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An Attempt to Design a Naturally Ventilated Tower in Subtropical Climate of the Developing Country; Pakistan

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***Abstract* – A large proportion of the world's population resides in developing countries where there is a lack of rigorous studies in designing energy efficient buildings. This study is a step in designing a naturally ventilated high rise residential building in a tropical climatic context of the developing country, Pakistan. Karachi, the largest city of Pakistan, lies in the subtropical hot desert region with constant high temperature of average 32 °C throughout the summer and no particular winter season. The *Design Builder* software package is used to design a 25 storey high rise residential building relying primarily on natural ventilation. A final conceptual design is proposed after optimization of massing, geometry, orientation, and improved building envelope design including extensive shading devices in the form of trees. It has been observed that a reduction of 8 °C in indoor ambient temperature is possible to achieve with passive measures and use of night time ventilation. A fully naturally ventilated building can reduce the energy consumption for cooling and heating by 96 % compared to a building using air conditioning systems.**

***Keywords* – Climate; developing countries; *Design Builder*; global warming; Karachi; natural ventilation; Pakistan; residential living; subtropical cities; tropical**

1. INTRODUCTION

The world's population has grown to about 7 billion, and is anticipated to reach by 9 billion by 2050. This increase, together with a rapidly urbanizing population is driving a significant increase in building construction. According to UNEP 2015, at present buildings contribute to about 40 % of the world's overall energy consumption and are a cause of 1/3 of the global greenhouse gas emissions (GHG). Residential and commercial buildings consume about 60 % of the total world's electricity consumption. Many developed countries including United States of America and UK, have started to develop policies and have established building codes and Green Building Regulations such as ASHRAE, CIBSE (UK) and LEED (USA) which are forcing the architects and designers to include the principles of sustainability in their designs. As a result of which these countries are able to reduce the energy consumption and carbon emissions through their buildings.

A very important strategy for making a building energy efficient is the use of "Climate" and "Natural Ventilation", a passive design strategy to reduce the impact of a building on the environment [1]. Traditionally, the very simple buildings designed by mankind were comfortable, because man incorporated the climate into his building design. Thus today, large buildings are responsible for accommodation of a number of people, providing jobs, education and better quality living [2], therefore, the need of the hour is to include natural ventilation in tall buildings, especially in hot or difficult climatic locations of developing countries.

The need for making greener skyscrapers arises from the fact that they are the reason of consumption of a large amount of energy, materials and resources although using a small footprint

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and accommodating a large human population. In a developing country, where many resources are subjected to shortage such as power failure, a high rise tower provides more options of an ecologically responsive architecture [3]. It can be integrated into the environment, harnessing the wind and solar power available to it, thus making limited use of the natural resources.

1.1. Challenges Associated with Natural Ventilation in Buildings

Some of the challenges associated with passive design of towers are discussed briefly as:

1.1.1. Relation of Height with Wind Patterns and Relevant Climatic Parameters

A highly significant challenge in designing a high rise building for driving air flow within its spaces is the behavior of wind. Wind shows variation with increase of height and also in different climates, its behavior is different. So, while designing a building in a particular climate, good attention needs to be given in determining that how wind profile changes with altitude in that specific climate.

When Dubai was used in a case study by [4]; it was found that wind speed increases with height whereas air pressure decreases. This study is also supported by [5] adding that the geometry of buildings around the considered building site, and wind patterns corresponding to the urban or rural context, also needs to be studied in detail for effective design. This would therefore also require the consideration of humidity levels, air density and dry bulb temperature variations with height as these factors contribute to airflow in and out of a building. This is also associated with the risk of non-availability of detailed climate data of proposed site.

1.1.2. Noise and Air Quality

A disadvantage of using more active means, such as mechanical HVAC systems, for controlling a building's environment is that they may cause unpleasant odors in the long run for the occupants, due to chemicals used in them [6], thus the more passive means used in a building, the healthier its indoor environment. Hence it is always better to deal with the challenges of natural systems, rather than the mechanical ones, as another concern associated with Natural Ventilation concept is the control of noise: caused by air flow at high speed and to ensure that air quality of fresh air is good for the occupants, a difficult task for polluted urban dense locations.

1.1.3. Mixed Mode or Hybrid Ventilation Systems

For non-domestic multistory towers, there are not sufficient examples of completely naturally ventilated buildings, rather there are mixed mode or hybrid ventilation systems, which can turn on the natural ventilation when possible, and otherwise use mechanical systems, if the climate of the site does not allow natural ventilation. A difficulty with these systems is that they are complex to integrate and understand [5].

One psychological advantage of hybrid or HVAC systems is that the occupants feel freedom in controlling or adjusting the environment within the building according to the needs, e.g. they can turn on the fan or AC as they want. This puts an expectation while designing to accomplish completely naturally ventilated buildings that the designers should allow the users control their surrounding environment, even if there are no or less mechanical systems. Double skin façade, commonly used in office buildings, is a building façade example which gives the inhabitants the freedom to control their indoor atmosphere [5].

There is a need to ensure efficient fire safety systems installed in a building since the aims of natural ventilation often contradict with fire safety. While stack effect can be powerful in enhancing air flows, it can also lead to rapid fire distribution through the space [7].

1.2. Basis of Natural Ventilation

Natural ventilation design requires space. In order to utilize the concept of natural ventilation, some strategies are adopted in design to drive the flow of air inside the building. Mainly the pressure differences generated by the wind profile on the building envelope, is important. The pressure difference generated depends on:

- Wind direction and speed (wind driven ventilation) – dominating on a windy day;
- Temperature differences between building inlets and outlets or air density difference (buoyancy driven ventilation) – mainly effective if the outdoor temperature is less than the indoors;
- A combination of both wind and buoyancy driven ventilation.

The wind pressure difference Δp due to wind is generally expressed by Eq. (1) regardless of the type of building [8]:

$$\Delta p = 0.5 \cdot \rho \cdot U^2 \cdot \Delta C_{\mathrm{p}}\,, \tag{1}$$

where

U Wind speed measured at the height of the building;

ρ Density of the air;

ΔC_{p} Coefficient of pressure difference which depends on the factors of building shape as well as direction of wind.

The above equation also clearly reflects that in a tall building, as the height of the building increases, wind pressure increases with the increased wind velocity as investigated by [7] and thus points out towards essential control measures to be adopted for a wide range of wind pressures.

The pressure due to buoyancy effects can be expressed as:

$$\Delta p = \rho \cdot \mathrm{g} \cdot h \cdot \Delta T, \tag{2}$$

where

ΔT The temperature difference over the height h;

g The gravitation constant.

Consequently the buoyancy effects can be large of the whole height of the high rise building is considered.

The natural ventilation strategy of a building should take into account both wind driven and stack ventilation effects since there are many times of the year where wind speed might not be significant to drive the air flow. Combination of wind and stack effects can be observed in Fig. 1.

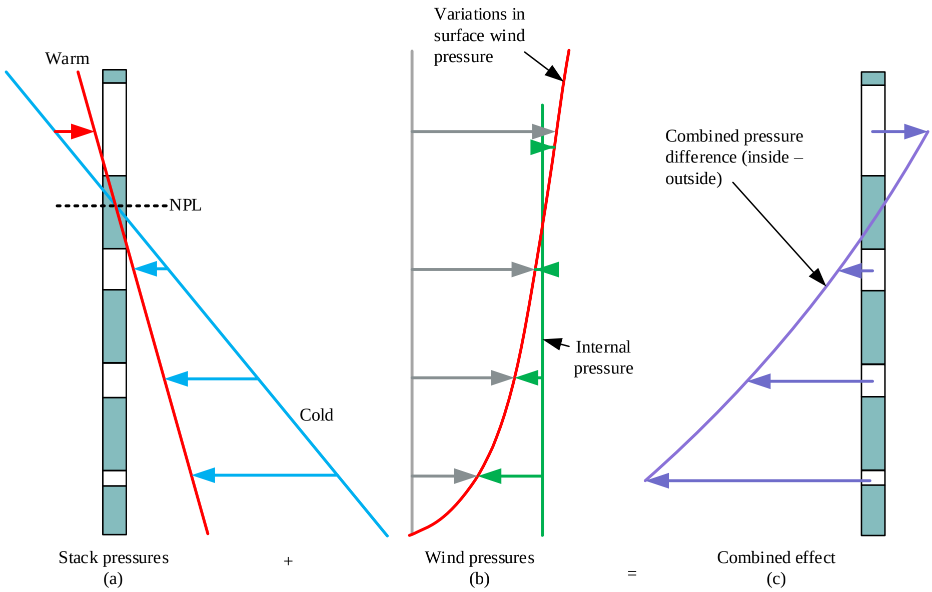

Fig. 1. Combining wind and stack pressures. Neutral pressure level (NPL) can be varied on changing the opening sizes [8].

1.3. Role of Architectural Design in Making Natural Ventilation Possible

The architectural design of a building can contribute to a better comfortable internal environment in many ways. The important aspects to consider which are implemented in this research are:

1.3.1. Orientation

Orientation of a tower will decide its ability to allow wind flow or solar gain within its spaces. The orientation of different spaces within a building type, e.g., placing primary occupied areas of a residential building towards the façade openings, is also essential and it also deals with the location of window openings. It is generally considered that the built form should have a 1:2 to 1:3 length ratios, for climatic zones near equator and long length of building should face north-south [3]. This enables majority of windows to be designed along north-south walls to have benefit of sun (and vice versa for non-equatorial zones).

1.3.2. Massing

By massing we mean the overall shape and size of the building. It may involve the organization of a number of buildings together to provide daylight access, wind access and ability to exploit natural ventilation and keeping in view the acoustic barriers of design.

1.3.3. Geometry

Geometry defines the overall height and depth characteristics of the building Spaces. To achieve good daylight drives ratios of around 1:2 and 1:4. For ventilation, the depth/height ratio is typically driven by the difference between the room height and the floor and drives ratios of around 1:2–3 for single sided and 1:5 for double sided spaces [8].

2. DESIGNING BUILDINGS IN KARACHI, PAKISTAN

Karachi, the largest city of Pakistan, is also the economic and financial hub of the country. Despite the existence of many impressive high rise buildings in the city e.g. Dolman Mall, Metro Twin towers, the city lacks energy efficient building design. The city is also facing power shortage problems which impresses upon the need of buildings to consume less energy.

The city's high rise buildings are currently dependent on mechanical systems, which are in turn a burden on the country's resources. As discussed earlier, as more people are moving towards the cities, the importance of high rise living is increased. This research therefore focuses on a multi-story residential tower in Karachi, with an attempt to derive benefit from the cool sea breezes maintaining a comfortable temperature throughout the year.

2.1. Site Analysis

The selected site is located in Block 1, Clifton, Karachi; an area primarily known for housing societies or real estate activities and some high rise residential apartments in the premises. The site has a 15° angle tilt from with respect to east. As evident from the Fig. 2 below, the site will not be subjected to high levels of noise pollution as surrounding buildings are residential spaces, with less traffic problems. There is a high rise tower on the southern site of the proposed site, which may lead to overshadowing the proposed building which might be however useful in generating a cooling effect for the building in hotter months. However, in this large area of approximately 14 500 m^2, the proposed building can be positioned in such a way to benefit from the maximum advantages of the surroundings.

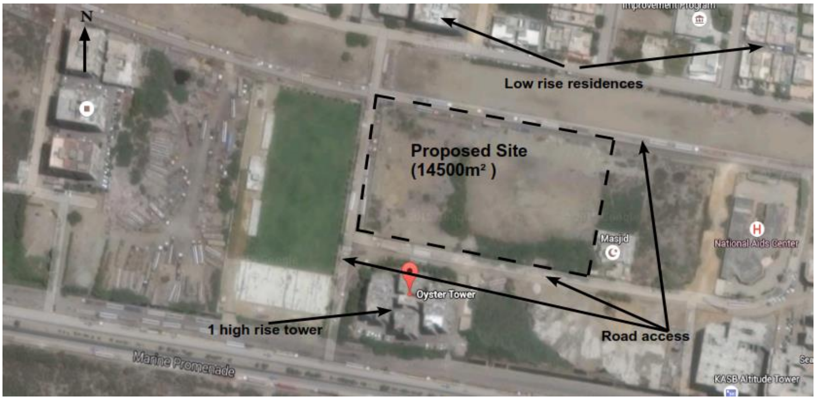

Fig. 2. Proposed site in Block 1, Clifton, Karachi, Pakistan. Source: Google Maps, 2015.

The site also seems beneficial in driving air flows for natural ventilation around the building, since the presence of already present low rise structures can generate wind pressure differences beneficial for the natural ventilation strategy of the building in hottest months. Trees and vegetation can be incorporated efficiently around and within the concept design building to counter pollution levels and to serve as acoustic barriers for traffic noise.

Moreover, it is also to be noted, that the site has an obvious sea presence on the Southern end as reflected from Fig. 3, which can attract fresh air streams from that side. It also explains, why the primary wind direction is South West or South, as discussed in Karachi Climate Analysis in the next section, as Arabian Sea might be one of the main reasons.

Fig. 3. Proposed site features, Karachi, Pakistan. Source: Google Maps, 2015.

2.2. Climate Analysis of Karachi

Karachi lies in the region of subtropical hot desert according to [9], with mild winters and warm summers and is located at the latitude 24.86° N and longitude 67° E. The amount of precipitation is generally low throughout the year, with some monsoon rains during July–August (average annual values of 250 mm approximately).

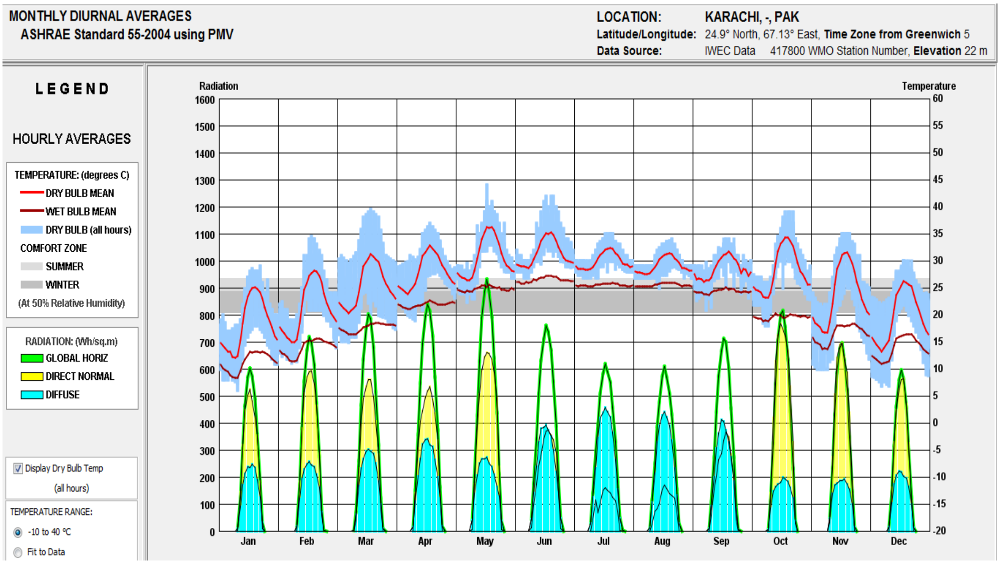

Fig. 4. Monthly diurnal temperature averages, Karachi, Pakistan. Source: Climate Consultant.

The primary wind direction is West/South-West with average wind speeds of about 3–6 m/s, indicating the possibility of a natural ventilation strategy. The summer period normally ranges from April to June, with average temperature of 30 °C as also shown in Fig. 1. The autumn season runs from July to September, with the average temperature of 29 °C. The diurnal temperature variations can be as high as 7–8 °C during many months except the hottest periods, where it is merely 3–4 °C as also evident from Fig. 4.

3. METHODOLOGY

The software package used for the design of a naturally ventilated building is *Design Builder* using the *Energy Plus* simulation engine, since it is one of the efficient software tools which can model realistic Natural Ventilation air flows with less effort and is also considered excellent for early stage building design [10]. It also has the ability to select a building location and the hourly weather data of that particular location can be analyzed. With its day-lighting and energy simulation tools, the energy consumption of the proposed building will be determined realistically with and without using Natural Ventilation; to carry out comparative analysis.

Design builder software is used to first propose 3 concept design options and a summer design week simulation is run on all these 3 options using "Calculated Natural Ventilation" option to determine which concept has a better performance in terms of its internal gains and energy consumption. This would give an idea about the optimum Massing and Geometry effective for driving Natural Ventilation air flows through the building. Based on the results, a better option will then be selected and following passive measures should be made to that single design option to improve the indoor thermal environment and to reduce the internal gains of the building:

- Effect of building orientation on energy consumption;
- Effect of night time window opening percentage and local shading;
- Impact of internal thermal mass in the form of different construction materials;
- Effect of additional shading elements e.g., trees and window to wall glazing ratios;
- Optimizing the façade according to air flow rates with respect to height of the building.

4.

4.1. Calculated Natural Ventilation

Throughout the course of this research, the "Calculated Natural Ventilation" is carried on the models within *Design Builder* software. The calculation engine of *Design Builder* uses information about building fabric and openings in conjunction with weather data and internal gains and temperature data to calculate the air pressure differentials and air flow rates through each zone. It allows air into the space if the zone air temperature is greater than the set point temperature, which in this case is set to 21 °C.

On the basis of stack and wind pressure differences, ventilations rates (q) through the cracks and window openings are calculated as:

$$q = \mathrm{C} \cdot (DP)^{\mathrm{n}}, \tag{3}$$

where

q	Volume flow rate through the opening or crack;
DP	Pressure difference across the opening;
n	Exponent varying between 0.5 for fully turbulent flow and 1.0 for fully laminar flow;
C	Flow coefficient depending on size and shape of opening/crack.

The pressure induced on a building façade P_{w} due to wind can be shown as:

$$P_{\mathrm{w}} = 0.5 \cdot \rho \cdot C_{\mathrm{p}} \cdot v_z^2, \tag{4}$$

where

C_p Wind pressure coefficient on the surface depending on wind direction, building shape and its exposure level;

v_z The average wind speed at height z [7].

4.2. Settings for Building Level Tabs

People living in residential spaces have a direct role in making their homes energy efficient as depicted by a European Research [11]. Therefore, settings made here reflect the activity of common people of Karachi. The activity tab is the area where the input data for the building occupancy, heating, cooling and ventilation set point temperatures, minimum fresh air requirements and equipment usage is entered. As this is residential building in Pakistan therefore, a new occupancy schedule is created with an occupancy density of 0.06 persons/m^2 or maximum 6 people in a 3 bedroom apartment and 4 people in a 2 bedroom apartment.

In Pakistan, normally there are 1–2 people present in each apartment from 9 pm to 5 pm, since some women do not work and look after the small children. Children and other family members are usually present at all periods from 7 pm to 8 am. During weekends, all the members are normally in the house. For the holidays, some families may travel to other places, while majority relax at their homes. 15 holidays are set for whole year which include public holidays and religious occasions.

The heating and cooling set point temperatures can be seen in Fig. 5 where the heating and cooling control temperatures are set as 18 °C and 23 °C based on winter and summer operative temperatures recommended by [8]. This reflects that the HVAC template will control the heating and cooling up to the set temperatures. As shown in Fig. 5, the heating set back is set to 15 °C showing that heating is switched on if the outside temperature reaches below this temperature and likewise mechanical cooling will be switched on if outside temperate rises above 28 °C.

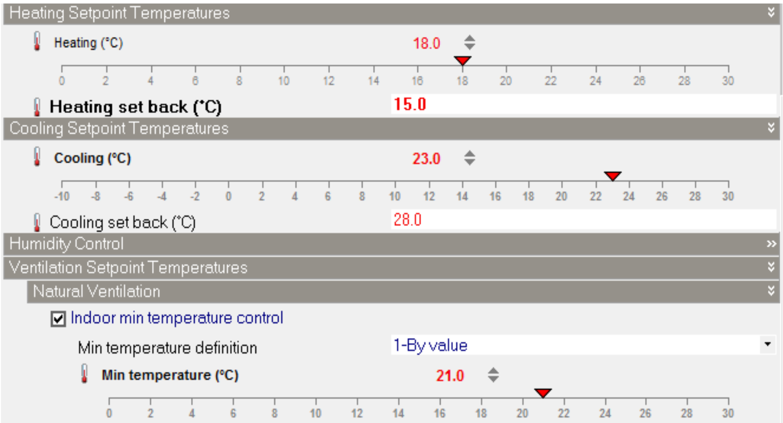

Fig. 5. Set point temperature controls in activity tab in *Design Builder* software.

As natural ventilation option would be switched on in the HVAC tab, therefore, the ventilation cooling set point temperature is set as 21 °C. For the current analysis, mechanical cooling is switched off by the HVAC Template settings, therefore, the cooling set point temperatures would be irrelevant.

Other settings made for simplicity are:

– Best practice (early design) heavy weight construction is loaded at building level, since it is a building where thermal mass will play a major role in night purge cooling. Moreover tradition buildings of this region also work on the heavy weight construction strategy e.g. Lahore Fort, using massive sand stone construction etc.;

- Model infiltration is switched on and crack template is set as "good" assuming a new construction, reflecting good air tightness;
- Minimum fresh air is set as 10 L/s;
- Best practice lighting template is loaded with the "daylight control" option turned "on" maintain the overall illuminance levels at 100 lux [12];
- Window gazing ratio is set to about 30 % and it is assumed that 40 % of these windows will be open for the air flow during occupied hours. Natural ventilation airflows will be based on this opening percentage. No individual window shading is applied at this stage, only component block shading is set for each option as discussed above. The effect of local shading and window shading on different façades will be discussed later.

4.3. Summer Design Week Simulations

A "summer design week" simulation is run for all the 3 options in *Design Builder* for simplicity and in order to save time. As for a 25 storey tower, an annual simulation will take hours to run leading to inefficient use of time for this research. This simulation is run from a period of June 3–June 9, since it is the hottest week of Karachi, as determined by the software through the *Energy Plus* weather data file, loaded in *Design Builder*. This type of simulation provides a worst case scenario by which the 3 options can be compared and the better one can be selected for making further improvements in improving natural ventilation performance of the building.

The option "Normalize by floor area" is selected in the data viewing options in simulation tab of *Design Builder* since the surface areas of these three buildings is not similar, therefore, a realistic comparison would be accessing the values per m^2 of the building.

There are two HVAC templates used for deciding which building out of the 3 options is performing better, while keeping other settings the same, as discussed above. The first setting in HVAC section of design builder uses pure "natural ventilation with hot water radiator heating" implying that the simulation results of the building will only be based on external air entering into the building. This option allows the model to be checked for realistic air flow rates within the building zones, as well as gives an insight on the total heat gains during this period, for each option. It will evidently contain some discomfort periods within the zones and provision for further modifications, to be considered while the better option is decided.

The second template "mixed mode with natural ventilation and hot water radiator heating" is loaded to obtain the energy consumption of each building, for maintaining a comfortable temperature throughout the summer design week. This mode adopts a hybrid approach by introducing active cooling into the space when external air is not cool enough to provide comfort to occupants. In this way, a comparison can also be made between the 3 options to select the building which is most energy efficient.

It is to noted that here the results of the 3 options are compared at "building level" and the data shown by *Design Builder* at building level such as internal gains and temperature are floor weighted averages for the whole building. Although data like this more meaningful at zone level, yet it provides the necessary option wise comparison sufficient for selecting the best option.

4.4. Annual Simulation

After combining the successful strategies, a final building design will be produced and an annual simulation will be run on this design to compare the energy consumption when the building is using:

- Complete Natural ventilation;
- Mixed Mode System;
- Fan Coil Unit without Natural Ventilation.

4.5. High Rise Tower Design and Natural Ventilation Heuristics

The 3 options are briefly viewed below by Fig. 6, Fig. 7 and Fig. 8 are designed using architectural rules of thumb for better natural ventilation in tropical climates [3]:

- Shallow plan layout: each residential unit has a maximum depth of 6 m;
- Depth of floors is 3.5 m in each of the 3 designs;
- Cross ventilation: all of the buildings have openings on both sides of each residential unit to allow cross air flows;
- Perimeter shading of depth 1–2 m on each side of the units, where 2 m depth shading may represent balconies;
- 3 m wide corridors, often symbolizing green garden spaces;
- Building layout consisting of narrow and segregated spaces to allow sufficient provision of cross ventilation;
- Rectangular residential units – most effective shape for housing purposes, also reflected by many residential case studies e.g. Bedok Court, Singapore and Penggiran Apartment Towers, Malaysia etc.;
- Apartment size ranging from 70 m^2 (for double story units) to 120 m^2 (for single story apartments) maintaining an aspect ratio of 1:2.8 and 1:3.3 respectively, closer to the recommended aspect ratio of 1:3 for tropical zones [10];
- Each building is oriented along East-West axis to have maximum number of openings on North-South axes, and also to benefit from the primary wind direction from South/South-West in Karachi.

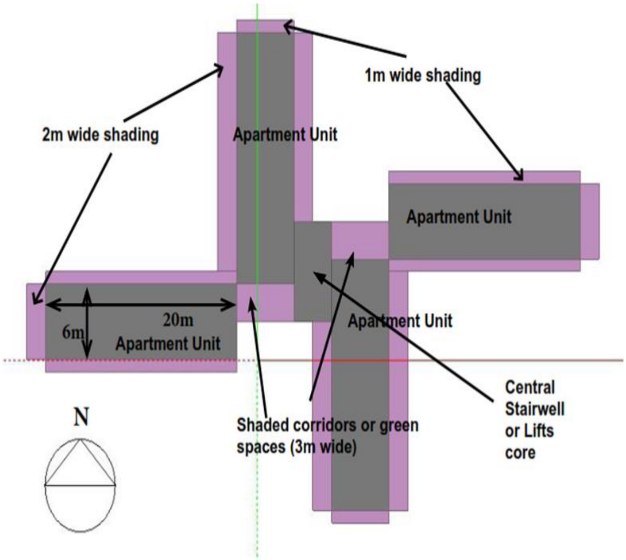

Fig. 6. Option 1 plan view.

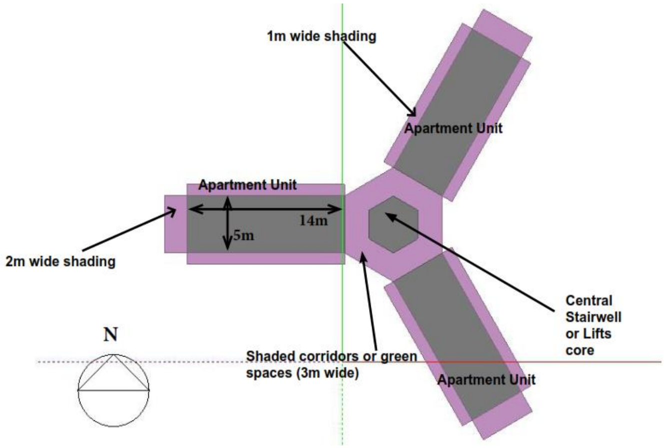

Fig. 7. Option 2 plan view.

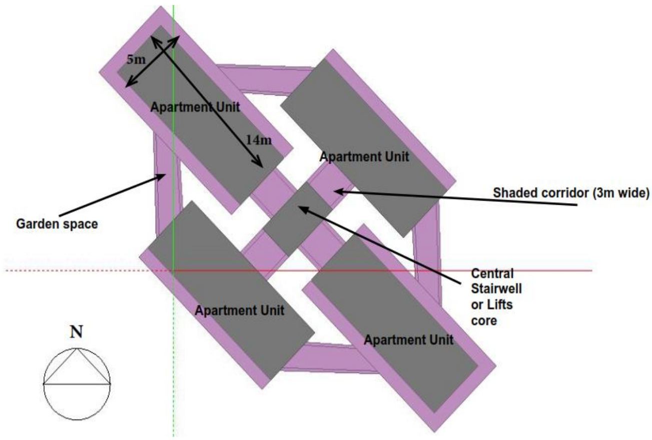

Fig. 8. Option 3 plan view.

5. Results and Analysis

The results are primarily discussed on the whole building level as floor weighted averages per m^2 of the building space. The simulation outcome for the solar gains of the hottest day of June and energy consumption for the whole summer design week as a comparison between the 3 options can be seen in Fig. 9 and Fig. 10.

5.1. Determination of Appropriate Massing and Geometry

It can be stated by looking at the solar gains data for Monday 3rd of June in Fig. 10, that option 3 has the least gains into the building reaching a peak value of 150 W/m^2 at a time of about 9:30 am, which is 25 % less than the peak gains of 3rd June in comparison to option 1 and 2 at the similar time. This is because the geometry of option 3 provided shading to the adjacent buildings at different times of the year whereas option 2 is subjected to maximum solar exposure, consequently showing the highest solar gain of 224 W/m^2.

Thus option 3 has proven to be presenting the best case for massing and geometry, implying that a high rise building should be designed in a way to provide maximum protection against the sun, which is provided by the seggregated arrangement of apartment units, shading each other and allowing air from different directions in case of option 3, as a result of which it has minimum heat gains into the space. This is directly related to the summer design week energy consumpion of each building, as reflected from Fig. 9, explaining that higher the gains into the space, more the cooling load, and hence higher the energy consumption.

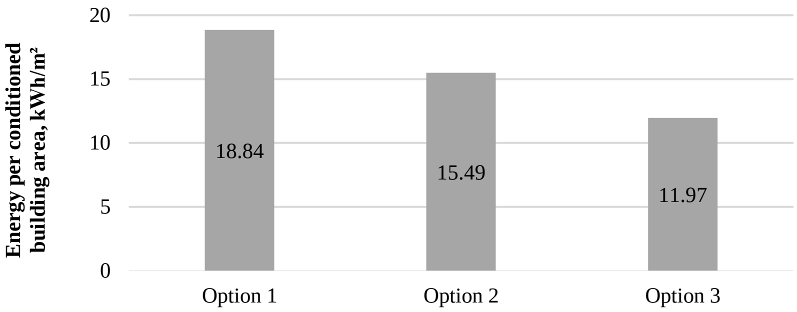

Fig. 9. Comparison of the energy use per conditioned building area between the 3 options during summer design week.

Following the procedure of step by step improvements in building design, option 3 will be considered for further analysis.

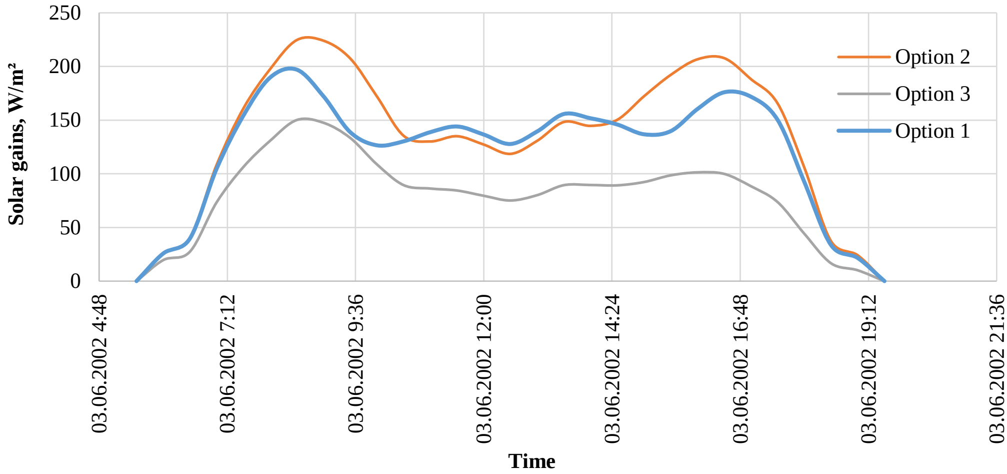

Fig. 10. Comparison of the building solar gains between the 3 options on Monday, June 3.

5.2. Effect of Building Orientation

A summer design week simulation was run on 5 different orientations of the building using mixed mode system with natural ventilation and comfort cooling. The results offered by Fig. 11 reflect that NS orientation is not recommended for the building's longer axis, since East and West façades are the areas of maximum solar gain [3], therefore, the highest energy consumption of 12.5 kWh/m^2 is observed.

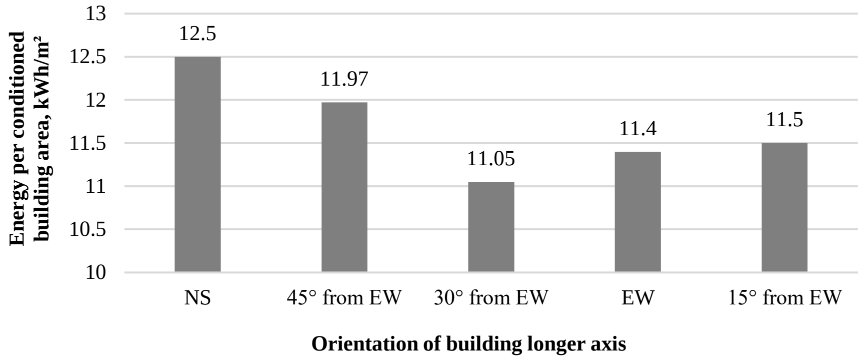

Fig. 11. Summer design week energy consumption with respect to building orientation.

It is interesting to note that there is only a maximum difference of 1.5 kWh/m² among energy consumptions of different orientations highlighting that orientation for this climate and location is not of significant importance since the sun is usually overhead. Nevertheless, for further analysis, the orientation of building would be fixed at 30° from East axis, since it shows the least energy usage for the hottest week of the year.

5.3. Effect of Local Shading and Window Opening Percentages

In order to reduce the solar gains through windows, the building is applied with a combination of a 0.5 m projected overhangs, louvers and side fins on the whole building, along with inside medium reflectivity blinds. The blinds will only consequently operate during the day time from 8 am to 5 pm. This is accompanied by comparing the indoor temperatures with respect to the night time window opening percentages of 30 %, 50 % and 100 % respectively.

The results indicated a 40 % reduction in solar gains as a result of application of solar shading devices, however, at night, the indoor ambient temperatures were not significantly reduced by increasing the window opening percentages. This is because increasing the window area to be opened increases the wind flow through the spaces, however, since the dry bulb temperature is not low enough to cool the space, i.e. reaches about a minimum of 28 °C, therefore, the comfort temperature is only improved by maximum of 1 °C with increasing opening area. Nevertheless, 100 % window opening at night shows a comparatively better performance, hence, will be continued for further analysis.

5.4. Effect of Internal Thermal Mass

Based on the limited timeframe of this research, three different types of wall materials on inside surface of external wall have been tested to observe their effect on the inside average temperature of the building.

TABLE 1. CHARACTERISTICS OF THREE TYPES OF BUILDING MATERIALS USED

Inside material	Density, kg/m^3	Specific heat, J/(kg·K)
Concrete	1400	1000
Sandstone	2200	710
Aerated brick	1000	840

Wall type with sandstone on the inside has obtained a reduction of 2 °C in the indoor peak temperature. This is because sandstone has the maximum density and hence the highest thermal mass, which implies that heavier the material, more heat would be required to change the temperature of that material [13], [14]. Although aerated brick has a greater thickness compared to concrete, yet its specific heat and density is low, hence, has a better cooling performance giving a decrease of 1 °C in the peak daytime temperature.

5.5. Effectiveness of Additional Shading, Trees and Window Glazing Ratios

Some simple rectangular surfaces were modeled to represent trees in the courtyards between the apartment blocks, where they were set a transmittance schedule to allow only 30 % of sunlight during summer months and 70 % sunlight during winter months [15]. This is one of the characteristics of deciduous trees, which provide effective shading in summer, while shed trees in winter. In addition, some additional vertical shading elements have been added at east and west façades of the building as recommended by [3].

After applying these passive measures, three different window to wall glazing ratios are compared reducing 30 % to 25 % and 20 %. It was observed that the reduction in indoor comfort air temperature is directly related to the reduction in glazing ratios and also a reason for the reduction in annual required cooling energy reflected through a study by [13].

5.6. Improved Building Design, Results and Discussion

After including the better performing parameters from section 4.1–4.5 in building design, a final design was obtained, the results for indoor air temperature and solar gains can be seen in Fig. 12 and Fig. 13.

The Fig. 13 illustrates that there is about 57 % reduction in solar gains following the application of shading measures to the building and Fig. 8 represents an average of 3 % reduction in the indoor air temperatures and a difference of 8 °C between indoor and outdoor peak temperatures, against a diurnal swing of only 3–4 °C, as a result of the passive measures applied from step 4.1–4.5. It is to be noted that the results represent a significant improvement in indoor thermal comfort from the perspective of the summer design week. As summer design week always estimates somewhat higher temperatures than the actual ones, the results imply that the building will be even more comfortable for the majority of the year, since the average high temperature of 32 °C exists in Karachi.

According to the Eq. (5) provided by European Standard EN 15251 considering the concept of adaptive thermal comfort, if the running mean temperature T_{rm} of the last seven days in Karachi prior to summer design week is 35 °C, then the comfortable temperature T_{comf} can be calculated as:

$$T_{\mathrm{comf}} = 0.33 \cdot T_{\mathrm{rm}} + 18.8 = 30.35\ ^{\circ}\mathrm{C}. \quad (5)$$

The above temperature is relating with the indoor air temperature obtained in Fig. 12 while utilizing natural ventilation. It is also to be noted that for the majority of the occupied periods of the building, i.e., from 7 pm to 7 am in the morning, the indoor air temperatures are as low as 28.5 °C.

Which makes this research a success in achieving reasonable comfort levels as a result of night ventilation. In addition, as mentioned earlier, *Design Builder* also has not included the cooling effect generated by trees which can further lower this temperature on the graph by 2–5 °C [3], [16].

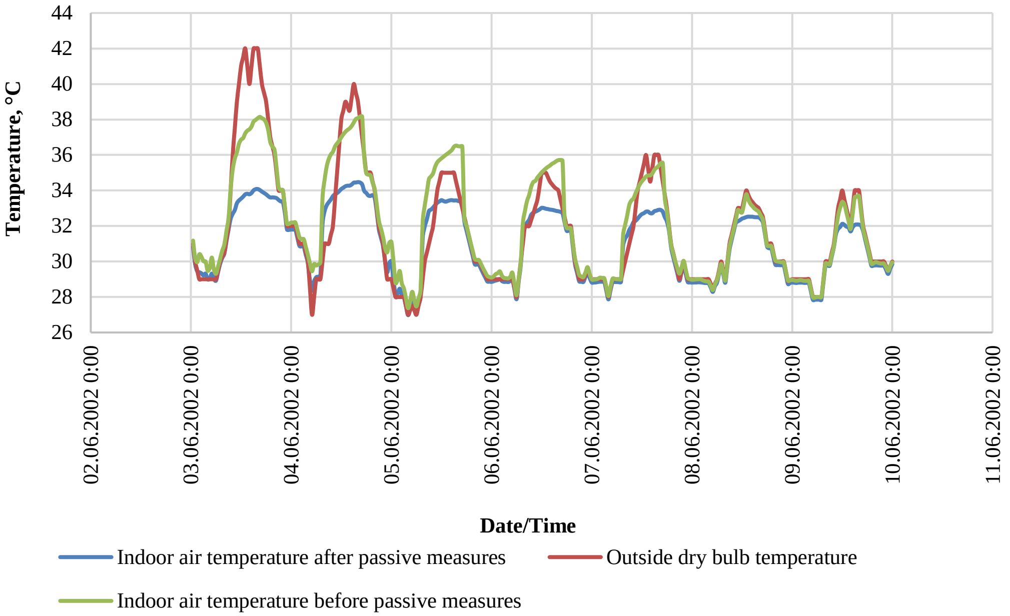

Fig. 12. Comparison of indoor air temperature improvement before and after passive measures.

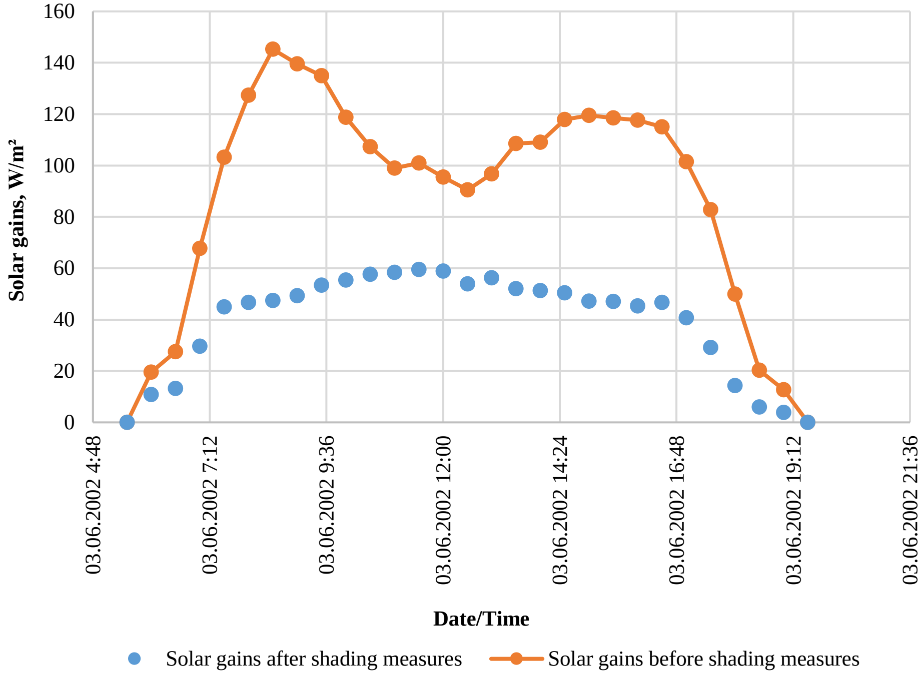

Fig. 13. Comparison of solar gains on Monday, June 3, before and after the passive measures.

The results of an annual simulation also show that a building designed with the passive measures explained above and relying completely on natural ventilation saves about 96 % of the energy consumed for heating and cooling for a building not using natural ventilation at all. Using mixed mode system can save the energy consumed by a fan coil unit by about 22 %.

6. PROJECT VALIDATION

The primary verification method is to compare the volume flow rates as determined by *Design Builder*, with the calculated values using the formulae for wind pressure and buoyancy effects. For this purpose [8] is used to analyze the effectiveness of cross ventilation in the southern façade of the building. The South façade is selected because it is almost perpendicular to the primary direction of wind in Karachi since the formulae used also assume wind to be normal to the window openings.

The wind speed for openings at different heights of the building are calculated using Eq. (6):

$$U_{\mathrm{site}} = U_{\mathrm{met}} \cdot \mathrm{k} \cdot z^{\mathrm{a}}, \tag{6}$$

where

U_{site}	The wind speed on site;
U_{met}	The wind speed measured at 10 m at the reference location (5.1 m/s);
z	The building height;
k, a	The constants that depend on the terrain;
a	0.25;
k	0.35;

$$\Delta\rho = \frac{\rho \Delta T}{T_E + 273} = \frac{1.2 \cdot 0.45}{30 + 273} = 0.0078\ \mathrm{kg/m^3}, \tag{7}$$

where

T_{E}	External temperature = 30.00 K;
T_{I}	Internal temperature = 29.55 K;
ΔT	Difference in temperature=30.00–29.55 = 0.45 K;
ρ	Reference density = 1.2 kg/m^3.

If windward side is given a label of A, and leeward as B then considering both wind and buoyancy effects, the pressure difference across each opening is calculated as:

$$\Delta P_{\mathrm{A}} = -\Delta P_{\mathrm{B}},$$

$$\Delta P_{\mathrm{o}} - \Delta\rho \cdot \mathrm{g} \cdot z_{\mathrm{A}} + 0.5\rho \cdot U^2 \cdot C_{\mathrm{p}} = -[\Delta P_{\mathrm{o}} - \Delta\rho \cdot \mathrm{g} \cdot z_{\mathrm{B}} + 0.5\rho \cdot U^2 \cdot C_{\mathrm{p}}], \tag{8}$$

$$\Delta P_{\mathrm{o}} = 0.5 \cdot \rho \cdot U^2 \cdot (2 \cdot C_{\mathrm{p}}),$$

where

$\Delta\rho$	Density difference;
C_{p}	Co-efficient of pressure for windward sides = 0.5;
C_{p}	Co-efficient of pressure for leeward sides = –0.5;
z_{A}	z_{B}.

The pressure drop across each opening is then calculated using Eq. (9):

$$\Delta P_\mathrm{A} = P_\mathrm{o} - \Delta\rho \cdot \mathrm{g} \cdot z_\mathrm{A} + 0.5 \cdot \rho \cdot U^2 \cdot C_\mathrm{p}\,. \tag{9}$$

Finally, the volume flow rate through the opening is calculated using the Eq. (8) below, and then compared with the results of *Design Builder*, summarized in Table 2:

$$Q = C_\mathrm{d} \cdot A \sqrt{\frac{2\Delta P_\mathrm{A}}{\rho}}, \tag{10}$$

where

C_d Co-efficient of discharge = 0.65.

TABLE 2. COMPARISON OF VOLUME FLOW RATES ACROSS THE OPENINGS OF SOUTHERN FAÇADE OF THE BUILDING, AS CALCULATED BY FORMULAE AND BY *DESIGN BUILDER* FOR THURSDAY 8 PM

Opening number	Height z, m	U_met, m/s	ΔP_o, Pa	ΔP, Pa	Area, m^2	Q_DB, m^3/s	$Q_\mathrm{calculated}$, m^3/s	Difference, %
1	1.75	2.05	1.26	2.50	9.14	9.94	12.13	18.00
2	5.25	3.19	3.05	6.05	9.14	15.50	18.86	17.80
3	42.00	4.54	6.18	11.63	9.14	19.05	19.06	0.05
4	45.50	4.63	6.43	12.06	6.10	14.08	13.00	8.30
5	82.25	5.37	8.65	15.71	6.10	16.33	15.05	8.50
6	85.75	5.43	8.85	16.19	6.10	15.00	15.23	1.533

Table 2 illustrates that there is a maximum percentage difference of 18 % between the calculated and *Design Builder* values of volume flow rates. This might be because design builder may sometimes show volume flow rates according to the wind direction, which might not be perpendicular every time. Anyhow, this calculation does validate that wind pressures increase as the height of the building increases as also stated by Etheridge and Ford [5]. Higher values for volume flow rates at the middle storey (13th floor) are not only due to height, but due to increased window opening area of 20 % window to wall gazing ratio. Above this storey, the glazing ratios are reduced to 15 %, thus represented by relatively lower values of Q.

7. CONCLUSIONS AND FUTURE WORK

In the light of the challenging climate of Karachi, Pakistan, this study has been an effort to design a naturally ventilated high rise residential building relying on natural ventilation for most part of the year. The study has investigated some successful natural ventilation heuristics employed previously by many researchers in similar climates and it can be concluded that with careful integration of massing, geometry, orientation and envelop design, it is possible to design a tower relying solely on natural ventilation in Karachi. The simulation results on the initial three design concepts indicate that a narrow plan building with provision of air movement across its edges from all directions proves to be most effective in driving the natural wind flows.

It has also been observed that for similar climates, where the diurnal temperature range is not high in hottest months, natural ventilation would solely rely on wind driven ventilation as stack effects would be minimized because of negligible temperature difference between day and night temperatures.

A building for this climate should be heavy weight in its construction with the construction materials of high density and high specific heat, which must be able to provide cooling with the help of night ventilation. Sandstone has proven to be effective in cooling the inside air temperature, as the internal thermal mass. It has also been observed that solar gains are the major source of heating up a tower in this weather, therefore, glazing ratios should be kept to a maximum of 10–20 % which is sufficient to provide fresh air for occupants.

This study also suggests improvements in the software *Design Builder*, in terms of calculating the indoor air temperatures by giving consideration to the evaporative cooling effect of trees or even fountains in a building. After applying suitable passive measures, the final building design in this research was surprisingly able to receive an 8 °C reduction in indoor air temperature compared to the outdoor conditions, reaching to about indoor peak of 33.5 °C if outside peak temperature is 42 °C. These results were achieved without considering the evapotranspiration effect of shading devices, symbolizing trees. The integration of trees and vertical landscaping can reduce the indoor air temperature to about 35 °C in comparison to unshaded spaces [3], [17], [18].

If the effects of evapotranspiration of trees were included by *Design Builder*, including the precipitation effects on trees, then this study could have been a pioneer in designing energy efficient buildings in Pakistan and similar climates, able to maintain 27 °C even if the outside temperature is as high as 42 °C. This can completely solve the problem of climate change and its drastic effects as a result of energy consumption of tall buildings, since a building relying on natural ventilation would consume about 96 % less energy compared to a fully air conditioned building.

The results of this study also prove *Design Builder* as a user friendly software, which can be used by designers, architects or engineers in initial planning of a building in terms of its energy consumption and thermal performance and one can even present a holistic picture of environmental impacts and cost benefits of low cost apartment design. However, one of this risks in completion of the project turned out to be the time taken by simulations for a high rise building using “Calculated Natural Ventilation” which makes this software not recommended for large structures unless improvements made. To manage this risk, a separate computer have to be resourced from departmental help and also a cloud simulation engine was used. Nevertheless, the tool is highly recommended for small scale studies where CFD can also be used for better natural ventilation analysis as carried out by [19] also in a developing country; Iran.

7.1. Future Work

The work presented in this dissertation can be extended in a number of ways:

- The study was focused on analyzing the effectiveness of cross ventilation through single apartment units. Due to limited time, the apartments were not architecturally planned in the form of individual rooms e.g. bedrooms, living, dining rooms etc. This is because internal partitions would have blocked the cross-ventilation and the building would have solely relying on single-sided ventilation in most of the rooms. Further study could involve the effect of massing, geometry, internal space arrangements on driving the natural ventilation air flows through the individual internal spaces. It would have also assumed to have doors and internal openings operating to maximize both cross flow and single sided ventilation;
- An important point to be noted that the detailed weather data used for this dissertation contains information corresponding to the year 2002, which implies that after 10–13 years, this data could have been changed by now. Therefore, for better accurate results, further investigations need to be made e.g. making field measurements of

the weather data for this location. *Energy Plus* database also needs to be updated with the recent weather data of a number of cities of Pakistan, and other developing countries, since at the moment, it only contains the weather data for a single city of Pakistan;

– There was lack of data available for noise and air pollution in Karachi, which can be used for building simulations, further studies can study the impact of air pollution as the height of the building increases and how trees and vegetation can help reducing the filtering the pollutants entering into the building;
– There is a need for further research in many passive strategies discussed in this research, which include, changing the position of insulation in the external wall construction, effect of different glazing systems, designing each façade of the building differently to analyse the effect on indoor thermal environment, which could further lower the indoor peak temperature obtained by this research;
– It would be beneficial if the effect of water in the form of fountains or rain falling on trees can be studied in any software including *Design Builder*. This can then be compared using Computational Fluid Dynamics to evaluate their performance in reducing the temperature of the surrounding spaces. Wind tunnel testing can also be used to optimize the design of a building including window opening areas.

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