up public housing blocks and problems associated with its use;
- Quantifying the effectiveness of many design measures on airflow performance in a multi-space case study rather than simplified

models as had been done in most of the previous studies, as well as identifying the effect of previously untested measures; and

- Introducing practical treatments of the ventilation performance in the most currently effective case study in the Egyptian context, which in turn casts a practical and economical effectiveness of this work.

9.3. Proposal for further work

Proposed design measures in this work tripled the performance of the airflow for ventilation purposes in the case study. Further research is required to investigate ways of achieving higher levels of airflow performance inside the case study that could help also in filling some gab still identified the knowledge . These ways could be as follow:

- New designs of lower density public housing blocks need to be considered in the so future to integrate other ventilation design measures in housing design such as, i) using internal courtyards, ii) using double-skin facades, iii) employing ventilation devices such as those used in traditional Egyptian architecture and v) using dynamic breathing walls;
- Further research is needed to investigate and enhance the thermal properties of the case study building fabric in order to decrease its heat absorbance and, hence maximize the effectiveness of using the treated airflow in night ventilation;
- The performance and enhancement of the thermal buoyancy-driven ventilation, in particular, through internal courts and stairwell should be investigated, which was not possible in this work due time limitations;
- The effect of the used measures on the natural lighting level inside the spaces and the indoor air quality should be investigated and taken into account;
- Further investigation is required to quantify the effectiveness of applying the multi-section wind catcher that uses the Venturi effect to the case study;
- At the moment, there are no specific environmental or natural ventilation standards for housing in Egypt. Hence developing a new version of such standards is essential for the future.

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Appendices

11.1. Appendix (A): The case study's architectural drawings

11.2. Appendix (B): Weather data interpolation

11.3. Appendix (C): FloVent validation models, results and analysis

11.4. Appendix (D): Monitoring data and analysis

11.5. Appendix (E): FloVent model, results and analysis for the monitored block

11.6. Appendix (F): The questionnaire's script translation

11.7. Appendix (G): The questionnaire's data and analysis

11.8. Appendix (H): Enhancement simulation cases' results and analysis

11.9. Appendix (I): Airflow movies for the original base case and the enhanced case

11.10. Appendix (J): The published research papers