STUDY ON THE IMPACT OF WINDOW SIZE AND PROPORTION ON INDOOR AIR TEMPERATURE OF BEDROOMS IN APARTMENTS

by

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DEDICATION

To

My Parents
Mr. Moazzem Hossain Salim and Mrs. Ismath Ashrafi

and

Parents-in-Law
Dr. Ehsanur Rahman and Mrs. Masuma Rahman

for being my inspiration

and

My Husband

Ar. Mashudur Rahman Fahim
for giving me unconditional support and consent.

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ABSTRACT

Globally, over one-third of total energy is consumed by the residential building sector (IEA, 2013). In Bangladesh, more than 40% of electricity is consumed in the domestic sector by air-conditioning (AC) and fans for comfort cooling (JICA, 2015). Windows, the drivers of natural ventilation, if designed and adopted properly can offset energy guzzling AC devices, while providing thermal comfort. During the design phase, sizing windows against room area and wall area have a considerable effect on achieving thermally acceptable indoor air temperature for occupants. This simulation based study analyzes the impact of varied window-to-floor area-ratio (WFR) and window-to-wall area-ratio (WWR), on bedroom air temperature in residential apartments, thereby providing possible design options for such spaces, to offset energy consumption, while keeping air temperature within a comfortable limit. Initially, a base-case bedroom simulation model was formulated by conducting a random questionnaire survey and case study analysis of high-rise apartment buildings of the upper middle income group of Dhaka along with a comprehensive literature review on comfortable air temperature in such rooms. Simulation was done in Ecotect Analysis and WinAir to figure out indoor air temperature and air movement pattern respectively for the base case, as well for varied WFR and WWR. Simulation outcomes were validated, by comparing with measured values from a pilot survey conducted inside a bedroom of the topmost floor of an existing high-rise residential building. Comparative analysis was used to predict the best possible WFR and WWR configurations for obtaining a comfortable air temperature within this space. The result reveals that WWR, ranging from 20% to 30%, is preferable for inducing lower indoor air temperature in the south west corner rooms of naturally ventilated buildings.

Keywords: Window Size and Proportion, Indoor Air Temperature, Thermal Comfort, Bedrooms of High-Rise Apartment Buildings.

Chapter 01: INTRODUCTION

1.1. Background

Globally, reduction of the energy used for heating and cooling of buildings, has been a crucial need since the mid-1970s. Energy-efficiency within buildings, is now the major concern of building researchers and designers. In developing countries, the largest portion of the total energy demand takes place due to the energy consumption for upholding an adequate environment inside the buildings. Likewise, in developed countries, the share of energy usage for buildings is larger than that used in other purposes (industrial processes, transport, etc.). Building energy consumption mainly depends on various systems such as air conditioning, lighting, electrical equipment, etc. But, since energy is limited or scarce, natural ventilation can be an efficient option for removing the building heat load to achieve thermal comfort, reducing dependence on air conditioners.

A significant number of countries are situated on the tropical belt, which are subjected to high temperatures and/or humidity. The climate, in addition to the population growth, increases demand for building services and stringent comfort levels and lead to a greater use of air conditioning (Bastide et al, 2006). Air conditioning is often perceived as the only means of reaching indoor thermal comfort, especially during the hottest season. However, the associated energy consumption is significant, and simultaneously, the energy situation, particularly in the tropical zone, is becoming strained as the demand for electric power continues to grow, although the means of production remains limited.

1.1.1. General Problem

Worldwide, power consumption for air conditioning alone is forecasted to surge 33-fold by 2100, as developing world incomes rise and urbanization advances (Henly, 2015). Thus, growth in population, increasing demand for building services and comfort levels, together with the rise in time spent inside building seems to indicate that this percentage will grow with time (Perez-Lombard et al, 2008). In tropical climates, the use of air conditioning is so pervasive that it has resulted in drastic increase of electricity consumption by building industry, making it the main consumer of energy. The use of air conditioning is particularly predominant in the case of tall buildings. Studies show that people are becoming more affluent, making air conditioning more popular to achieve desired the thermal comfort (Mohanty, 2013).

Although the concept of natural ventilation is not complicated, it is a challenge to design naturally ventilated buildings, as air flow is difficult to predict and control. Natural ventilation is the intentional flow of outdoor air through an enclosure under the influence of wind and thermal pressure through controllable openings (Rofail, 2006). The arrangement, location and control of ventilation openings combine the driving forces of wind and temperature to achieve desired ventilation rate and good distribution of fresh air in the building.

Natural Ventilation is an important part of achieving energy efficient design in many climatic zones. This issue has surfaced recently with the increased awareness in the community of climate change, and of mankind's impact on the environment. Natural Ventilation is particularly applicable to residential buildings, where there is the highest scope to reduce reliance on mechanical systems. Conventionally, the applicability of natural ventilation has been limited to low-rise buildings, but recently, greater emphasis has been placed on natural ventilation in codes and planning policies. Now-a-days, for tall building also, the use of natural ventilation principles is being attended by both architects and developers. Tall buildings have the advantage of being able to generate higher pressure differentials across the habitable area, presenting the potential to achieve thermal comfort for occupants by means of natural ventilation. Today many planning policies provide guidelines that stipulate the need for adequate natural ventilation in residential buildings. Research shown that the risk of non-compliance can be significantly reduced by incorporating natural ventilation principles into the design at an early stage (Peddie and Rofail, 2011).

Operable windows are one of the most convenient ways to provide natural ventilation into living spaces, especially for buildings with adequate peripheral access. Windows, when operable, can be opened and closed; while non-operable windows mainly serve as aesthetic features and daylight sources. The use of operable windows has proven to reduce the annual energy consumption in high occupancy buildings if properly configured and controlled. However, improper control of operable windows can also significantly increase the energy demand of the HVAC system (Daly, 2002).

The critical issue in designing a natural ventilation system is the control procedure of the apertures. The amount of the airflow rate through operable window varies, depending on building geometries, ambient temperature, wind speed, and direction. According to Gross and Hu (2011), the design challenge is to control window openings, as a function of the ambient environmental condition, so that the incoming airflow brings an acceptable amount of fresh air, to sustain indoor environment in terms of both ventilation and thermal comfort.

Computational building evaluation tools have the potential to provide an effective means to support informed design decision making (Mahdavi and Bellahy, 2005). Recognizing the implications of design decisions, made by the different team members on the energy and environmental performance of the building, all the design team members can engage in performing simulations. As a result, the Architecture-Engineering-Construction (AEC) industry have recognized simulation as a necessary design support tool (Attia, 2010). From an AEC perspective, an advanced analysis of building thermal simulation in building modeling programs has become a critical part of high-performance buildings. The conceptual design phase of thermal modeling is used to investigate the first degree of feedback about the impact of various building configurations on annual thermal performance (US GSA, 2010).

1.1.2. Specific Problem

A rapidly growing country, like Bangladesh, needs a huge amount of energy to feed its large growth appetite. In the past decade, primary energy consumption increased over 100% and this trend will be sure to be continued. A recent work done by JICA on Bangladesh's current sector wise energy demand, shows that industry has the biggest share of 47.8%, followed by residence and transportation at 30.5% and 11.5%, respectively (JICA, 2015).

The thermal performance of the majority of buildings in Dhaka is poor; e.g., single glazed windows without adequate solar shading. Research on the thermal environment indicates the need for using passive means to tackle the thermal environment challenges (Ahmed, 1994). It is clear that solar heat gains are in excess of what can be efficiently tackled by natural or hybrid ventilation systems (Mourshed, 2011). The current energy consumption of ACs is 2237 GWh/year, which accounts for almost 50% of the total energy and for fan, it is 6181 GWh/year (JICA, 2015). The projected increase in temperature are likely to exacerbate the situation (Ahmed et al, 2011). As buildings have a typical lifespan of 50 to 100 years, prompt actions to regulate the environmental performance of buildings are necessary to enhance the resilience of Dhaka's buildings to climate change (Mourshed, 2011). The need to tackle residential buildings is a priority, given the affordability of the inhabitants (Tariq, 2016).

Many research confirmed that passive strategies play a significant role in reducing building energy consumptions (Section 2.4 and 2.5). In particular, natural ventilation has a direct effect on reducing cooling load as well as maintaining proper indoor air quality. Window size and proportion are the key elements in determining indoor thermal and visual comfort induced by natural ventilation (Section 2.7).

1.1.3. Problem Statement

Energy consumption in the residential sector is increasing day by day, most of which is needed for achieving thermal comfort. In order to resolve the issues of energy consumption the specific questions need to be satisfied:

- Are new buildings designed to meet clients need, without much attention to the local climatic context and energy consumption, presenting uncomfortable indoor thermal stress to the dwellers?
- Are windows provided in the high-rise apartments, working properly to facilitate natural ventilation for achieving thermal comfort?

1.1.4. Objective

The study aims to develop an understanding of the passive features, focusing on the potential of window size and proportion for modulating indoor air temperature through natural ventilation inside bedrooms of high-rise residential buildings of Dhaka, Bangladesh. It concentrates on the bedrooms located in the south west corner of the apartment during the summer months of the year. The research also intends to suggest a precise combination of the window size determinants, WWR (window-to-wall area ratio) and WFR (window-to-floor area ratio). The core objectives of the research are summarized as:

i. To investigate the relationship of window size and proportion against indoor air temperature in residential apartment buildings.
ii. To identify specific combination of WFR and WWR for achieving comfortable indoor air temperatures, for typical south-west facing bedroom in apartments of middle income groups.
iii. To examine the effectiveness of varied ventilation and different air exchange rates, coupled with window proportion to lower indoor air temperature of such bedroom during the summer months.

1.1.5. Significance

Residential buildings consume big share of energy to achieve thermal comfort by mechanical means. However, if thermal comfort is achieved by natural ventilation, load on natural resources can be reduced. Proper window size and proportion and varied ventilation strategies can help to improve comfort condition in naturally ventilated residential apartment.

The study focuses on optimization of WFR and WWR, integrating variable/night ventilation, to reduce indoor air temperature in naturally ventilated bedroom of residential apartments. Thus, the indication from the study can act as an initial guideline for designing window of naturally ventilated residential building.

1.2. Research Methodology

The study was conducted in four main phases, illustrated in Table 1.1. The first phase consisted of desk studies to establish criteria for the research, the second was the data collection phase for validating the tools being used, followed by the third phase, the simulation. The final phase involves the analysis and evaluation of the obtained data for establishing trends as design guidelines, where the main data were gathered based on previously established criterion.

Table 1.1: Schematic Diagram of the Research Methodology of this Study

Phase 01: Literature Review	Residential Buildings' Energy Consumption for achieving Thermal Comfort	Passive Features and their effects on Indoor Air Temperature	Climatic Characteristics of Bangladesh and Dhaka	Comfort Temperature Range for Tropical Climate & Bangladesh	Different income groups and their preferred apartment size and location in Dhaka
Phase 02: Data Collection	Questionnaire Survey + Interview + Case Study Analysis	Field Measurements of Temperature for January, April & May, using Data	Modelling and Dynamic Thermal Simulation of Base Case Bedroom in Ecotect	Validation of Simulated Data by Comparing with the Logged Data	
Phase 03: Simulation	Generation of Bedroom Models varying WWR & WFR in Ecotect	Dynamic Thermal Simulation of Varied Cases in Ecotect	Computational Fluid Dynamics Analysis of the Best Cases in WinAir		
Phase 04: Analysis	Comparison with the Identified Comfort Temperature for Dhaka	Analysis to Identify the Trend of Impact of Varied WFR & WWR on Indoor Air Temperature	Analysis to Find Out the Optimum Combination of WFR & WWR for Comfort Temperature		
Result	Recommendations as Preliminary Design Guidelines for Size and Proportion of Windows of Master Bedroom in South-West Orientation				

1.2.1. Literature Review

The first phase defined the theoretical framework for this study. A range of national and international established journal papers, books, researches and documents have been reviewed extensively. This phase helped to understand the theoretical basis of parameters of window, contributing in reduction of energy use in naturally ventilated buildings, the climatic context of Bangladesh and finally to identify the target income group and their preferred apartment size in the context of Dhaka. In addition, it identified the methodology of analysis and issues that were investigated in the case study, field survey and simulation phase.

1.2.2. Data Collection

The second phase is divided into two sub phases: the first part being case study analysis along with questionnaire survey and non-structured interviews, and the second is the field study part.

In the first part, an investigation was done on twenty apartments of randomly selected mid-rise residential buildings, constructed by developers, enlisted in Real Estate and Housing Association of Bangladesh (REHAB). The general characteristics of a typical high-rise residential apartment, ideal for upper-middle income group people of Dhaka, were identified. Apartment size, location, master bedroom location and size, window specifications and occupants, activity pattern, were determined, by analyzing the twenty collected plans. The investigation also included questionnaires, filled by five selected REHAB enlisted developers and interviewing specific REHAB members, developers, architects and other concerned people about passive architecture practice. The data obtained, were then explored to identify a typical case, which was used as the 'model' in the Dynamic Thermal Analysis, constructed and simulated in Ecotect.

Quantitative and qualitative data were collected from the case study building. All the information analyzed during this phase, were intended to fulfil the criteria and structure outlined in the literature review of the first phase. Secondary sources such as articles in local newspapers or in the internet were also used to complement the information.

The second part involved field measurements of indoor air temperature inside the case study, a master bedroom, of size similar to the one identified in the case study part. The bedroom is located on the topmost floor, at the south-west corner of a south facing apartment of a multi-unit residential building. The apartment size was representative of the mid-rise residential buildings, preferred by the upper middle class of the city. The fieldwork was done during April and May, to observe indoor summer temperature, and later in January, to understand the winter condition. The measurements were taken using data loggers (Section 4.3.4 and Appendix I) and used for comparison with simulation results for the same and subsequent validation. The field investigation was supplemented with physical observations and non-structured interviews of the occupants, to identify the existing room and window state, and activity pattern of the occupants (Section 4.3).

1.2.3. Simulation

The third phase comprised of simulation study of the existing case with varying window proportions and sizes. The simulation phase was divided into two sub-phases: first Dynamic Thermal Simulation (DTS) studies, in Autodesk Ecotect Analysis, were carried out of the base case and the varied cases, followed by a Computational Fluid Dynamics (CFD) analysis, in WinAIR V4.1b, a plugin of Autodesk Ecotect Analysis. A base case model of a master bedroom, based upon the findings of the data collection phase, was generated in Ecotect. The base case was then simulated, to understand the state of indoor air temperature of the existing case. DTS were also carried out for the varied cases, where the window sizes were varied for different values of WWR and WFR. This part was done to analyze and evaluate the effect of varying window sizes on indoor air temperature for different natural ventilation strategies, and for varied ventilation. The CFD simulations were done in WinAIR to perform wind flow analysis, on a mesh using Ecotect. The CFD analyses were carried out for the best cases, as identified during the DTS, to understand the indoor air flow pattern for such variations in window sizes and proportions**.**

1.2.4. Results and Analysis

All the generated data were categorized, tabulated, plotted in graphs, and recombined to address the primary purpose of the study. Facts and discrepancies identified, were crosschecked by using triangulation, as explained in Chapter 4. Specific techniques include comparing thermal analysis graphs (sinusoidal), thermal simulation plots, CFD simulation flow pattern and vector plots, temperature distribution graphs, creating matrices of categories, tables and excel spreadsheets. Results obtained from the simulations were compiled in excel format for analysis.

Results obtained from the simulation were matched with the identified comfort temperature for Dhaka. Initially, regression and sensitivity analysis were proposed to evaluate the results, however, comparative analysis is found to work better with this research. Thus, a number of comparative analysis were carried out to understand the trend of impact of varied WFR and WWR on indoor air temperature and to identify the optimum combination of WFR and WWR to maintain indoor comfort temperature. Amalgamation of all data finally, led to a probable recommendation for WFR and WWR in South-West oriented bedroom in residential apartments.

1.3. Validation

The data obtained from different steps of the research have been validated by triangulation. Triangulation, as Johansson (2003) says, is the most important way of making the results of a case study valid. Stake (1995) defines triangulation as a process of using multiple perceptions to clarify meaning by identifying different ways in which the phenomenon is seen. According to Patton (1990), there are four different methods of triangulation in connection with qualitative methods:

- Data triangulation: Several sources are used to collect data about the same phenomenon.
- Researcher triangulation: Several researchers study the same phenomenon.
- Theory triangulation: The same data is analyzed using different principles or theories.
- Method triangulation: Several methods are used to gather data about the same phenomenon.

Among the different methods of triangulation described above, data triangulation, researcher triangulation and method triangulation were used in this study.

1.3.1. Validation of the Results from Case Study Analysis

Twenty different residential buildings, of REHAB enlisted developers, situated at various locations of Dhaka city, were analyzed (Appendix B). The analysis was done to identify the typical master bed room size and window specifications in the apartments of interest, mentioned in Section 3.6. Method triangulation, including interview (Appendix A), observation and photographs, were used to investigate the same. Based on the findings of the case study, a building with apartments size of interest, was used for field measurements. The results from field investigation were confirmed by collecting the temperature measurements during January, April and May. Day long readings, at an interval of one hour were taken for the last ten consecutive days of April (21 to 30), first 10 days of May (1 to 10) and later on, for mid-10 days January (11 to 20), during the year 2016. The data retrieved from data logger and the data from simulation, for the above-mentioned days, and the method of comparing the data, are given in detail in Appendix E.

1.3.2. Validation of the Software Used

Theory triangulation and method triangulation were used to validate the accuracy of the software, Autodesk Ecotect Analysis. A number of established national and international research were studied to understand the scope and possibility of the software used. Almost all the research confirmed the use of Ecotect, as an efficient approach, both in the preliminary design stage, as well as, during the overall design process (Appendix H). Finally, a CFD analysis, of the best cases, identified in DTS, were done, to understand the wind flow pattern inside the models, with variable window sizes and proportions.

Based on the findings of case study analysis, physical survey and interviews with the occupants of the building that was used for logging temperature measurements (Section 4.2 and 4.3), a building model, with a similar room at the south-west corner of same size, material and window location and proportion, was constructed in Autodesk Ecotect Analysis. Dynamic thermal simulation, using the same software, was conducted on the same dates, exactly when the temperature data were logged. The indoor conditions of the modelled room were setup, as similar as possible like that found in the surveyed room. The results of Ecotect were authenticated by comparing the data obtained from the field investigation and the simulated value for the same case. The temperature variation between the simulated values and measured data of indoor air temperature showed a slight degree of variation, of around 6.57%, which is within the acceptable range of 5 to 10%, which is discussed in detail in Appendix E.

1.4. Scope of the Research

From extensive literature review, this research hypotheses that natural ventilation can play a significant role in reducing load on conventional energy use. Operable windows, being an important feature of natural ventilation, also plays a significant role in increasing air movement and reducing indoor air temperature.

Optimization of WFR and WWR, integrating variable/night ventilation and different air exchange, to ensure appropriate indoor thermal temperature, was the main objective of the research. The focus of the research was to study the reduction of indoor air temperature in naturally ventilated bedrooms of residential apartments, and thus reducing impacts on national grid electricity. The present trend of window size and proportion used in existing mid-rise residential building had also been studied. The apartment size and master bedroom size preference by mid-middle income people, were also investigated in this research work. Thus, indications from the study can act as an initial guideline for designing windows for naturally ventilated residential buildings, suitable for the middle-income group in the city.

Since field measurements varying window sizes and proportions and keeping all other parameters constant in a naturally ventilated building, were only possible by creating a number of controlled experimental setups, a simulation based study was chosen to fulfil the objective of the study. Experimental analysis would be very expensive and time consuming, whereas field survey would be impossible to conduct, as keeping all the parameters constant and varying only window size would be a critical combination to manage. Numerical simulation, on the other hand, is a cost-effective and efficient approach to predict indoor thermal conditions in naturally ventilated buildings (Section 2.9).

The analysis was done, focusing mainly the indoor air temperature for summer months in the south-west orientation. The research can be further extended for all seasons, taking account of daylighting and a detailed analysis of indoor air flow pattern to investigate optimum window size and proportion, and also for choice of material and indoor humidity content to low indoor air temperature in residential buildings.

The findings of this work will provide some general guidelines that can be used to develop specific standards for window sizes and proportions, appropriate for alleviating indoor air temperatures of bedroom of naturally ventilated residential building. The findings can also be used for local compliance for residential buildings. The research-outcomes will be valid in the climatic context of Dhaka city and any other regions having similar climatic context.

1.5. Conclusion

This chapter has described the selected research topic, the background and necessity of this study. It reveals the objective and significance of this research. It also elaborates on the structures of this research work, which includes the type of research design, strategy, methodology as well as data collection, analysis and interpretation processes involved in this research.

Chapter 02: BUILDING ENERGY USE, NATURAL VENTILATION AND WINDOW PARAMETERS

2.1. Background

Ever since the world's energy crisis in the 1970's, it has become paramount for countries to find ways of reducing its energy usage in all aspects. Control and management of energy consumption is becoming more and more important due to the rapid depletion of fossil energy resources, and the increased environmental problems caused by them. It's currently estimated that the total power used by humans worldwide amounts to 16 terawatts – a number that is swiftly rising as the population swells, and developing countries require more power to support rapid economic growth and increasingly energy-intensive lifestyles (Corbis, 2011).

Since 1980, the industrial sector was the highest primary energy consumer worldwide, but the trend has been decreased. Global energy use in the commercial and transport sectors have increased slightly, but residential sector has been constant. Figure 2.1 shows that in 2005, the manufacturing industry was the end-use sector that globally consumed the most energy, with a 33% share. It was closely followed by households (29%) and transport (26%) (IEA, 2008).

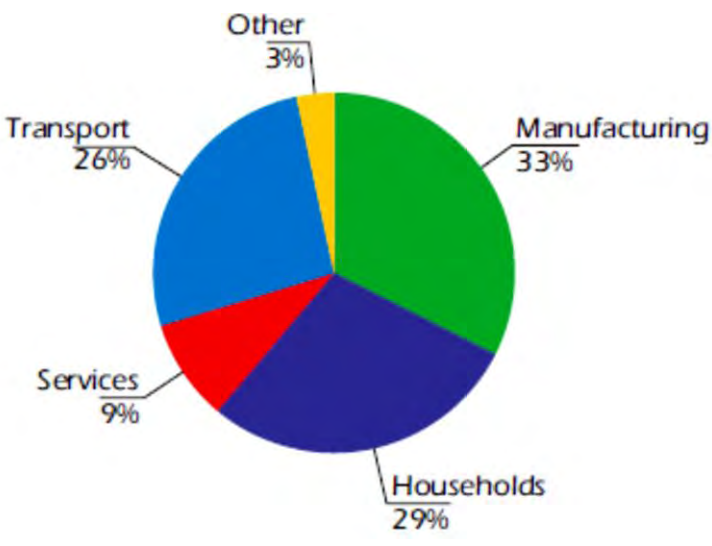


Fig. 2.1: Total Final Energy Consumption: 285 EJ
Sources: IEA, 2007c; IEA, 2007d; IEA, 2007e.

As house owners are those responsible for meeting cost of energy in households, any inefficiency in the residential sector is found to significantly affect the life style and household budgets. This research focuses on the residential sector, in order to address this issue of affordability, also highlighted in the previous research (Tariq, 2016**).**

2.2. Energy Use in Buildings the Sector

A large amount of energy is consumed during the utilization phase of the building. Therefore, priority is given to applications that reduce the amount of energy consumed during the utilization phase throughout the lifetime of building. The buildings sector, which consists of residential and commercial end users, accounts for one-fifth (20%) of the total delivered energy consumed worldwide. According to the International Energy Outlook 2016 (IEO 2016) reference case, worldwide, delivered energy consumption is projected to increase by an average of 1.5%/ year in building sector from the year 2012 to 2040. Residential buildings' energy consumption grows by 2.1%/year from 2012 to 2040 in the non-OECD (non-Organization for Economic Cooperation and Development) nations. This accounts for 80% of all growth in world residential energy use over the 28-year period, which is seen as a result of strong economic growth and rising standards of living (IEO 2016).

Energy use in the residential sector is defined as the energy consumed by households, excluding transportation uses, accounting for heating, cooling, lighting, and water heating and for many other appliances and equipment. Energy consumption in the residential sector, is mainly influenced by income levels and energy prices, in conjunction with various other factors, such as location, building and household characteristics, weather, equipment types and efficiencies, access to delivered energy, availability of energy sources, and energy-related policies.

Of the different sources of energy, electricity has become increasingly important for the residential sector. The electricity share of world residential energy consumption is predicted to grow from 39% in 2012 to 43% in 2040, and by 2025 electricity surpasses natural gas as the leading source of residential delivered energy (IEO 2016).

2.3. Effects of Urbanization on Energy Demand

Research has shown that urban density and spatial dispersion are key determinants of residential energy consumption (Hossain et al, 2015). Multi-country studies on the effects of urbanization on energy use have reported two opposing effects: improvements in energy using equipment, such as air conditioning units, increase efficiency in urban lifestyle, simultaneously higher numbers of households and increased penetration of air conditioning increase energy use (Safirova et al, 2007).

According to the International Energy Outlook (IEO 2016), rising incomes and a natural preference for comfortable indoor air temperatures are resulting in rapid growth of energy use for space cooling in developing countries around the world. Fans and air conditioners are the two most predominant cooling technologies for buildings, of which air conditioners use much more energy. A recent estimate on global energy mandate suggests that air conditioning demand would be about 50 times higher if all countries around the world adopted space cooling habits (IEO 2016).

An analysis of building energy consumption in Hong Kong, Singapore and Saudi Arabia shows that the building envelope design accounts for 36%, 25% and 43%, respectively, of the peak cooling load (Cheok-Chan, 2008; AL-Najem, 2002; Lam and Li, 1999;). In Ghana, more than 100,000 room air conditioners are sold each year with the number expected to grow by about 8% each year. (IEA, 2007). A study of household energy use by the Center for Environment, Technology and Development, Malaysia, found that air conditioning, being the largest consumer of electricity in the home, takes up nearly 45% of the average household electricity consumption (CETDEM, 2006), and the total number of households with air-conditioners increased from 229,000 in 1990 (6.5%) to 775,000 in 2000 (16.2%) and then to 1,414,591 in 2010 (22.3%) (GRPH, 2010; GRPH, 2000; Maliha et al, 2004). The impressive expanding AC systems market in China, where 35 million air conditioners were sold in 2010 (Michel et al., 2011), is the main producer and exporter of this appliance worldwide. According to Lin and Rosenquist, (2006), 40% of the peak summer electricity load was due to air conditioners, which were the main reasons for the several power shortages occurring between 2002 and 2004. In Thailand, a tropical country, where electricity consumption basically concentrated in the residential and commercial sectors, air conditioning loads represent 46% of residential consumption of electricity (Sangsawang 2010). Air conditioners in India increased by 20% annually in recent years (Song,2010) and a recent major market study estimates that the market for air conditioners in India will grow by 10%/year from 2015 to 2020 (Sivak, 2013). These numbers suggest the world-wide potential for significant growth in demand for air conditioning and energy consumption for space cooling. The cooling load in Bangladesh is becoming a matter of great concern. The difference in power load between high summer and deep winter is as much as 1500 MW, implying that the cooling load is probably more than 2000 MW (Hossain, 2013).

2.4. Active and Passive Strategies for Reducing Buildings' Energy Consumption

In the past 20 years, severe energy crisis has undergone in developing countries especially during summer season to combat the cooling load requirements of buildings. The energy consumption in buildings is quite high and is expected to increase further because of improving life standards and ever increasing world population. As a consequence, air conditioning use has increasingly penetrated the market during the last few years, resulting in the upsurge of absolute energy consumption (Kamal, 2012). There are a number of ways to manage the energy usage of a building. Three broad groups of strategies may be applied to buildings in order to save electricity. Nonetheless, they are similar in many ways but they may be separated and identified as active strategies, demand management strategies and passive design strategies (Quarmby 2013).

'Active' features of a building refer to intelligent technological devices installed to bring a building to 'zero' energy. Examples of active technologies will include: improved HVAC systems; heat pumps; air or ground water heat sources; solar heaters; solar photovoltaic panels and low-energy electrical lighting (PHIUS, 2016; Ochoa and Capeluto, 2008).

On the other hand, a 'passive' building is a comprehensive system that takes advantage of free natural energy like sunshine during the day, wind and the coolness of nights to bring a building to "zero" energy. Energy flows naturally while the building responds passively, needing a minimum of imported energy' (PHIUS, 2016; Ochoa and Capeluto 2008, Holm and Viljoen, 1996). Ochoa and Capluto (2008) define passive design as one in which the designers have utilized design strategies whilst developing a building that has given due regard for climatic requirements and aims to ensure that the building is designed in such a manner so as to adequately respond to these requirements, whilst providing a high level of living quality with a minimum effect on the environment (Ralegaonkar and Gupta, 2010; Ahmed, 2003).

In most climates, the active control requirements will be reduced by the utilization of passive design principles. This design will make provisions for thermal comfort and, assuming that there are equal occupational requirements, provide for a net reduction in energy (Haase and Amato 2009). The use of passive principles such as improvements to building envelope design; increased insulation; natural ventilation; shading; and better performing windows contribute to achieving a highly energy-efficient building. A renewed interest in the passive design of buildings as a viable solution to the energy crisis as well as pollution has become evident in recent years because of its environmentally friendly characteristics (Sadineni et al, 2011). According to Victor Olgyay, the most important lesson to be learned is that architecture is at its finest when it is performing alongside and not in opposition to nature (Hawkes et al, 2002).

2.5. Passive Architecture

Tropical climates are those where heat is the dominant problem, and, for the greater part of the year buildings need to keep the occupants cool, rather than warm. The annual mean temperature is not less than 20°C. Human thermal comfort is a dominant problem in tropical climate. The shelter, the building envelope, should give a satisfactory performance in controlling heat and light, as well as sound (Koenigsberger, et al, 1973).

Givoni (1997) and Lauber (2005), both stated that a building in the tropics means a conflict of construction and function with extreme climatic condition. The climatic elements in tropical climates have both negative, as well as positive impacts on the building design. The climatic parameters of tropical climate, causing most common impacts, are temperature, relative humidity, solar radiation, rainfall and prevailing wind. Rajapaksha et al., (2002) assert that the indoor thermal environment is much affected by local climate, and therefore air movement through the building is necessary to decrease indoor discomfort due to overheating conditions in tropical climate. Research specifically in Dhaka's tropical condition identifies natural ventilation as the dominant design determinant (Ahmed and Ahmed, 1997).

Passive Architecture is a term coined to describe buildings designed to be responsive to the local climatic conditions, such that comfortable indoor condition is created naturally, for as long as possible (Zaki et al., 2007). The terminology is expressed as 'passive' to portray a defensive or protective approach of house design in shielding occupants from the local climate elements; and the term 'architecture' places this responsibility on the Architect, while the profession is obligated to create good building design (Zaki et al., 2008). Climate responsive design of buildings is important for achieving comfort and energy saving implications for its users, and as well it helps preserve valuable resources in our planet (La Roche and Liggett, 2001). In designing passive buildings in tropical countries, the critical external factors to be taken into account, grounding to various studies, are as follows:

2.5.1. Orientation

As stated by Thomas and Garnham (2007), building orientation is a vital criterion for making "passive" building and it should be determined by aspects of the sun and the prevailing winds. In determining a building's thermal efficiency, building's orientation plays a major role (Belgaid, 2011). According to La Roche et al. (2001), large fenestration on the west and east should be avoided for buildings in the tropics, because these two sides receive approximately twice the amount of solar irradiation, compared to on the north. In tropical climates, the most critical building orientation that needs to be protected is the south surface, (Ling, et al, 2007). Thus, the best orientation is 0°North and the worst orientation is 240°South West (Fadzil and Sia, 2004).

2.5.2. Building Form

Tropical buildings are inevitably rectangular, elongated east-west in order to limit the exposure on east and west sides (Konya, 1980), which consequently results in shallow floor plan that encourages natural cross ventilation (Tombazis and Preuss, 2001). A study on analysis on Dhaka's tropical context reveled that plan layout has a significant impact on electricity consumption needed for thermal comfort (Tariq, 2016).

2.5.3. Wall and Roof Insulation

Konya (1980) stressed that in the tropical countries roof should be properly insulated as maximum heat gain takes place on top of a building. Koch-Nielson (2007) suggested that air is the best insulator and that stack effect and cross ventilation releases hot air that gets trapped in the roof space**.** An average gradient of around 2.7ºC between double roof and flat concrete slab, has been observed on clear sky days on Dhaka’s climatic context (Tariq and Ahmed, 2013).

2.5.4. Window Openings for Ventilation

Window openings in the hot and humid climate should be large enough to catch breeze from the prevailing wind, and rooms should be arranged in a single bank to facilitate cross ventilation (Konya, 1980). Studies have demonstrated that this is also true for Dhaka’s climate, where single sided ventilation creates stuffy conditions. (Ahmed, 2002).

2.5.5. Sun Shading Device

Sun shading devices should be designed in accordance to the sun path. For tropical countries, the most effective type and position for sun shading devices are projected canopy at the top of windows, horizontal louver blades or externally applied venetian blinds on the south and north; where their performance is measured in vertical shadow angle. Protruding fins or louver blades in a vertical position are effective for windows on the east and west façade, their performance being measured in horizontal shadow angles (Koenigsberger et al, 1973).

Studies have confirmed that this phenomenon is similar for Dhaka’s context, where vertical shading devices may not be practical for windows in the south-west corner, rather adjacent wall should be adequately planned to shade the western wall (Ahmed, 1987).

2.6. Passive Cooling

Building envelope components have a significant impact on the total heat gain or loss within the building. Building design approach addressing heat gain control and heat dissipation in a building to improve the indoor thermal comfort with low or nil energy consumption is termed as Passive Cooling.

(Santamouris and Asimakoupolos, 1996; Samuel et al, 2013). Prevention of heat from entering the interior (heat gain prevention) or removal of heat from the building (natural cooling) are the two main approaches of passive cooling (Limb, 1998). Natural cooling depends both on the architectural design of the building as well on a site's natural resources to use as heat sinks (i.e. everything that absorbs or dissipates heat), rather than mechanical systems to dissipate heat (Niles et al, 1980).

2.6.1. Night Flushing

Night flushing (also known as night ventilation, night cooling, night purging, or nocturnal convective cooling) is a passive or semi-passive cooling strategy that requires increased air movement at night to cool the structural elements of a building (Santamouris and Asimakoupolos, 1996; Samuel, et al, 2013). Typically, night flushing requires the building envelope to remain closed during the day, causing excess heat gains to be stored in the building's thermal mass, which cools down during the night through air exchange with the outdoor. The building structure, acting as a heat sink, absorbs heat gains from occupants, equipment, solar radiation, and conduction through walls, roofs, and ceilings throughout the day, whereas at night when the envelope is opened, the outside cooler air passes through the building, allowing the stored heat to be dissipated by convection (DeKay and Brown, 2013).

Night flushing is most effective in climates with a large diurnal swing, i.e. a large difference between the daily maximum and minimum outdoor temperature (Givoni, 1991). Finn et al. (2007) asserts that increasing building mass from 800 to 1600 kg/m2, the peak daily indoor temperature was reduced by up to 3^{o}C. Reducing internal gains from 40 to 20 W/m2, and ventilation rates up to 10 ACH were also found to have a significant effect on internal comfort, with a reduction in peak internal temperature of up to 1^{o}C.

Many studies have been carried out to evaluate the effect of different parameters on indoor thermal environment and the efficiency of night ventilation. The parameters generally assessed are as follows: air change rates, thermal mass and internal heat gains. For the night flushing strategy to be effective at reducing indoor temperature and energy usage, the diurnal variation and the total air change rate must be high enough to remove the internal heat gains from the space at night and the thermal mass of the building should be comparatively higher, which helps to reduce the internal gain. (DeKay et al., 2013; Grondzik, et al., 2010; Artmann et al., 2008; Finn et al.,2007)

2.6.2 Natural Ventilation

Natural ventilation is one of the most important passive cooling techniques. In general, the ventilation of indoor environments can help reduce cooling load, enhance thermal comfort condition and maintain proper indoor quality, provided that the outdoor condition is favorable. (Asimakopoulos and Santamouris, 1996).

Traditionally, ventilation requirements were achieved by natural means, where infiltration levels in older buildings were just enough to provide considerable amounts of outdoor air, while additional requirements were satisfied by simply opening the windows. Modern architecture and the energy-conscious design of buildings have reduced air infiltration to a minimum, in an attempt to reduce its impact on the cooling or heating load. Better construction has resulted in buildings being sealed from the outdoor environment. A good understanding of the air flow patterns around a building and the effect of its neighboring can result in a successful design of a naturally ventilated building (Asimakopoulos and Santamouris, 1996) When indoor air movement is desired, the building should be designed as such to try to capture as much of the available wind as possible. (Koenigeberger, et al, 1973), that is the objective of natural ventilation is to aerate the largest possible part of the indoor space. The fulfillment of this objective depends on the window location, interior design, wind characteristics and ventilation type.

2.6.2.1. Wind-Driven Cross-Ventilation

Wind-driven natural ventilation is an effective way to maintain a comfortable indoor environment in residential and commercial buildings, as well as to reduce the energy consumption required for mechanical ventilation (Allard, 1998; Aynsley, 1999). Wind-driven cross ventilation occurs via openings on opposite or adjacent sides of an enclosed space, called the inlet and outlet (Fig, 2.2). The sizing and placement of the ventilation inlets and outlets will determine the direction and velocity of cross ventilation through the building (koenigsberger et al., 1973). However, wind-driven ventilation depends on the external wind speed and direction, as well as, openings and building configurations (Aynsley, 1999; Linden, 1999). A significant difference in wind pressure between the inlet and outlet openings, minimal internal resistance to flow by limiting the building floor span depth in the direction of the ventilation flow are needed to ensure sufficient ventilation flow to effectively remove the heat and pollutants from the space by typical driving forces. Thus, a simple and accurate method for assessing the effectiveness of wind-driven ventilation is needed to be adopted.

Study conducted by Ahmed, et al, (2006) shows that, from the point of energy savings and indoor comfort, cross-ventilated rooms, with windows on adjacent walls, are more effective, than on opposite walls, for Dhaka. Dual windows, with cross ventilation, or displacement ventilation, significantly increase outward flow, air change rate and indoor comfort potential (Ahmed Z. N., 2002; Venkatachalam and Amirtham, 2011) conducted a study on thermal comfort conditions in naturally ventilated low-rise apartment units of Chennai. Their study showed that internal temperatures of the cross-ventilated rooms show similar trend as that of exterior temperature and the diurnal variation is high and directly proportional to window to wall ratio in all the rooms studied. Moreover, the study also confirms that cross-ventilated rooms experience discomfort for five months in a year (April to August) and rooms without cross ventilation experience discomfort for eight months in a year (March to October). Annual comfort percentage range of the cross-ventilated rooms ranges from 96.5% to 98.8 %, while that of rooms without cross ventilation is 64.9% to 88.1 %. Also, annual comfort percentages of cross-ventilated rooms are almost similar for all the four major orientations, while they differ by a maximum of 2% in the case of other rooms. Therefore, façade parameters like WWR and WFR are more crucial in optimizing the thermal comfort of rooms designed without cross-ventilation. (Venkatachalam and Amirtham, 2011).

2.6.2.2. Single-Sided Ventilation

Single-sided ventilation typically serves single rooms, and thus, provides a local ventilation solution (Fig, 2.2). The ventilation airflow in this case is driven by room-scale buoyancy effects, small differences in envelope wind pressures. Consequently, the driving forces for single-sided ventilation tend to be relatively small and highly variable.

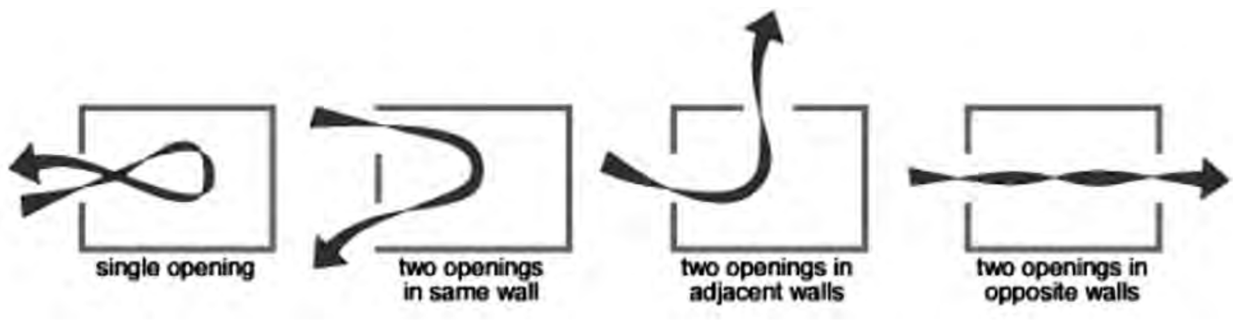


Fig. 2.2: Single-Sided and Cross Ventilation Methods
Source: Brown and DeKay, 2001

Hassan and guirguis (2007) investigated the effects of window combinations on ventilation characteristics in buildings by CFD simulation and wind-tunnel experiments. El-Agouz (2008) studied the effect of internal heat source and opening locations on natural ventilation. A conclusion was drawn that two openings with longer horizontal distance is better than shorter, as far as single-sided ventilation performance is concerned. Evola and Popov (2006) analyzed the wind driven natural ventilation in buildings by CFD-based programs. Three opening configurations, single-sided ventilation with an opening on the windward wall, single-sided ventilation with an opening on the leeward wall, and cross ventilation, were investigated. It was concluded that when dealing with single-opening ventilation, positioning the opening on the leeward side will result in a larger ventilation rate inside the building than on the windward side. Jiang and Chen (2001) compared several CFD models and concluded that for single sided ventilation, instantaneous flow information is necessary, in order to correctly predict the ventilation rate and air change effectiveness. Wei et al, (2010) investigated the potential of a single-sided naturally ventilated building model, considering a number of factors in China. The paper analyzed four typical cities in different climatic regions in China, and calculated the pressure difference Pascal hours (PDPH). According to Ahmed (1987), single sided ventilated spaces presents discomfort throughout the year, however an average air change of approximately 30ACH can present comfort in urban residential spaces. Moreover, in single-sided ventilation, adaptive comfort hours are significantly fewer than in two-sided ventilation, while ventilation volumes is also much less.

2.7. The Window and its Features for Natural Ventilation

The most common design element for natural ventilation is the operable window, for which the mechanism involved is primarily wind-driven ventilation, although buoyancy may have a non-negligible effect. (Roulet and Ghiaus, 2005). According to the Carmody et al. (1996) a window has been defined as an opening in a wall, door and roof of a building or a vehicle that allows the passage of light and, if not closed or sealed, air and sound. A well-positioned, shaded window on a building can induce a significant reduction of the energy usage of the building as reported by Szokolay (2004). Windows can also have a strong influence on the use, productivity, and comfort of the people who occupy the building (Al-Tamimi and Syed, 2011).

Windows, when properly installed with maintained daylighting system, can also have a strong influence on the use, productivity, and visual comfort of building occupants (Al-Tamimi et al., 2011). Natural light and pleasant outdoor views help to maintain good health, decreases stress levels of the occupants and increasing productivity, thus, in turn, increases the work efficiency (Edward and Torcellini, 2002).

Among the many parameters of fenestration system, which effect thermal performance of a naturally ventilated building, a window plays a significant role in increasing or lowering indoor air temperature, by modulating the air exchange rate between indoor and outdoor. The wind incident on a building façade will induce positive pressure on the windward side and relative negative pressure on the leeward side. This pressure difference drives air into the building through the windows located on opposite or adjacent walls in a cross ventilation set up. Designing windows for comfort not only depends on the number of air changes but also on the distribution or pattern of air flow inside the building (Kukreja, 1978; Allard;

1998; Dascalaki and Santamouris, 1998). Heiselberg et al (1999) have described the effect of window type and opening configuration on ventilation flow rate, efficiency, thermal comfort and indoor air quality in the occupied zone. The result of designing buildings with excessively large areas of glazing is; substantial heat gains during the day and heat losses at night (Holm and Viljoen, 1996,); as well as incurring excessively high electrical demands (Menzies and Wherrett, 2005, Ralegaonkar and Gupta, 2010,). In sub-tropical monsoon or composite climate, it is difficult for the designer to properly design openings as many conflicting situations arise and compromises have to be effected. (Ahmed, 1987).

In residential buildings, natural ventilation can improve thermal comfort and indoor air quality, and help to reduce cost associated with mechanically ventilated buildings, where thermal comfort satisfaction and indoor air quality modification is achieved with higher operation costs (Aflaki et al, 2014). The appropriate combination of the orientation, size and location of the various openings on the building's envelope is of vital importance, and will also have characteristic effects on the airflow inside the space, as well as, on indoor thermal condition. Thus, the window size and proportion factor, the area of window to the area of exterior wall/floor, can have significant impact on the thermal conditions within a building. Therefore, window-to wall ratio (WWR) and the window-to floor ratio (WFR) of the building, should be given attention in buildings of tropical countries. These parameters can be defined as:

$$\text{WWR (Window-to-Wall Area Ratio):} \quad \frac{\text{Total Floor Area of the room} \times 100}{\text{Total Glazed Area of the room}} \quad \text{………………...… Eq. 2.1}$$

$$\text{WFR (Window-to-Floor Area Ratio):} \quad \frac{\text{Total Wall Area of the room} \times 100}{\text{Total Glazed Area of the room}} \quad \text{…...................… Eq. 2.2}$$

The values are non-dimensional.

2.7.1. Window-to-Wall Area Ratio

WWR is the specific value of the area of the window and that of the exterior facade of the room. Unit area of room facade indicates the area enclosed by the room height and the standard width of the bay (CABRj. 2010). The fenestration responsibilities of air movement of any building are generally better performed by windows than by doors. Windows are also vital as they add aesthetic values to the building from an architectural standpoint (Menzies and Wherrett 2005; Sadineni et al, 2011,). The natural lighting performance is better when the WWR increases. However, for providing aesthetic satisfaction, sufficient daylighting, windows that are operable through the control of the occupant, allowing natural ventilation, valued by most people (Gratia et al, 2004). Thus, windows also play a critical role in modulating indoor thermal balance of building and needs to be considered comprehensively.

2.7.1.1. WWR and Energy Consumption

Many studies have focused on the relationship between WWR and building energy consumption. Kim et al. (2014) have confirmed in a study on energy analysis indicator by the window elements in Korea that the variation of the window elements such as the orientation, WWR, SHGC, and U-value affects energy consumption. Wang et al. (2012) explored the energy saving effect of building envelope in China through experiments and simulations during summer. As a result of advancement of computational capability, the optimum window size and types to minimize energy consumption of buildings have been explored using computer simulation. Kontoleon and Bikas (2002) modeled and analyzed thermal zone in south orientation to determine the influence of glazing opening percentage, and type of glazing on the indoor temperatures and energy efficiency, during winter and summer in the Mediterranean climate. Overheating can be avoided and energy savings can be obtained with the proper selection of glazing opening percentage, as well as the type of slab insulation. Bostancioglu and Telatar (2013) reported in their study on varied window size on residential buildings' energy cost in Turkey, that building energy cost increase as the WWR increases by 0.46%. Feng and Yang (2001) analyzed how solar radiation influences the thermal process of windows and presented the design principles of WWR on building energy efficiency in the hot summer and cold winter zone. Al-Homoud (1997) carried out an optimization study on building design variables in order to minimize annual energy consumption and observed that minimum glass area of 15% was the best, except during the cold climate, when larger glass area was required to use solar gain for heating. Goia et al. (2013) investigated the optimum configuration of a facade module for office buildings and concluded that the north-exposed facade suffers the most when a wrong configuration is adopted, while the influence of WWR is the least in south-exposed façade. The minimum total primary energy demand is always achieved when WWR is in the range of 35– 45%. Yang et al. (2015) investigated the impact of WWR on heating and cooling consumption of residential buildings. They observed that reducing the WWR of bedrooms in hot summer and cold winter zone would provide significant energy saving benefits. Johnson et al. (1990) examined the economically optimum window size and orientation, and concluded that the WWR of less than 20% resulted in the minimum life-cycle cost and north orientation was preferred for large WWR.

These studies have shown that large window size may result in the increase of a cooling load, while it causes the decrease of a heating load because of the enhanced solar gain. In a research to understand the effect of window position and size on the energy demand for heating, cooling and electric lighting, Bokel (2007) concluded that, for window located at the top half of a facade, WWR should be 30% and 20% to 40% is also very acceptable whiles greater WWR does not have any effect on the lighting loads. In an investigation of 280 residential buildings in the sub-tropical climate of Hong Kong, it is observed that the WWR of living rooms and bedrooms ranged from 15% to 50%; and about 90% of buildings had WWRs between 25% and 35% to reduce air-conditioning cooling load. (Lam, 2000).

2.7.1.2. WWR and Energy Simulation

Persson et al. (2004) used the DEROB-LTH simulation tool to investigate the influence of south and north window size on energy consumption in Swedish climate, and reveal that it is possible to enlarge the window area facing north to achieve better lighting conditions in the traditional way of building passive houses.

Based on ECOTECT simulations, Binarti (2009) investigated the influence of shading devices, WWR, and window height and glazing type on energy consumption for supplemented lighting and mechanical ventilation inside classroom in warm tropical climate of Indonesia. The study concluded that projected clerestory should be applied on classroom design, considering WWR, the clerestory height to room height ratio, and WFR to achieve energy efficient design. Nasrollahi (2010) studied the effect of window area and shading devices on the energy consumption of office buildings in Tehran. The simulated result showed that for buildings with the same window ratio without shading devices in all orientation, the optimum WWR for heating, cooling and lighting is respectively 80%, 10% and 40%, and to reduce total energy consumption, the optimum WWR is 50%. Muhaisen et al, (2015) conducted a parametrical study using "IES virtual environment" and "ECOTECT" to estimate the effect of orientation, size, and thermal properties of the windows of a typical residential building and room models in Gaza. It has been concluded that the appropriate window design can effectively reduce the energy demand and meet the requirements of thermal comfort. The study also reported that the optimum WWR ratio is 10% for all facades and the direct impact of south window is considered the worst, as it causes the large energy consumption. Although minimizing the window size ensures low energy load, it may fail to provide the required ventilation rate in naturally building.

2.7.1.3. WWR in Naturally Ventilated Building

The study, based on coupled simulations between ESP-r and CFD-Fluent, of the impacts of various ventilation strategies and building envelopes on indoor thermal environments for naturally ventilated residential buildings in hot–humid climate of Singapore, stated that full-day ventilation strategy is the best way to increase indoor thermal comfort, and WWR of 24% can improve indoor thermal comfort for full-day ventilation and 600 mm horizontal shading devices are needed for each orientation to improve thermal comfort. (Liping et al, 2007).

Another study by Haase and Amato (2009), investigated the impact of natural ventilation and building location on thermal comfort in different climatic zone. Natural ventilation has good potential in tropical regions. In Kuala Lumpur, the improvement of thermal comfort by natural ventilation ranged between 9% and 41%. A study by Tamimi et al. (2011), assessed the thermal performance of ventilated and unventilated glazed rooms, using field measurements and computer simulation tools, was conducted in Malaysia. Rooms with a large glazed window area are relatively cool during night-time only, whereas small glazed window area performs well both during day and night-time. Rooms in the east are always hotter than those in west, regardless of applying natural ventilation or changing WWR. In general, it was concluded that thermal comfort can be improved by applying natural ventilation and WWR of 25%, though, sometimes, mechanical ventilation is necessary to improve occupiers' thermal comfort in such climatic conditions. Koranteng et al. (2015) WWR between 10-30% are ideal for residential buildings in Kumasi, Ghana, although 40% is tolerable. Increasing the WWR may improve the ventilation and the number of comfort hours in naturally ventilated buildings in the city of Florianópolis, Brazi, but it may also increase solar heat gains (Longo et al, 2011).

2.7.2. Window-to-Floor Area Ratio

Window size, especially its location in respect to floor area and orientation of the building determines the efficiency of air movement in a house. The latter also determines the comfort of users with regard to indoor heat or temperature. WFR is the total area of the window divided by the floor area of the same room. (Atolagbe, 2015). Ishwar (1976) specifies a range of 20-30% of WFR for effective and adequate ventilation in the warm humid climates of the World. Liping et al. (2007) established that in hot-humid climates, naturally ventilated residential buildings can have WFR ranging from 10% to 40% for all orientations, however, an optimum ratio of 24% was stipulated to address the conflict between daylighting provision and solar penetration for improved indoor thermal comfort. Atolagbe's, (2015) study depicts that occupants' satisfaction as well as WFR decreases with increased density of the residential zones of warm humid climate of Tropical Nigeria, and also with increased number of occupants in each room. The presence of more aired spaces, elements like soft landscape-water, flowers, trees, etc, adds to better natural ventilation. A WFR of 25% is proved to have good impact on daylight and ventilation, with a shading device of 1 to 2m, yet was still large enough for generous view of the outside scenery. (Goncalves, and Bhatla, 2012).

A study conducted by Ahsan et al. (2014), asserts that total window area and total WFR are the key predictors of annual electricity consumption of naturally ventilated residential apartment of Dhaka, if the effect of the influence of household characteristics, such as household sizes and number of ACs, are excluded. An increase in WFR decreases annual electricity use, whereas large window area increases electricity use. The study also concluded that small sized windows, in relation to larger floor area, would not admit sufficient daylight, resulting in the use of artificial lights, which would contribute to an increase to in the total electricity use.

2.7.2.1. WFR for Daylighting

Among other design parameters, like ceiling height, internal reflectance's, depth of room, WFR also accounts for penetration of daylight into a room (Capeluto, 2003). For instance, Smith (2005) explained that WFR of 20% can provide sufficient day lighting up to a depth of approximately 1.5 times the height of room in non-domestic buildings (Ibrahim, 2009). Robson advised that 20% WFR can provide adequate lighting in the classroom (Wu and Ng, 2003).

The rule of thumb for WFR is often cited in literature of architecture and building codes. In Malaysia and Singapore, legislative requirements state that a minimum of 10% WFR can be imposed on any room (residential, commercial, or others), designed for daylighting requirement. (Nedhal et al, 2016). WFR of 10 to 12.5% is also recommended in Neufert Architecture's Data (2000). Gutherie (1995) prescribed that the ratio of WFR for day lighting must be 10 to 25%. British Local Government Board by laws of 1920s and the LBA (1894-1909) suggested that WFR of 10% as a design requirement. Nevertheless, countries with cooler climate recommended 20% to 25% of WFR, mostly considering the penetration of daylight depending on room depth and building type. According to Bangladesh National Building Code, the exterior wall of habitable rooms such as those used for sleeping, living, study, dining etc. should be minimum 15% of the floor area, excluding doors (BNBC, 2006).

The above studies revealed that WWR and WFR accounts for ventilation, building heat balance, indoor environmental quality, energy balance, daylighting, views and construction as well as operation cost of any building. Most of these studies considered the size of windows with reference to wall area and floor area ratio. However, only a few studies focused on the effect of optimum operable window area on indoor thermal condition and thus occupants' comfort.

2.7.3. Air Change Rate per Hour

Air changes hour (ACH), also known as air change rate per hour, abbreviated ACH or ac/h, is a measure of the air volume added to, or removed, from a space (normally a room or house) divided by the volume of the space (ASHRAE, 2013).

Air change rate per hour can be expressed as;

$$ACH = 60 \times CMM / V \qquad \text{Eq. 2.3}$$

Where; ACH = Air Change per Hour
CMM = Volumetric Flow Rate of Air in Cubic Meter per Minute
V = Volume of the Room in Cubic Meter

If the air in the space is uniform or perfectly mixed, air changes per hour is a measure of how many times the air within a defined space is replaced. Indoor to outdoor temperature differences, opening size and duration, and outdoor wind effects and window geometry (de Jong and Bot, 1992), have been shown to directly affect the ACH of a building (Johnson, 2004; Howard-Reed et al., 2002; Jordan et al., 1963). Chandrashekaran (2010) identified that ACH of 5-500 is necessary to achieve thermal comfort within building. A higher ACH during the cooling period increases the amount of heat that is flushed out of the building, lowering the temperature of the mass, and also the maximum temperature for the next day (La Roche and Milne, 2004). Window openings have been shown to significantly affect ACH and can be easily controlled by residents. Higher ACH is associated with higher speed within the room. According to Cicelsky (2010), at 50 ACH, the air speed would be within ASHRAE thermal comfort standard air speed limits for naturally cooled buildings (ASHRAE, 2013). If, in the case of natural ventilation, the wind entering the building, was at the upper ASHRAE limit of 0.8 m/s passing through $6m^2$, and is equivalent to 57.6 ACH. In Autodesk Ecotect Analysis 2011, 50 ACH is defined as the cross-ventilated state under still condition, and 200 ACH is for windy state in cross-ventilated state (default setting of Autodesk Ecotect Analysis 2011).

The wind chill effect allows room occupants to tolerate higher temperatures because of air in motion (USGBC Guide, 2016). In a study of effects of climates on design and location of windows in naturally ventilated residential buildings in Bangladesh, Ahmed (1987) calculated the hourly air change rates, ranging from 4 to 224 ACH, for assessment of thermal conditions in three categories – comfortable, uncomfortable and stuffy, for three types of inlet – outlet combinations (adjacent windows on same wall, windows on adjacent wall and windows on opposite wall).

For this research, ACH values of 50 and 100 have been used in cross-ventilated and single-sided ventilated state, to assess the impact of varying values of WWR and WFR on indoor air temperature. 100 ACH is considered to be a moderately windy state. This is because usually the windows, being mostly sliding, are partially operable in the residential buildings of Dhaka (Appendix B), and also, buildings in Dhaka are found to be densely packed (Section 3.3), having very little in-between spaces to allow high speed wind flow through and around the buildings. Thus, 100 ACH has been used in this research, considering it as a moderately windy state, being double the still air value.

2.8. Thermal Comfort

The simplest definition of Thermal Comfort is given by Givoni, where the range of climatic conditions considered comfortable and acceptable to humans, is termed as thermal comfort (Givoni, 1997). Studies of human response to thermal environment have been conducted by ASHRAE since the 1920s. Some significant studies in this area include the ASHRAE Comfort Charts, Olgyay's Bio-climatic Chart, Givoni's Building Bio-climatic Chart and Fanger's Predicted Mean Vote (Sreshthaputra, 2003). Thermal comfort is being reported as being highly contextual as revealed in a study by Ahmed (1987).

ASHRAE Standard 55 (2004) specifies conditions of indoor thermal environment that will make users comfortable based on adaptation method. The adaptation method does not predict comfort responses, rather it states a range of thermal conditions under which people feel comfortable (Owen and Kennedy, 2009). Figure-2.3 shows the range of acceptable operative temperature (T°c) in this adaptation method, where T°c is a function of outdoor temperature. This method does not also specify any humidity level or air speed limits and was developed in the context of conditioned buildings in developed countries (Lomas et al, 2008). Thus, it was less effective for this research, as non-conditioned, naturally ventilated building was addressed in this study.

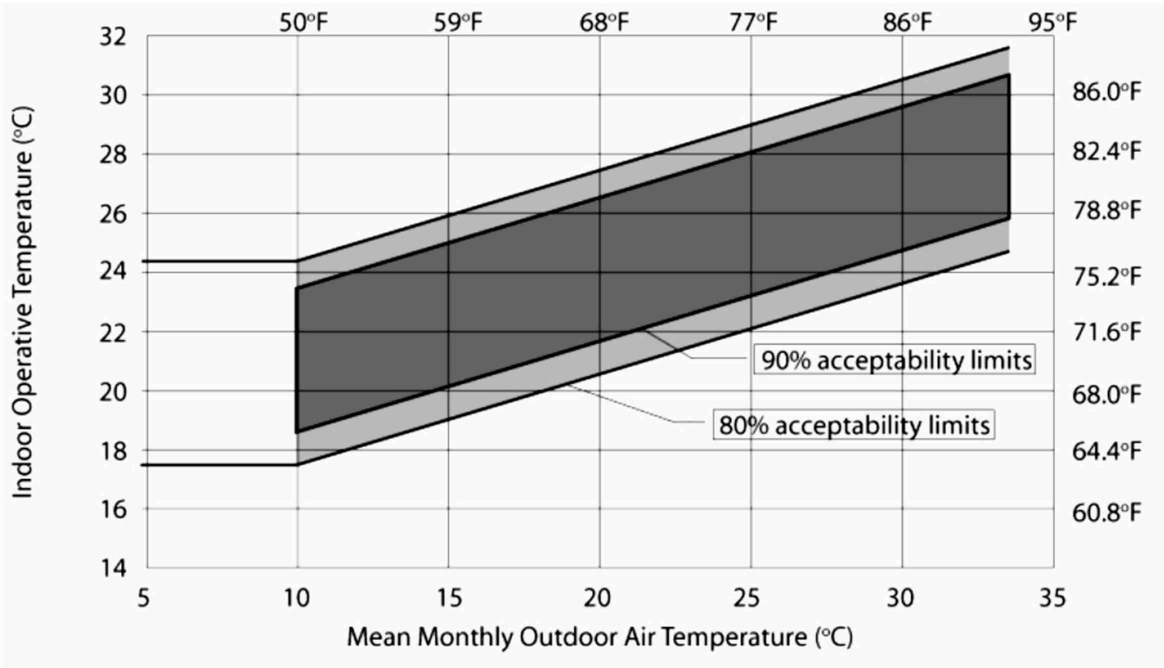


Fig. 2.3: Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces
Source: ASHRAE Standard 55, 2004

Beside ASHRAE and other mentioned standards, there are several other comfort indexes for diagnosing comfort conditions for a given place. Victor Olgyay was the first to develop the comfort indexes, in the form of graphical chart, named Bioclimatic-chart (Figure-2.4), developed in the 1950. It was one of the first attempts at an environmentally conscious building design to incorporate the outdoor climate into building design (Givoni, 1992). The chart indicates the zones of human comfort in relation to ambient temperature and humidity, mean radiant temperature (MRT), wind speed, solar radiation and evaporative cooling. Dry bulb temperature is the ordinate and relative humidity is the abscissa on the chart. The comfort zone is in the center, with winter and summer ranges indicated separately (taking seasonal adaptation into account. The lower boundary of the zone is also the limit above which shading is necessary. At temperatures above the comfort limit the wind speed required to restore comfort is shown in relation to humidity. Variation in the position of the comfort zone with mean radiant temperature (MRT) is also indicated. (Olgyay, 1963).

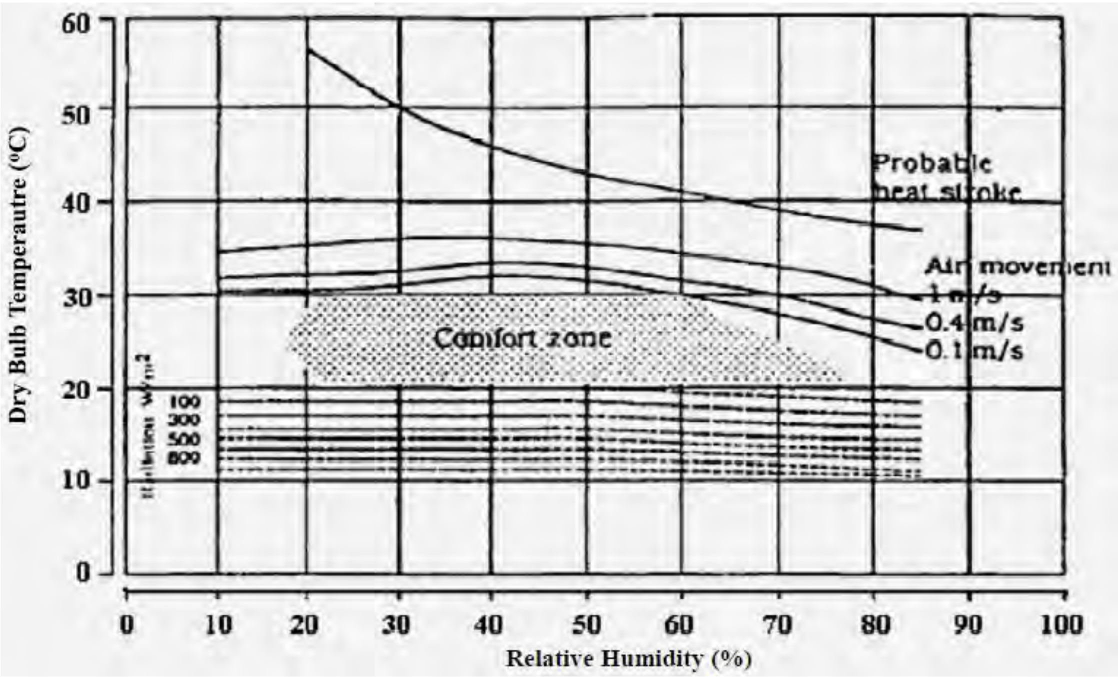


Fig. 2.4: Olgyay's Bioclimatic Chart
Source: Olgyay, 1963

However, Olgyay's bio-climatic-chart was strictly applicable only to outdoor spaces and light-mass and all-day-ventilated building at 40^{o} latitude, under the assumptions that outdoor and indoor temperature remains same in such buildings. According to Olgay, it could be changed to other latitudes, but since, it is a very rough model in estimating comfort zone and not suitable for all climates as well as, for high-mass and night-time-ventilated buildings, this chart would not be applicable for this research.

Givoni (1992) developed the Building Bio-climatic Chart (BBCC) (Figure 2.5) to overcome the mentioned drawback of Olgyay's bio-climatic chart. According to Givoni's BBCC, whose study was based on Israel for still air (less than 0.25m/s), thermal comfort range is 20^{o}C to 27^{o}C in summer. For a light breeze of 2.0m/s, thermal comfort range is 20^{o}C to 30^{o}C in summer.

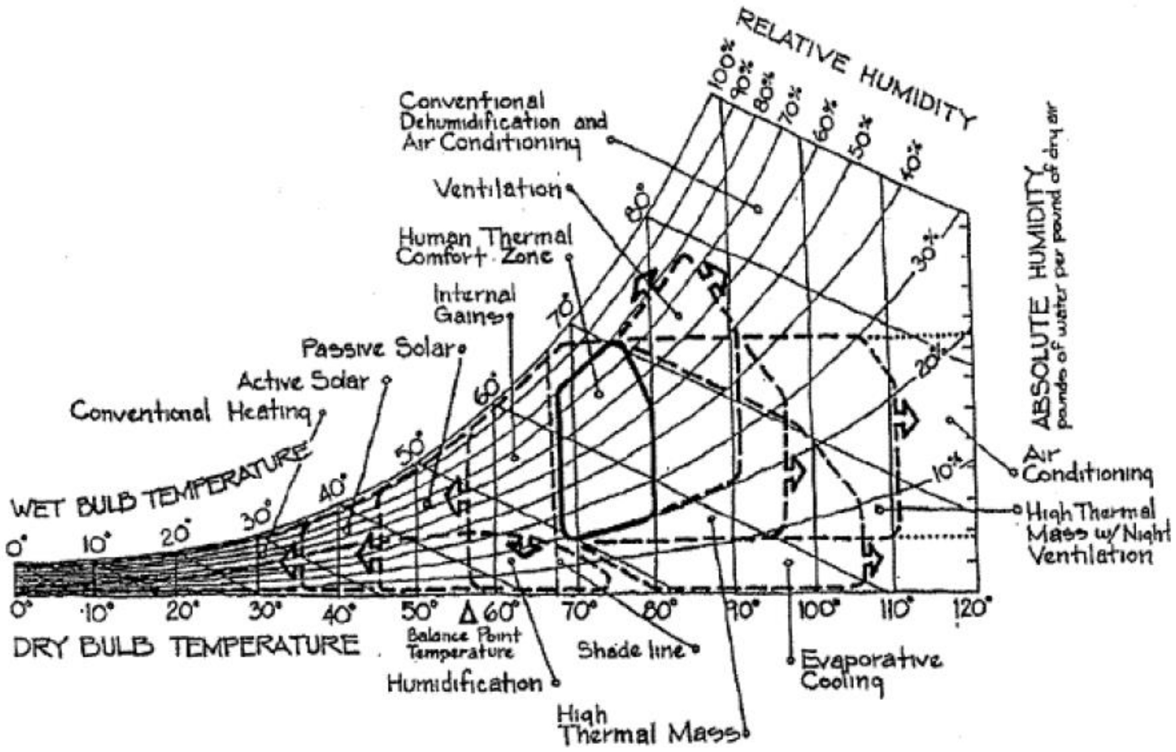


Fig. 2.5: Givoni's Building Bio-Climatic Chart
Source: Sreshthaputra, 2003

Givoni's building bio-climatic chart is not acceptable for tropical climate, since it was based on the climate of Israel, which shows a mixture of Mediterranean and arid climate.

Beside contextual and cultural factors, the influence on peoples' thermal comfort, a person's thermal comfort sense is also related to the body's heat exchange with the environment (Olesen and Brager, 2004). Air temperature, radiant temperature, humidity, and wind speed are the four environmental parameters that influence this heat exchange. There are two personal parameters – clothing level and activity level, which also influence this heat exchange (ASHRAE 55, 2004).

Generally, there are two main widely accepted theories about thermal comfort: the steady-state model by Fanger and the adaptive model by Nicol (Taleghani et al, 2013). The steady-state model is the most commonly used one for air-conditioned space. The theory is based on a specific environment. Humphreys and Nicol (2002) and Fountain et al. (1996) argued that Fanger's steady-state model, of air conditioned office buildings, were controlled within a very restrictive range of temperatures as opposed to what was allowed by ASHRAE 55 standards. An air velocity of 0.15m/s and a relative humidity of 50% were assumed as the prerequisite. In reality, the air velocity and humidity will definitely fluctuate. Based on numerous field surveys all over the world, de Dear and Brager stated that PMV (predicted mean vote) prediction fits to air-conditioned buildings well. However, the result for naturally ventilated buildings was not predicted precisely by the PMV theory (de Dear et al, 2002).

The situation is different in naturally ventilated building. There is almost total agreement among researchers that the PMV model, especially in warm to hot climates do not predict occupant's thermal sensations well in naturally ventilated buildings, and the findings of many researchers do not support the applicability of PMV in hot to warm environment (Feriadi and Wong, 2004; Humphreys and Nicol, 2002; Wong et al, 2002; Brager and Dear, 1998; Busch, 1990; de Dear and Auliciems, 1985). This has been admitted by the author of the PMV model as well (Fanger and Toftum, 2002).

Nicol and Humphreys established the adaptive thermal comfort theory in 1970s (Taleghani, et al, 2013). This theory is widely used in naturally ventilated buildings all over the world. According to the research by Nicol (2004), in a naturally ventilated environment, a thermal balance model does not reflect people's feeling correctly. The adaptive thermal comfort theory shows the principle below:

"If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Fergus et al, 2012).

Since the theory is "adaptive", it also indicates that it might adapt to local climate, leading to a different neutral temperature for adaptive thermal comfort (Zheng, 2015). It is necessary to mention that many studies in hot climates have found that subjects, can be comfortable at temperatures up to 30^{o}C and even higher, when occupants were especially using fan (Nicol, 2004) whereas the PMV model predicts much lower temperature compared to field studies.

2.8.1. Thermal Comfort in High-Rise Residential Buildings

Though there are many high-rise residential buildings constructed all over the world, the thermal comfort level in them was only checked in a few of them, most of which were carried out in Southeast Asia.

In Hong Kong, during summer, a questionnaire survey was done in a few high-rise residences. The results suggested that more than 70% of the respondents felt stuffy because of the poor IAQ (indoor air quality), while two thirds of the respondents didn't know that a ventilation switch could be turned on to improve indoor air quality (Lin and Shiming, 2006).

In Singapore, a questionnaire survey was carried out by N.H. Wong. It was found that residents in the middle part of the building tend to be more dissatisfied with the thermal comfort situation, while the residents on the top floor hold a more positive opinion about that. However, a percentage of residents on the top floor held the opinion that the wind was too strong (Wong, et al, 2002). Though strong wind is usually annoying, it can also become positive factor in such hot climates as found in Singapore.

In Kuala Lumpur, Malaysia, two high-rise dormitory buildings were studied by onsite measurements. It was found that the temperature in the high-rise building rises with the height and is apparently higher on west side (Dahlan et al 2008).

In Hyderabad, India, the thermal comfort in naturally ventilated apartments was investigated for three months in 2008 by Madhavi (2010). It was found that adaptive opportunity is vital in thermal sensation. The percentage of subjects who voted comfortable on thermal sensation scale rose from 40% to 94%, when there was adequate chance to adapt to the indoor climate. Indian people can adapt well to the climate, when they wear the traditional cloth-lungi, which can be easily adjusted without changing clothes. The air velocity was found to remain at around 0.4 m/s most of the time, as the subjects had control over the environment (Madhavi, 2010).

2.8.2. Thermal Comfort in Tropical Countries

People modify their behavior and manage their building in response to change in climate (Krüger and Givoni, 2008; Brager and de Dear, 1998). Several studies (Nicol and Humphreys, 2010; Tanabe, 1988; Nicol, 1974; Humphrey and Nicol, 1970) showed that people tolerate higher temperature if the place has higher annual average temperature. Givoni's BBCC (Figure-2.5) works in accordance with this fact. According to Givoni (1992), people in hot countries, living mostly in non-conditioned buildings, are acclimatized to and tolerate higher temperature and humidity, showing a clear connection with affordability. Tanabe's work (1988) also shows that an increase in air speed also increase tolerance to higher temperature (Sreshthaputra, 2003).

To predict the comfort temperature zone in the climate of Bangladesh, Ahmed, (1987) proposed adaptation of Humphreys and Nicols' (1970) neutral temperature model, which was found to be better fitted for the local context of Dhaka division (Table 2.1).

Table 2.1: Monthly Comfort Zone for Urban Areas of Dhaka, Bangladesh.

Month	**Average Temp. (ºC)**	**Humphrey's (ºC)**	**Comfort Zone for Dhaka (ºC)**
Jan	18.7	18	16.0 - 20.0
Feb	21.2	20.2	18.2 - 22.2
Mar	26.3	24.4	22.4 - 26.4
Apr	29.0	26.6	24.6 - 28.6
May	28.9	26.6	24.6 - 28.6
Jun	28.6	26.3	24.3 - 28.3

Jul	28.6	26.3	24.3 - 28.3
Aug	28.6	26.3	24.3 - 28.3
Sep	28.7	26.4	24.4 - 28.4
Oct	27.2	25.1	23.1 - 27.1
Nov	23.4	22.0	20.0 - 24.0
Dec	19.7	18.9	16.9 - 20.9

According to Table 2.1, April presents the highest average temperature profile for urban areas of Dhaka, and the comfort temperature range during this month also shows a higher band, ranging for 24.6°C to 28.6°C. However, in another work of Ahmed (1994), the upper limit for comfort temperature of Dhaka was said to be at 29.3°C, under given humidity condition and still air.

Later Mallick's (1996) work, based on the Bedford scale and ASHRAE scale, on acceptable thermal comfort conditions in urban housing of Dhaka, showed that people could endure high temperature and very high humidity, and remain in comfort. Comfort temperature ranges, under still-air conditions, for people wearing ordinary clothing and engaged in a range of household activities was found to be between 24 and 33 °C. For air flow of 0.3 m/s there is a rise in the lower and upper limits of temperatures by 2.4 and 2.2 ° C respectively. There are instances where people have reported to be comfortable in humidity above 95%. At an air temperature range of 24 to 32 °C and relative humidity of 50 and 90%, people feel comfortable without or in little air movement (Mallick 1996).

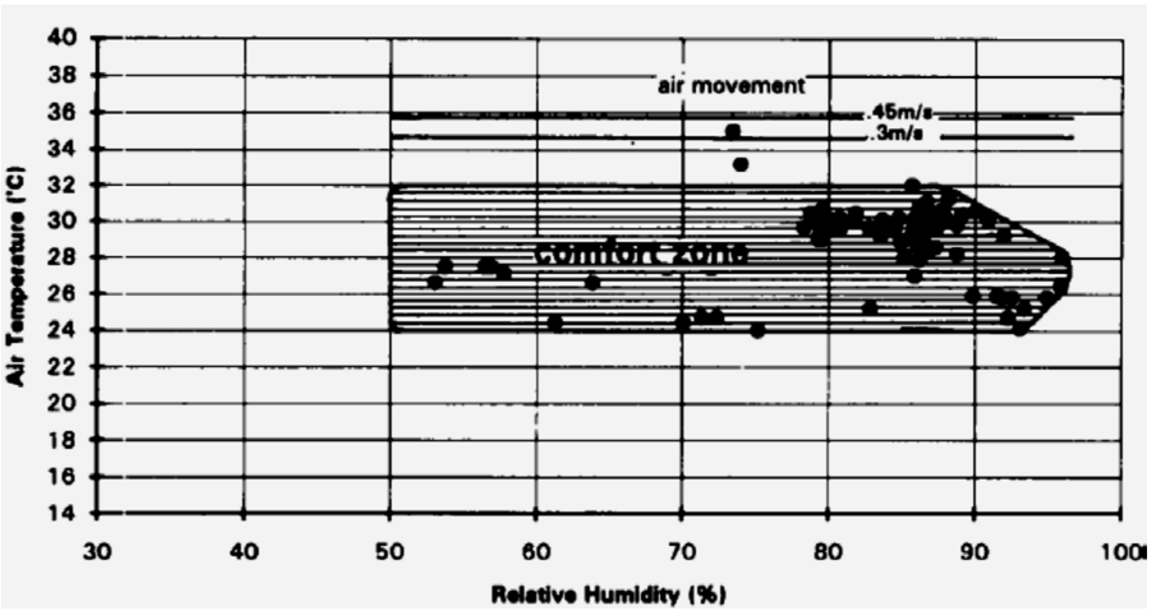


Fig. 2.6: Summer Comfort Zone for Bangladesh
Source: Mallick, 1994

A summary of the findings on comfort temperature discussed above are listed in Table 2.2. Since ASHRAE-55-2004, Olgyay's Bio-climatic chart, Givoni's Building Bio-Climatic Chart, and Mallick's work are all based on the adaptation method, and Mallick's work directly represents the context of Dhaka's non-conditioned apartment buildings, and a wider range is indicated, Mallick's work is used as reference comfort range in this research. Thus, the comfort temperature range used for this research is 24°C to 32°C, and temperature below 24°C is assumed to cool period temperature and temperature above 32°C is considered as warm period temperature.

Table 2.2: Thermal Comfort Range, based on Literature Review.

Study	**Min. - Max. Temp. (°C)**	**Humidity (%)**	**Wind speed**	**Clothing**	**Activity**
ASHRAE 55	17°C - 31.5°C				
Olgyay's Bioclimatic Chart (Olgyay, 1963)	20°C – 30°C		Upto 1m/s	1 clo	Sedentary
Monthly Comfort Temp. for Dhaka (Ahmed, Z. N. 1994)	24.6°C - 28.6°C ± 2.5°C	59% - 86%	(0.6 – 1.35) m/s		
Outdoor Summer Comfort Zone for Bangladesh (Ahmed K. S. 1995)	28.5°C - 32.8C°C	70%	Still Air	Summer clothing	Sedentary Activities or Stationary
Monthly comfort Zone for Summer (Mallick F. H. 1996)	24°C – 32°C	50% - 90%	Little air movement	(0.5 clo)	(0.8 - 1.2 met)
Assumed Comfort Temp. for Dhaka	24°C – 32°C				

In this research, the comfort temperature range for Dhaka's climate is assumed to be between 24°C to 32°C, and temperature below 24 °C is termed as cool temperature, and above 32 °C, as warm temperature, based on the data summarized in Table 2.2.

2.9. Importance of Simulation in Building Performance

Since the oil embargo experience in 1973, achieving better energy efficiency in buildings has become one of the world's major challenges. A considerable energy savings can be achieved from a conventionally designed building through careful planning for energy efficiency. The energy requirement of a building depends on the overall performance as an integrated system, where the individual performance of the envelope components such as walls, roofs and windows have major impacts (Hong et al, 2000).

The applications of simulation-based optimization have been considered since the year 1980s and 1990s, based on the rapid growth of computational science and mathematical optimization methods (Nguyen et al, 2014). Computational building evaluation tools have the potential to provide an effective means to support informed design decision making (Mahdavi and El-Bellahy, 2005). Several researchers pointed out that simulation should be an integrated element of the design process, performed within the design practice rather been used only for final performance confirmation (McElroy, 1999; Mahdavi, 1993; Holm, 1993; Augenbroe, 1992; Lawson,1990).

Simulation is the imitation of the operation of real-world process or system over time. The act of simulating first requires a model be developed; the model represents the system itself, consisting of the key characteristics and functions of the selected system or process, whereas the simulation represents the operation of the system over time (Banks et al, 2001). Since building analysis software has become more sophisticated, integrated, and easier to use, designers are faced with the opportunity and the necessity to improve the understanding of building performance, particularly, in terms of energy optimization. Consequently, simulation tools are now recognized as design support tools within the Architecture-Engineering-Construction (AEC) industry (Attia, 2010). The advanced analysis of building thermal simulation in building modeling programs, plays a significant role for designing high-performance buildings. The conceptual design phase of thermal modeling is used to provide the designer with first order of magnitude feedback about the impact of various building configurations on annual thermal performance (US GSA, 2010).

2.9.1. Simulation Study for Natural Ventilation

The methods for natural ventilation study to evaluate facade performance are categorized into three types: field measurements, controlled experiments and numerical simulations. Field measurements can only collect on site data from a few buildings, the locations of the instruments are restricted by on site conditions for the purpose of safety and security, and uncertainties of these measurements could be significant, thus making it difficult for further data analyses. Data obtained from a controlled environment, such as wind tunnel experiments and full-scale model experiments, are more reliable than those collected in field measurement. However, setting up and running these experiments are time consuming and expensive. The quality of the data acquired from experimental analysis is also limited by the accuracy of the instruments (Wang and Wong, 2009). Numerical simulation, rather, is a cost-effective and efficient approach to predict thermal performances of facades in naturally ventilated buildings.

Simulation methods for natural ventilation fall into two broad categories: Computational Fluid Dynamics (CFD) method and Building Simulation (BS) method. Building simulation can model heat transfer and radiation processes in seconds, based on heat balance methods, whereas CFD can predict reliable detailed airflow for outdoor and indoor. CFD simulation is a reliable tool for evaluation of thermal environment and contaminant distributions and provides detailed spatial distributions of air velocity, air pressure, temperature, contaminant concentration and turbulence by numerically solving the governing conservation equations of fluid flows. These results can be directly or indirectly used to quantitatively analyze the indoor environment and determine facade system performances (Wang and Wong, 2006). However, the application of CFD for natural ventilation prediction has been limited due to long computational time and excessive computer resource requirements. Moreover, solar radiation cannot be easily considered in CFD model and when grid size requirements for various computational domains are inconsistent, such as, indoor and outdoor airflow simulation and heat conduction and airflow simulation, CFD simulations require high computation cost.

BS tools basically include two fundamental modules: Dynamic Thermal Simulation (DTS) and Air Flow Network to solve the heat and mass transfer and airflow in the building systems. These tools rapidly provide predictions about thermal behaviors of facade, indoor airflow of the building and better understanding of the consequences of various design decisions, which greatly facilitates energy-efficient sustainable building design. However, BS programs assume the indoor air is completely mixed and uniform; so, BS results can only provide the uniform results for targeted spaces (Wang and Wong, 2008).

This study adopts both DTS and CFD analysis, as these two types of simulations together, can interpret the indoor thermal and air flow pattern, thus predicting the indoor thermal conditions of a building.

2.10. Conclusion

The primary concern of this chapter was, to develop an understanding on how window shape and proportion affects the rising energy demand in residential building, importance of operable window as a passive design element for ensuring natural ventilation, air exchange rate and night cooling and issues related to indoor thermal comfort in naturally ventilated building. The chapter also discussed about the importance of using building simulation tool as a means to identify various performance of building during the conceptual as well as design phase.

The process of determining window parameters is iterative in nature. Review of previous studies reveals that building layout, size and location of apertures, windows and doors, building orientation, and some vernacular elements are among the most applicable architectural elements for ventilation opening. The above studies specified that the variation of the window elements such as the orientation, glazing type, window-wall ratio, SHGC, and U-value affects the annual heating and cooling energy demand of the building. However, all these studies mostly involved buildings with mechanical ventilation. The value for WWR and WFR portrayed inconsistency, depending on the climatic condition, window orientation and shading device, the type of building use and on both glazing and other envelope materials. The importance of WFR and WWR, and identification of appropriate value for these variables, to modify indoor temperatures using natural ventilation, has hitherto not been investigated for the Dhaka's context. Based on these studies, frequent and repeated assessments were carried out to impart the specific combination of WWR and WFR, which can have substantial impact on indoor air temperature in naturally ventilated residential apartment.

Chapter 03: SETTING THE CONTEXT

This chapter will be discussing the context of this research, focusing on the climate of the region, the energy pattern of the inhabitants, and the apartment size preference by the middle-income group of Dhaka.

3.1. Bangladesh: An Overview

Bangladesh is a tropical country at the edge of Tropic of Cancer, lying between 20.34° N to 26.38 ° N latitude and between 88.01° E to 92.41° E. Except the hilly southeast, most of the country is a low-lying plainland, surrounded by land mass from three sides and the Bay of Bengal on the south. (Ahmed., 2006). The total area of Bangladesh is 147,570 sq. km of which 119,624 sq. km (81.0 %) is effective land area, 8,236 sq. km (5.6 %) is occupied by river networks and the forest area consists of 19,710 sq. km (13.4%) (BBS 2011). Bangladesh is also one of the world's most densely populated countries. The available statistics show that the total population of the country has increased by 72 million between 1974 and 2011, and the population density from 590/sq. km in 1981 to 976/sq. km in 2011 (BBS 1984 and 2012). If the current trend continues, the population of Bangladesh is expected to reach to about 194 million in 2050 (UN 2012). The ever-growing population in Bangladesh is currently placing enormous pressure on natural resources and energy. Landlessness and environmental degradation have become pervasive in recent times (Dewan and Corner, 2014). The pressure of urbanization creates ever increasing demand on scarce electricity and thus, designers need to give increased attention towards energy efficiency.

Fig. 3.1: Location of Bangladesh in the World Map
Source: www.worldatlas.com

3.1.2. Climate

Bangladesh has composite tropical monsoon climate (Ahmed, 1987), with wide seasonal variations in rainfall, generally warm temperatures and high humidity (Rashid 1991). From meteorological point of view, the year has been categorized into four seasons. They are pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November) and winter, which starts in December and ends in February. (Mridha 2002; Ahmed 1995; Hossain and Nooruddin 1993) (Table 3.1).

The pre-monsoon season, also known as summer, is the hottest part of the year, characterized by high evaporation rates. During the summer season (March to May) heating belt shifts northward due to apparent northward movement of the sun. The summer months experience high temperature and falling of air pressure over the country, resulting in strong gusty, hot, dry winds blowing during the day (Khatun et al, 2016). The mean temperature ranges from 27 to 31^{o}C, reaching the maximum in April, which is the middle of the pre-monsoon hot dry season. Average temperatures in April vary from about 27^{o}C in the northeast to 30°C in the extreme west part of the country. Rainfall varies spatially with the frequent occurrence of thunderstorms, which provide about 10–15 % of the annual total rainfall (Dewan and Corner, 2014).

The prominent features of wind climatology in Bangladesh are the circulations influenced by the strong southwest monsoon when warm and humid air moves towards the land. During the monsoon season, the persisting low pressure over northern Bangladesh intensifies and attracts the trade winds of the southern hemisphere. After that, it covers the whole of Bangladesh as a southwest monsoon (Khatun et al, 2016). Abundant rainfall occurs in the monsoon season with the influence of southerly or south-westerly winds. Temperatures drop with the onset of the summer monsoon, and approximately 75–80 % of total rainfall occurs during this season (Dewan and Corner, 2014).

In contrast, the winter season is cool and dry with little rainfall. The mean temperature in winter is 18^{0}C with the lowest being 3–5^{0}C in the northwest part of the country, and only 5% of annual rainfall occurs during this season. This is the sunniest period in Bangladesh with high solar radiation (Dewan and Corner, 2014). Clear sky, low temperatures, low humidity and light winds are the common weather phenomenon of the winter season. A gentle north-easterly land breeze blows over the terrain during the dry-winter season. (Ahmed, 2006; Khan et al, 2004).

Table 3.1: Average Monthly Maximum, Minimum and Mean Temperature from 1948 to 2010.

Season	Year (1948-2010)	Maximum (ºC)	Minimum (ºC)	Mean (ºC)
Winter	January	28.56	9.06	18.34
	February	31.80	10.65	21.27
Pre-monsoon (Summer)	March	35.64	14.60	25.55
	April	36.79	18.59	28.16
	May	36.59	20.31	28.71
Monsoon	June	35.44	22.37	28.48
	July	34.09	23.53	28.15
	August	34.31	23.68	28.26
	September	34.57	23.17	28.12
Post-monsoon	October	34.14	20.18	26.97
	November	32.13	14.91	23.50
Winter	December	29.14	10.82	19.89
	Yearly	37.67	8.79	25.43

Source: Hasan and Rahman, 2013

3.2. Dhaka

Dhaka City, the capital of Bangladesh, is located at the central part of the country, between latitudes 24º40´ N to 24º54´ N and longitudes 90º20´ E to 90º30´. The city has developed on the higher elevated Pleistocene terrace land or Order Alluvium of the central part of Bangladesh, otherwise referred to as the Madhupur-Bhawal Garh Region. In addition, a substantial portion of the adjoining low-lying areas have recently been brought under the structured zones of the city due to the accelerated rate of the urban growth in Dhaka. (Asaduzzaman and Rob, 1997). The city is bounded by the Buriganga river in the south; the Balu and the Shitalakhya rivers in the east; Tongi Khal in the north and the Turag river in the west (Islam et al, 2012).

3.2.1. Climate of Dhaka

Climatic characteristics of one city differs from others due to physical development such as surface qualities, density, heights (three dimensional objects) and other related factors and location, (Koenigsberger, 1973); in accordance to this fact, climatic characteristics of Dhaka city also differ from other cities of Bangladesh (Figure 3.2).

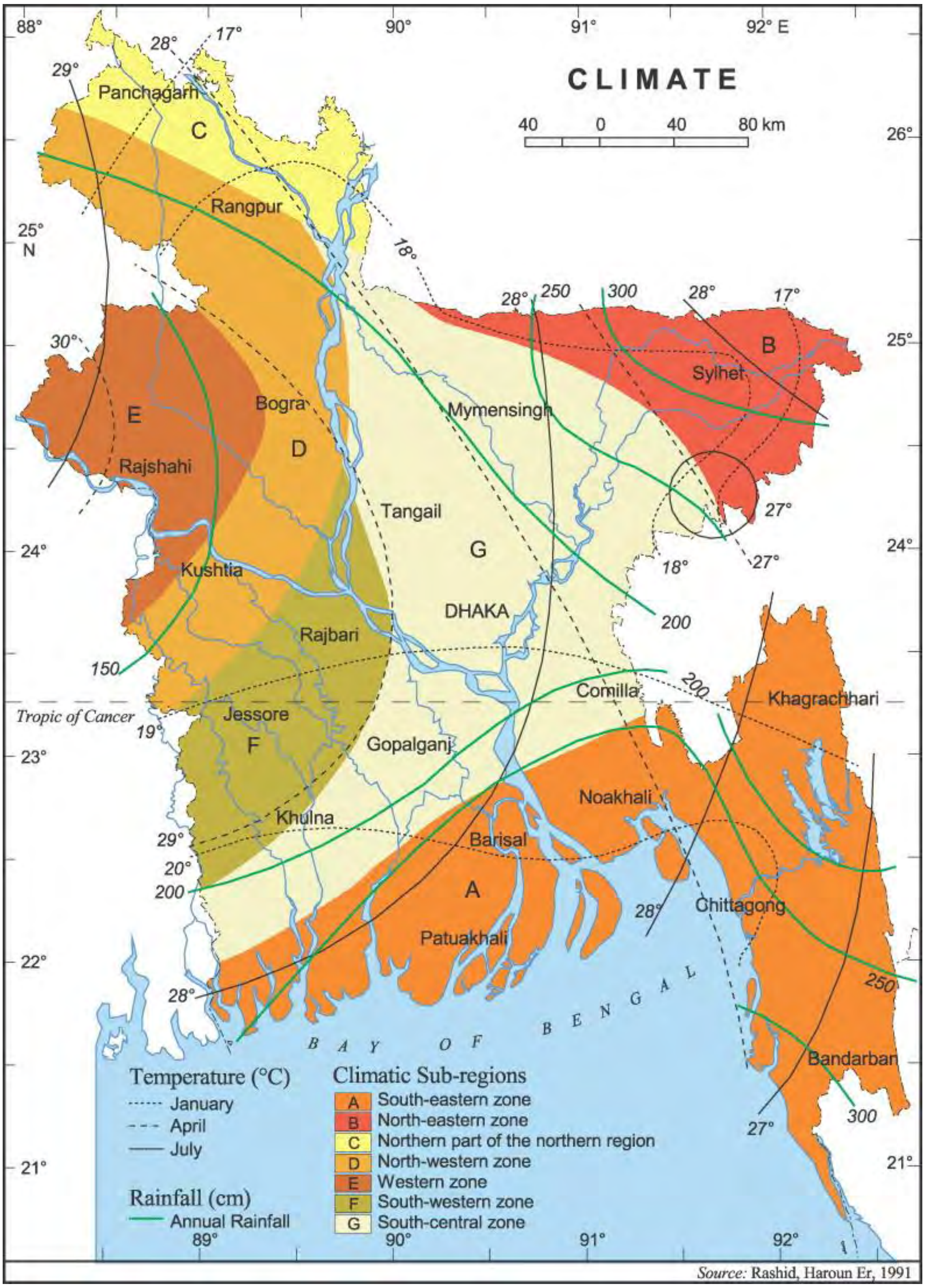


Fig. 3.2: The Climatic Sub Zones of Bangladesh
Source: Rashid, 1991

Table 3.2 shows that the maximum wind speed in Dhaka is found during the pre-monsoon (hot dry) season, attaining the maximum speed of 4.21m/sec in April (BMD 2016). The Table also shows that the monsoon season has the highest humidity record, whereas the cool dry winter has the least value, and the hot dry pre-monsoon period is the second least humid season. The monsoon season also accounts for the highest value of normal average rainfall in Dhaka.

Table 3.2: Wind Speed, Humidity and Rainfall Data of Dhaka

Dhaka's	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Av.
Normal Wind Speed (m/s)	1.23	1.60	2.59	4.21	3.80	3.70	3.64	3.21	2.24	1.28	0.93	0.92	2.45
Monthly Normal Humidity (%)	71	64	62	71	76	82	83	82	83	78	73	73	74.83
Average Normal Rainfall in mm	7.7	28.9	65.8	156.3	339.4	340.4	373.1	316.5	300.4	172.3	34.4	12.8	179

Source: BMD, 2016.

Average monthly maximum temperature is low during the winter period: December - February. Lowest maximum and minimum average monthly temperatures are found in January. Higher monthly average temperatures are observed in the pre-monsoon period: March - May, of which, April has the highest value (Mohiuddin et al, 2014).

In a study of Ahmed (1994), it is noted that maximum solar is received during April and lowest in December. The peak radiation on vertical surface is received by east facing wall in the morning. The south West facing walls receives direct solar radiation of high intensity in the afternoon. The south surface receives solar radiation almost the whole day, from 8am in the morning to 4pm, the intensity being highest at around 1pm. However, the west wall receives radiation during the later part of the day, yet the average intensity is almost double that received by the south wall and almost the same as that in the south west corner (Table 3.3). Solar radiation intensity is maximum at around 12 noon on horizontal surfaces and at 3pm on west surfaces. Beam radiation is also highest in April, showing maximum values at high solar altitudes (61% of global noon, compared to 44.1% at 06:00 hours) (Ahmed, 1994). According to the data retrieved from Bangladesh Meteorological Department, 7th April is found to be the hottest day of the year (BMD 2016, Appendix F). The daily maximum temperature is found between 2 to 3pm during the summer months (Ahmed, 1987).

Table 3.3: Direct Radiation in April in Wh/m^2

Hour	**Horizontal**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**
6	15	0	0	0	0	0	0	0
7	79	12	186	251	168	0	0	0
8	168	0	185	277	207	16	0	0
9	269	0	153	266	223	49	0	0
10	358	0	90	208	205	82	0	0
11	422	0	7	115	155	105	0	0
12	445	0	0	0	80	113	80	0
13	422	0	0	0	0	105	155	115
14	358	0	0	0	0	82	205	208
15	268	0	0	0	0	49	222	266
16	168	0	0	0	0	16	207	277
17	79	12	0	0	0	0	168	251
18	15	0	0	0	0	0	0	0
Total	3066	24	621	1117	1038	**617**	**1037**	**1117**
Average	128	1	26	47	43	26	43	47

Source: Ahmed, 1994

In a study of thermal environment in residential areas of metropolitan Dhaka, Roy depicted that clear sky, dry weather, higher solar altitude angle, higher solar intensity and higher duration of sun-shine hour have given April the status of 'hottest month' in this region (Roy, 2010). But according to the data retrieved during 2002-2008, pre-monsoon period accounts for higher maximum temperature in May (30.5 °C), while in the decade of 1950-1980, it was recorded in April (34.5 °C) (BMD, 2012), and from 2009- 2012, average temperature of April was also 34.5°C (BMD, 2016).

Thus, combining all these data, it can be interpreted from the data that, January is the coolest month and April is the warmest month for Dhaka city. Maximum solar radiation is received on the west surface and the south west corner but approximately for half of the day, whereas south wall receives solar radiation for almost the whole day, though its average intensity is half of that received on the west and south-west. (Mohiuddin et al, 2014; Ahmed, 1994)

During June to September (monsoon period), the average temperature remains steady at 28.6ºC. Coupled with high humidity values, this season also presents adverse thermal environments. Mean maximum temperature in monsoon period indicates relatively higher temperature over (31ºC) as compared to previous decade (BMD, 2012; Rashid, 2008) (Table 3.4).

The more current data for the year 2001-2012, shows some changes in magnitude of data, from previous sets of data (BMD, 2012). Figure 3.3 shows the monthly mean maximum and minimum temperature profile, for four time spans; 1950-1980, 1981-1990, 1991-2000, and 2001-2011. It is clearly evident that the annual average temperature is increasing with time, which also consistent with the regional data of Bangladesh (Mohiuddin et al, 2014; Tariq, 2014; Mridha, 2002).

Table 3.4: Air Temperature Profile of Dhaka City from 1950-2006, 2007-2012

Year	**Variables**	**Pre-Monsoon**			**Monsoon**				**Post-Mon.**		**Winter**			
		Mar	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Ann**
1950-1980	Mean Max Temp. ºC	32.6	**34.5**	33.0	31.4	31.0	31.1	31.4	30.8	28.7	26.0	25.5	28.5	30.4
	Mean Min Temp. ºC	19.7	23.5	24.8	25.8	26.2	26.1	25.9	23.7	18.2	13.3	11.7	14.5	21.1
	Ave. Temp. ºC	26.2	29.0	28.9	28.6	28.6	28.6	28.6	27.3	23.5	19.7	18.6	21.5	25.8
1981-1990	Mean Max Temp. ºC	32.4	**33.4**	33.1	32.4	31.5	31.9	31.9	31.8	29.9	26.7	25.8	28.4	30.8
	Mean Min Temp. ºC	20.5	23.5	24.6	26.3	26.3	26.5	26.0	24.0	19.3	14.7	13.2	15.8	21.7
	Ave. Temp. ºC	26.5	28.5	28.9	29.3	28.9	29.2	28.9	27.9	24.6	20.7	19.5	22.1	26.5
1991-2000	Mean Max Temp. ºC	32.6	**34.0**	33.2	32.7	31.8	31.9	32.1	32.0	29.8	26.6	25.0	28.0	30.8
	Mean Min Temp. ºC	20.6	23.7	24.7	26.3	26.4	26.5	25.9	23.9	19.2	14.0	12.7	15.9	21.7
	Ave. Temp. ºC	26.6	28.9	29.0	29.5	29.1	29.2	29.0	28.0	24.5	20.3	18.8	21.9	26.2
2002-2006	Mean Max Temp. ºC	27.5	29.0	**30.5**	29.8	29.4	29.5	29.0	28.0	24.3	21.0	19.8	24.9	26.9
	Mean Min Temp. ºC	24.5	27.6	27.9	28.4	28.6	28.7	27.7	26.9	23.5	20.3	16.3	21.9	25.2
	Ave. Temp. ºC	26.5	28.4	29.1	28.8	28.9	29.1	28.5	27.4	24.0	20.8	18.5	23.0	26.1
2007-2012	Mean Max Temp. ºC	32.5	**34.4**	34.2	32.8	32.2	31.9	32.4	32.1	29.8	25.6	24.3	28.2	30.9
	Mean Min Temp. ºC	21.6	24.5	25.2	26.3	26.6	26.6	26.4	24.4	19.7	15.5	13.2	16.6	22.2
	Ave. Temp. ºC	27.0	29.4	29.7	29.5	29.4	29.2	29.4	28.3	24.7	20.5	18.7	22.4	26.5

Source: BMD, 2016; Rashid, 2008.

Summer Months | Highest Temperature Record

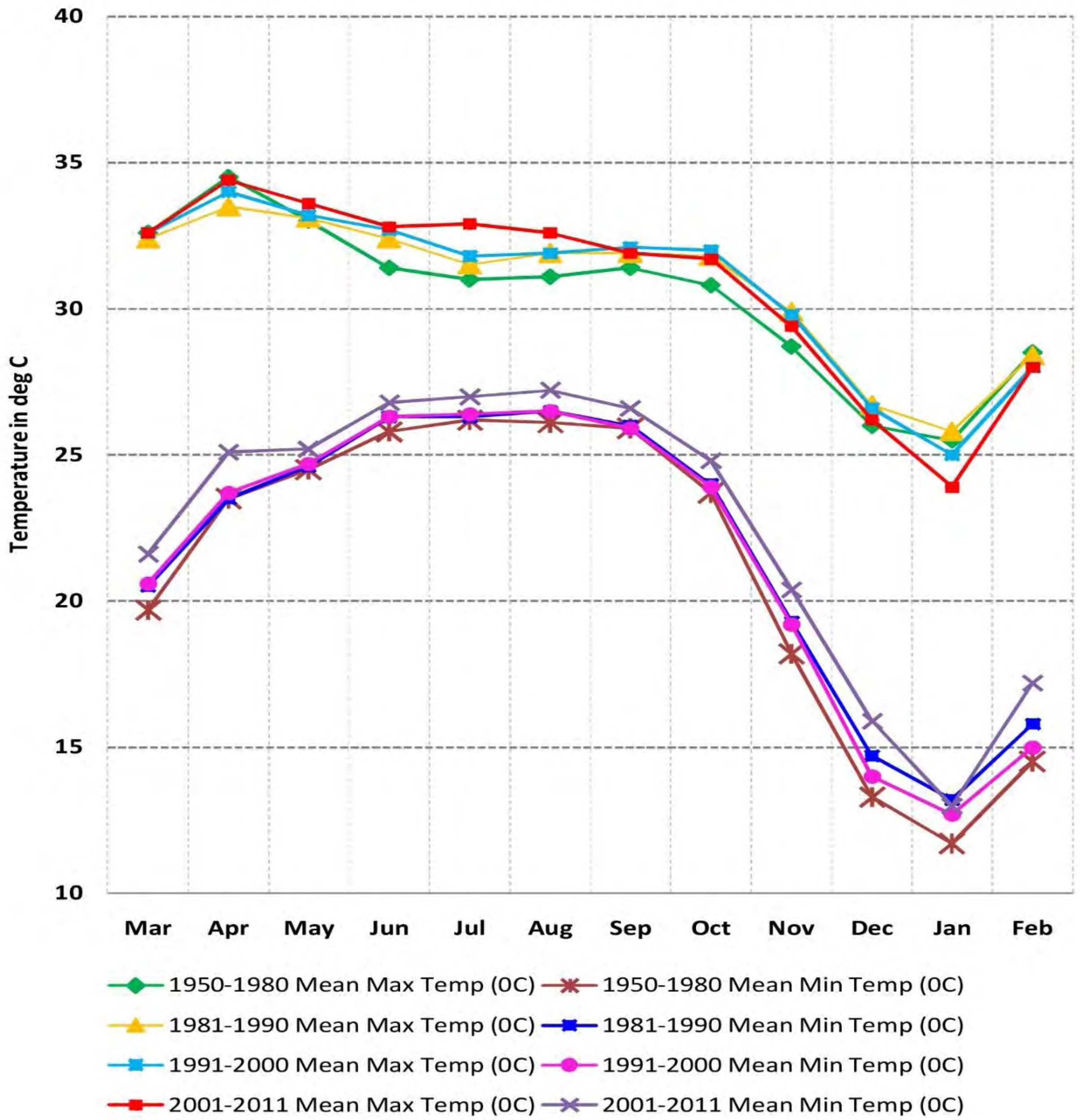


Fig. 3.3: Monthly Mean Maximum and Minimum Air Temperature Profile for the year 1950-1980, 1981-1990, 1991-2000, and 2001-2011
Source: Shahjahan, 2012

Rising temperatures is a growing environmental concern for Dhaka. Figure 3.3 shows the temperature trends during last 60 years (1950-2010) based on observed data of BMD (2012), where the maximum temperature follows rising trends. Mohiuddin et al., (2014) analyses the pattern of temperature change of Dhaka city over the period 1995 -2010, using the data of maximum and minimum monthly temperature. The study describes the probability of increasing maximum temperature by 6.8 °C in the next 100 years. During the pre-monsoon period, the average maximum temperature shows the inclination to increase following a trend of 2.2 °C rise in the 100-year period. The study also suggests that land surface temperature is increasing gradually because of urban development such as increasing built up area and earth fills or sand fills (Mohiuddin et al, 2014).

In a study of Mourshed (2011), current statistically averaged weather data for Dhaka, Bangladesh is morphed using climate model to generate future hourly time series of temperature in the 2020s, 2050s and 2080s. The result directs that higher temperatures occur more than lower temperatures, indicating an overall warming of the climate, which in turn will result in increased occurrences of building overheating; that is, temperatures above 28 °C occur for about 71.9% of the time of the year in the 2080s, compared to 31.0% in the present-day. This will result in continuous hot spells in future climates. This overheating and increased hot spells presents a challenge for energy efficient and low carbon building design and operation (Mourshed, 2011).

3.2.1.1. Temperature

Temperature is an independent climatic variable, whose variation causes corresponding changes in the pressure distribution both in the direction and velocity of wind, which controls atmospheric humidity, condensation, formation of cloud and their drifting in the sky, precipitation and storms. (Ishrat et al, 2013). Air temperature can be defined as the average temperature of the air surrounding the occupant, with respect to location and time. It is also the most important determinant of comfort which is measured by the dry bulb temperature (in degree Celsius, °C). A wide range of temperatures that can provide comfort when combined with the appropriate quantity of relative humidity and air flow (Tariq, 2014), Variation in the proper combination of these conditions can hamper human thermal comfort. To maintain the thermal balance, the body looses heat at lower temperature, and with higher temperature body gains heat by convection (Koenigsberger, 1973). The rate of convective heat exchange depends on airspeed (roughly proportional to the square root of the speed).

Extensive literature review and experimental findings suggests that there is a direct effect of the thermal environment on mental work (Wyon, 2000; Seppänen et al, 2004). The results of multiple studies on the effect of temperature are relatively consistent, and show that when the temperature is above 25°C, an average relationship of 2% decrement exists in work performance, per degree C (Seppänen et al, 2004). However, in the tropics, populations of different ages, are likely to have different thresh hold temperatures, before work performance is affected. Hence, a comfortable temperature must be attained inside residence to get maximum efficiency from the occupants.

Many research works investigated the future trends of ambient temperature by using statistical and stochastic models with various scenarios of GHGs emissions or of global warming, and predicted the impact of climate change on buildings' energy demand for heating and cooling (Wan et al, 2012; Xu et al, 2012; Mourshed, 2011; Wang et al, 2010;) or the impact on electric energy demand (Lebassi et al, 2010; Collins et al, 2010; Lam et al, 2010). The general conclusions are: temperature rise in the future increased frequency of extreme events, and future changes on energy demands of buildings for heating, cooling and electric energy. Changes in the ambient air-temperature will also have significant consequences upon cooling equipment performance, and the potential of using outdoor air for "passive cooling" (Papakostas et al, 2014).

3.3. Urbanization and Population Growth

Spontaneous rapid growth without any prior or systematic planning, has made modern Dhaka one of the most dense and populous Mega Cities in the world (Ahmed et al, 2009). Extensive administrative and infrastructure facilities, and extensive road and telecommunication networks is responsible for making the city the focus of urban expansion and the hub of economic activities. Due to its economic and sociopolitical significance, marginalized rural people are attracted to the area in the hope of better employment opportunities and improved lifestyles. As a result, Dhaka Megacity has turned out to be one of the fastest-growing cities in the world, primarily driven by explosive population growth (Dewan and Corner, 2014). At present, the population of the city is more than 14 million, with an average annual growth rate of 4.08 % between 1991 and 2001, (BBS 2008, 2012a, b) (Fig: 3.4 and 3.5); if the current rate of population growth continues, Dhaka's projected population will be of 22.9 million by 2025 (UN, 2012).

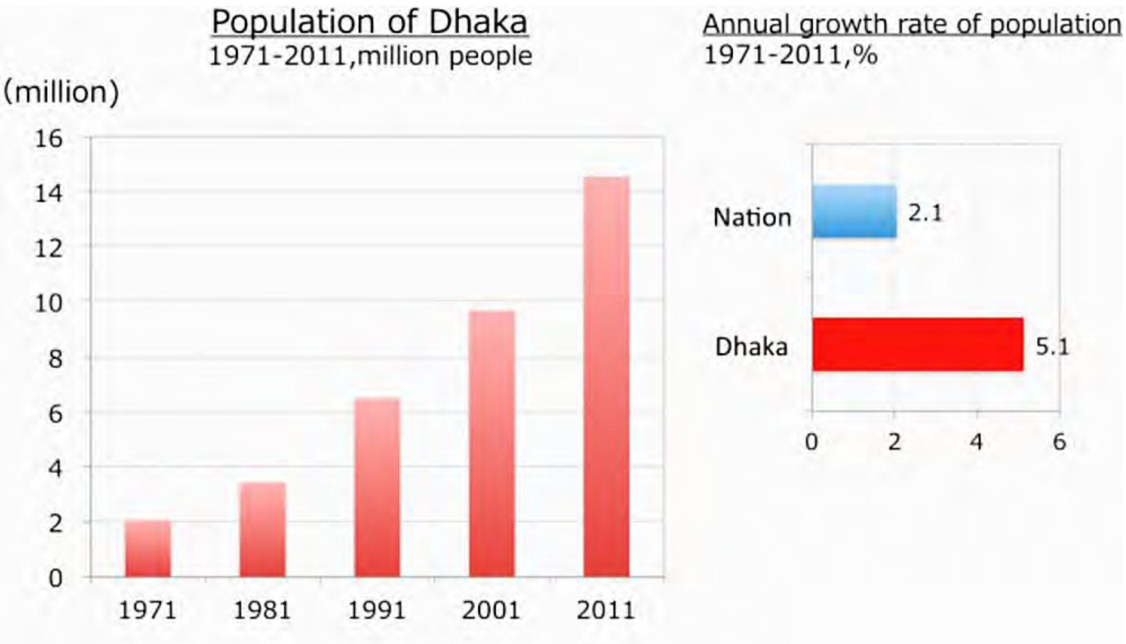


Fig. 3.4: Population of Dhaka and its Annual Growth Rate
Source: BBS 2008, 2012 (a, b)

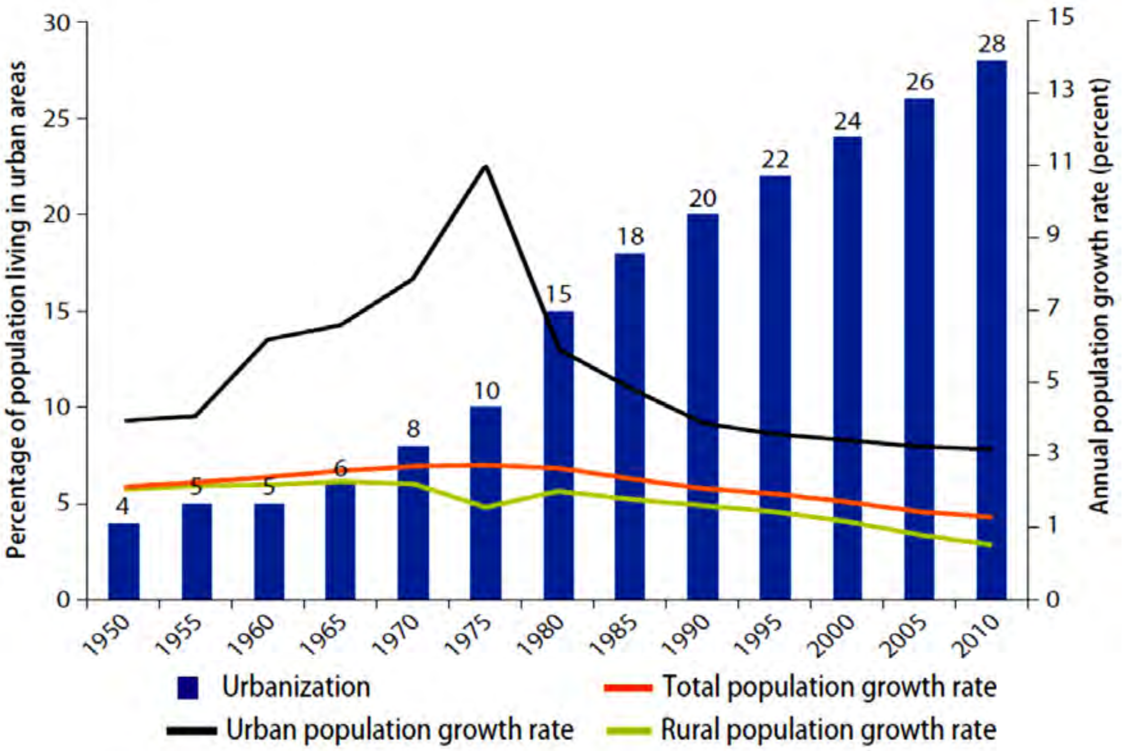


Fig. 3.5: Urbanization and Annual Growth Rates of Total Urban, and Rural Population in Bangladesh, 1950–2010
Source: UN, 2011

Figures 3.4 and 3.5 shows that both urban population and urbanization are growing faster in the cities of Bangladesh. With the growth of population, the need for housing has also increased exponentially, leading to land scarcity. Single ownership of land is changing to multiple ownership through apartment culture, creating high density residential areas, promoting mainly high-rise developments instead of low-density housing (Rahman, 2014).

As a consequence, the city has been experiencing significant environmental problems mostly due to the massive increase in population and unplanned development in the last few decades. Due to scarcity of suitable residential plots and growing demand for shelter, vertical expansion has become dominant (Begum, 2007; Mourshed and Mallick, 2012). Both vertical and horizontal developments have made the city a 'city of concrete' and vegetation cover has been greatly reduced in recent times (Dewan and Corner, 2014). Consequently, the local precipitation and temperature regimes have been changed (Alam and Rabbani, 2007). For instance, a long-term microclimatic study using time-series climatic data indicates that both maximum and minimum temperature have increased in response to rapid urbanization (Roy, 2010). Analysis of the normalized surface temperature values suggests that the temperature gradient between the built-up areas and their surroundings is more pronounced during the hottest part of the year.

3.4. Energy Status of Bangladesh

A rapidly growing country, like Bangladesh, needs a huge amount of energy to feed its large growth appetite. In the past decade, primary energy consumption increased over 100% and this trend is sure to continue. A recent work done by JICA shows the current sector wise energy demand in Bangladesh (Fig 3.6), where industry has the biggest share of 47.8%, followed by residence and transportation at 30.5% and 11.5%, respectively (JICA Report, 2015). Figure 3.7 shows energy consumption forecast of Bangladesh for 2030.

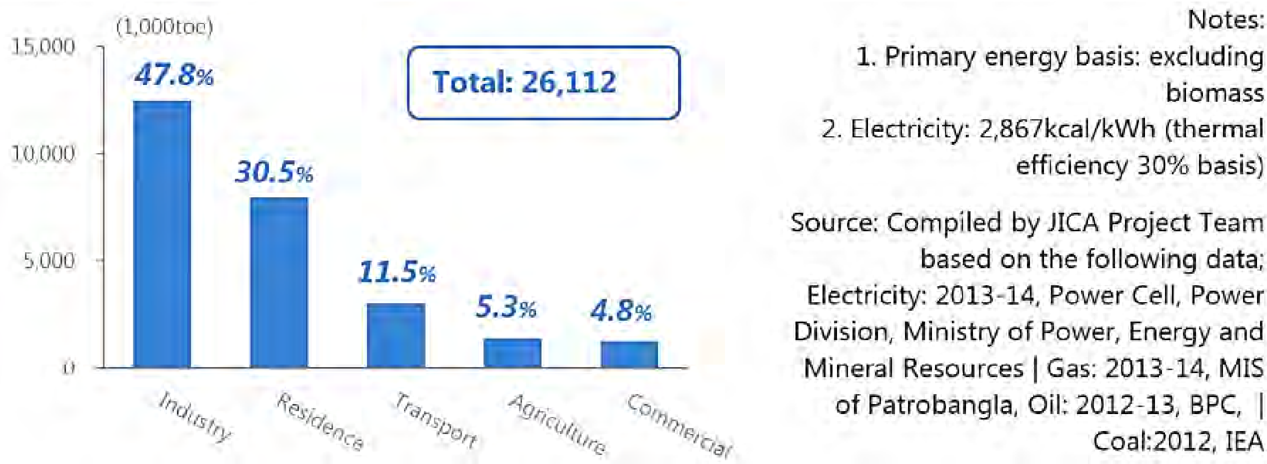
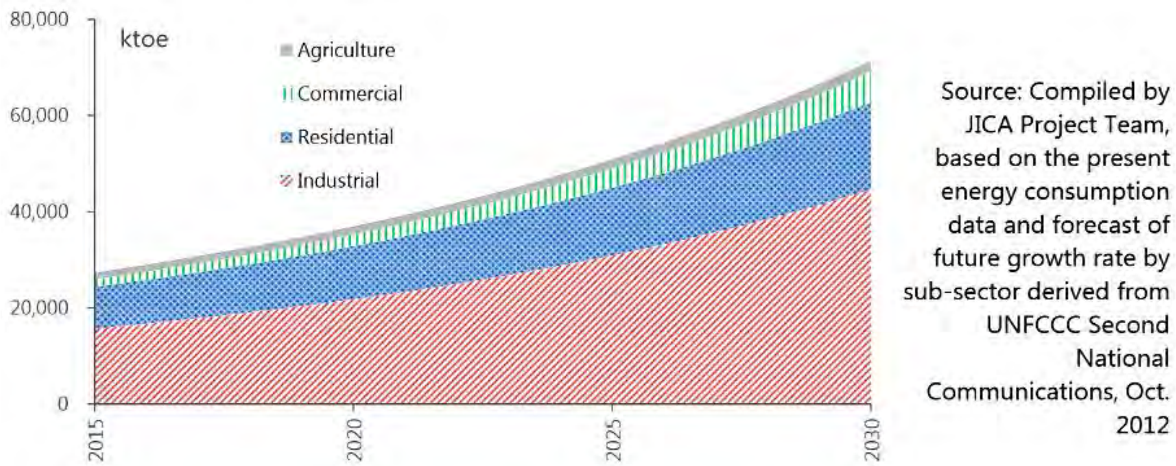


Fig. 3.6: Sector-wise Primary Energy Consumption of Bangladesh (2013 - 2014)
Source: JICA Report, 2015



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Industrial	15,678	16,724	17,854	19,075	20,394	21,822	23,366	25,038	26,849	28,812	30,940	33,247	35,751	38,469	41,421	44,627
Residential	8,772	9,187	9,625	10,088	10,577	11,094	11,640	12,218	12,829	13,475	14,158	14,881	15,646	16,456	17,313	18,219
Commercial	1,516	1,667	1,834	2,017	2,219	2,441	2,685	2,954	3,249	3,574	3,931	4,324	4,757	5,232	5,756	6,331
Agriculture	1,581	1,629	1,678	1,728	1,780	1,833	1,888	1,945	2,003	2,063	2,125	2,189	2,255	2,322	2,392	2,464
TOTAL (BAU)	27,548	29,207	30,991	32,908	34,970	37,190	39,580	42,155	44,930	47,924	51,154	54,642	58,409	62,480	66,881	71,642
TOE/GDP	184	183	181	180	178	177	177	176	175	175	174	174	174	174	174	174

Fig. 3.7: Primary Energy Consumption Forecast by Sector up to 2030
Source: JICA Report, 2015

Urban energy efficiency is essentially dependent on the energy efficiency of its buildings (Moushumi, 2010). Buildings accounts for at least 40% of the energy use in most countries in the world (UNEP, 2009). Rapid urbanization coupled with relatively weak planning control and building regulations results in compactly constructed buildings with inadequate thermal and/or ventilation performances, even in the present-day climates (Mourshed, 2011). The characteristics of dense residential developments in Dhaka have been investigated recently (Tariq, 2016; Rahman, 2014; Ali, 2007), in which the authors demonstrate how contemporary mid (=6 stories) to high rise (< 6 stories) buildings lack adequate open spaces to allow natural ventilation and lighting in interior spaces. As a consequence, buildings in Dhaka are expected to be adversely affected by any increase in temperature. Increased pressure on land for new buildings to house the influx of migrants from rural areas will worsen the situation (Ali, 2007).

The amount of energy consumption in buildings is rapidly increasing in the building sector in Bangladesh, especially in the city area with the pressure of new building construction. The energy demand of a building is influenced by a large number of variables, ranging from weather parameters (e.g., temperature, solar radiation, wind, moisture content of air, etc.) to the characteristics of the building (e.g., envelope, form, shape, materials, construction, etc.), the habits of its occupants (e.g., occupancy, activities, etc.) and its systems (e.g., type, performance, control schedules etc. (Mourshed, 2011). The urban micro climate, the urban geometry and building façades design, which affects the availability of daylight and air flow into the building, has a key role to play in determining residential energy use (Rattia et al, 2005). Residential energy end-use occurs mostly due to HVAC requirements, cooking, lighting, refrigeration and other uses for different electrical equipment (Moushumi, 2010).

The thermal performance of the majority of buildings in Dhaka is poor; e.g., single glazed windows without adequate solar shading. Hence solar heat gains are in excess of what can be efficiently tackled by natural or hybrid ventilation systems (Mourshed, 2011). The current energy consumption of ACs is 2237 GWh/year, which accounts for almost 50% of the total energy, while for fan it is 6181 GWh/year (JICA Report, 2015). The projected increases in temperature are likely to exacerbate the situation. As buildings have a typical lifespan of 50 to 100 years, prompt action to regulate the environmental performance of buildings are necessary to enhance the resilience of Dhaka's buildings to climate change (Mourshed, 2011).

There has been an increase in the demand for electricity in the recent years as a result of industrial development and population growth. More population means more consumption of electricity, but the generation of electricity is not increasing as required. With the improvement of the people's life standard, the demand for electricity has also increased. (Rahman, 2011). PSMP 2010 estimates that this intensity or elasticity of energy demand with GDP growth rate will continue to be 1.5% up to 2020. That means electricity demand will grow at a rate of 1.5 times of GDP growth rate (PSMP. 2011).

Therefore, an effective counter measure to mitigate this issue is needed. The electricity consumption by sector is shown in Table 3.5., where the residential sector accounts for the largest share. A recent study report of JICA depicts the individual home appliances electricity consumption. (Fig. 3.8).

Table 3.5: Sector-wise Grid Electricity Consumption of Bangladesh

	Residence	Industry	Commercial	Agriculture	Others
Electricity	51.66%	33.58%	9.30%	4.8%	1.33%

Source: Power Cell, Power Division, MPEMR, 2014

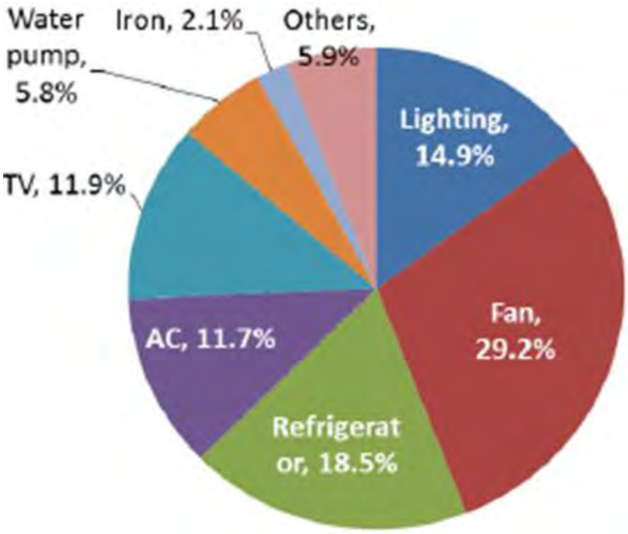


Fig. 3.8: Electricity Consumption of Home Appliances
Source: Energy Efficiency and Conservation Master Plan up to 2030, JICA, 2015.

Table 3.5 shows that the residential sector uses a major share of grid electricity, almost half of the generated amount. The household appliances like ACs, refrigerators and fans, mainly used for cooling, are responsible for the maximum electricity consumptions in residential sector (Fig. 3.8). Thus, if the use of these appliances, mainly ACs, can be replaced by natural means, the household electricity consumption can be reduced substantially.

3.5. Housing Demand of Dhaka

Dhaka is currently growing very fast compared to other cities in Bangladesh. The Population density is 20,000-135,000 persons per sq. km and the average occupancy per dwelling unit is 4.5 persons

(REHAB, 2012). The city is now accommodating 40% of the national urban population and around 50% people will be living in the cities by 2025, according to experts. About 40% of the city dwellers are said to be poor, 50% is of middle income range and the remaining 10% are of higher income group (Haque, 2008). Table 3.6 shows the monthly income range of different income groups of the city. The middle class is the broad group of people in contemporary society who fall socio-economically between the working class and upper class. Economists and real estate participants see the middle-income group as a huge market for the real estate sector. (Barua et al, 2010).

The huge increase in the urban density caused by the rush of rural people to Dhaka city and increasing house rent has created great demand of accommodation and housing services. Presently the city is expanding vertically and people are becoming used to living in multi-storeyed compact apartments within limited space. Broadly speaking, two types of apartment development can be noticed in Dhaka. Firstly, up to G + 5 storey buildings, usually of RCC frame structures, are walk up apartments. The second type of development are the high-rise apartment buildings, which are more than six stories (as defined by BNBC, 2006) (Kamruzzaman and Ogura, 2007). But the present regulations in Dhaka City allow twelve to twenty stories for buildings in this category (BNBC, 2006).

Although, the price of the apartment has increased in Dhaka, researchers found that need to live close to the work space and schools of their children are making the middle-income families inclined towards owning an apartment in this city (Begum, 2010; Zahur, 2007). In response to that, apartments are made affordable to middle income group by compromising the size, location and efficient climate-responsive design. Designer and suppliers are making adjustments with the cultural issues while making it compact to provide within affordable limit (Gomes, 2015). However, it is very difficult on the part of the government of Bangladesh alone, to ensure housing for all and meet increasing demand for shelter for the ever-increasing urban population. Here comes the need of private sector real estate development. Real Estate and Housing Association of Bangladesh (REHAB) is the only recognized formal organization for private sector real estate developers in Bangladesh (REHAB, 2016), and has, therefore, been used as the principle source of information about the housing sector in this research.

3.6. Apartment Location and Size Preference of Potential Buyers

Living in apartment houses is a pressing trend in the lifestyle of the citizens of Dhaka. (Hasan, 1991). The location and size preference for apartments varies, based on the income capacity, that is, affordability of the people. Residential environment and communication facility also guide the location and size choice for apartments, but in Dhaka, such preference is quite ambiguous. Family size, biasness due to pressure from relatives, living in the same area for long time, near to main road, are matters in choosing apartment sizes and preferring different locations (Labib et al, 2013).

Higher income groups prefer larger size apartments at prime location in the city, and are dependent on some specific developers; hence attracting them is always a challenge. Whereas, for upper-middle income and mid-middle income group, areas with better residential quality and better connectivity is required. (Labib et al, 2013). As a major portion of society belongs to the middle-income group, its demand is essentially high. (Barua et al, 2010). Middle and higher-middle income group are more eager to buy apartments (REHAB, 2012), as according to them having own plots and constructing house is beyond affordability in Dhaka (Seraj, 2012). The study of Labib et al (2013), depicts that after Mirpur and Uttara, buyers prefer Dhanmondi and Mohammadpur for buying flats. Another study conducted by REHAB (2012), reveals that real estate buyers mainly preferred planned residential areas, like Uttara, Mirpur, Bashundhara R/A, Mohammadpur and Dhanmondi, for living in apartments. Study conducted by Seraj (2012) asserts that planned residential areas like Uttara, Bashundhara, Banasri, Mohammadpur, have the maximum demand for apartments units, having floor area within $93m^2$ to $148.7m^2$, as these are mostly inhabited by middle and upper middle income groups in Dhaka city.

Based on a study of Seraj (2011), Table 3.6 shows different groups and their potentiality to buy apartments in Dhaka City. The lower and middle-income group, i.e. whose income ranges from BDT 20,000 – 40,000 and BDT 40,000 to 80,000, are more interested to buy apartments, but after long term saving. The higher-income group, i.e. earning BDT 80,000 to 1,00,000 or more, are keener to buy apartments within shorter span of time and sometimes even have the thought of buying a land also (Seraj, 2011 and REHAB, 2012). The upper-middle income and mid-middle income group are the highly potential groups, eager to buy apartments (Table 3.6).

Table 3.6: Different Income Groups and their Potentiality to Buy Apartments

Income group	**Income range (Monthly in TK)**	**Percentages**	**Remarks**
High income	80000-100000 and 100000+	20%	Potential group
Upper middle income	60000-80000	23%	Highly Potential
Mid-middle income	40000-60000	38%	Highly Potential
Low-middle income	20000-40000	19%	Low potential

Source: Seraj, 2011

In the study of Labib et al, (2013), the findings regarding buyers' apartment size preference revealed that, apartments less than 92.903 square meter are preferred by lower middle income group, 92.903 - 111.48 square meter for mid-middle income group and 111.48 - 148.65 square meter are chosen by middle-income group, while apartments above 148.65 square meter are considered for high income group. The study also found that the upper middle-income group people have the highest preference of buying apartments. Figure 3.9 shows that apartment size ranging from 111.48 - 148.65 square has the highest demand among the buyers, and also this size is mostly chosen by the upper middle-income group.

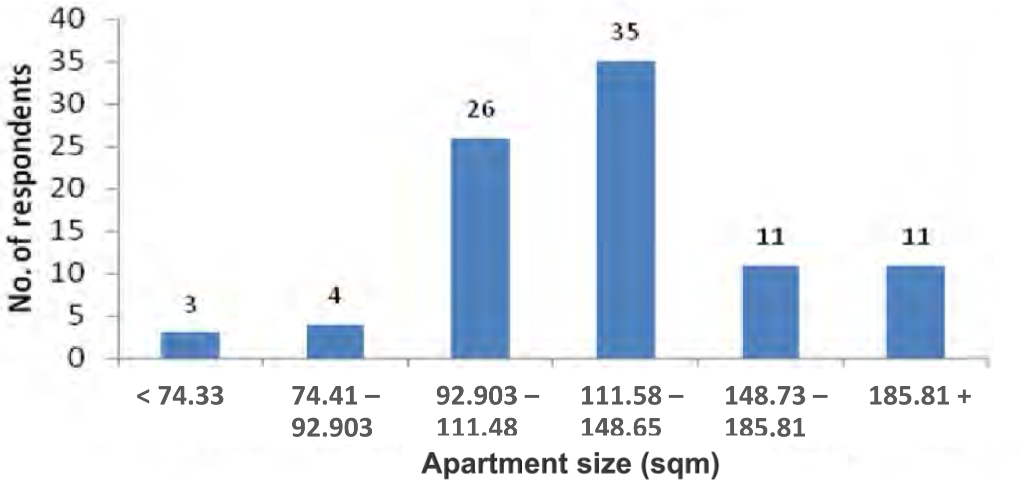


Fig. 3.9: Variation in Demand for Different Size of Apartments
Source: Labib et al, 2013

The middle-income group of the city constitutes the major portion of the society and they are more eager to buy apartments in planned residential areas rather than buying plots. The based on their affordability and ease of communication. The middle-income groups' most preferred locations for buying apartments are Mirpur, Uttara, Dhanmondi and Mohammadpur, and preferred apartment size ranges from 92.903 m^2 to 148.65m^2.

In this study, Lalmatia residential area has been selected as the study location. Lalmatia is a planned residential area, situated between Mohammmadpur and Dhanmondi, two of the most preferred planned residential areas by the middle-income group for buying apartments there (Seraj, 2011; REHAB, 2012 and Labib et al, 2013). The building, used for field survey, is located in Lalmatia. This building has been selected because of its ease of accessibility and proximity to the researcher (explained in detail in Section 4.3).

3.7. Conclusion

The primary concern of this chapter has been to develop an understanding of the context of the study, beginning with the present climatic situation of Dhaka, its past changes and potential future impacts on this region, through a range of national and international studies. This helped in identifying the appropriate critical period for environmental assessment of this research. Another major concern for this analysis is to comprehend the current population growth and the rising energy demand in residential sector of Dhaka city. Established related studies have been reviewed to categorize the most expanding income group of Dhaka and their preference for apartment size and location. This analysis facilitated to select the standard apartment size and location for the case study phase (Section 4.2), where typical window size and location in such apartments can be identified. The findings, related to climate of Dhaka, were essential because these were used as the basis of inputs in the thermal simulation phase (Chapter 5) for detailed analysis.

Chapter 04: DATA COLLECTION

4.1. Research Methodology

The study was conducted in three main phases. The first phase consisted of literature review (Chapter 2 and 3), the second was the data collection phase followed by the third phase, the simulation (Chapter 5). This chapter deals with the second, i.e. data collection phase.

The second phase is divided into two sub phases (Table 4.1): the first phase being an investigation on twenty randomly selected high-rise residential buildings, constructed by Real Estate and Housing Association of Bangladesh (REHAB) enlisted developers (REHAB, 2015). This was done to identify the general characteristics of a typical high-rise residential apartment, ideal for upper-middle income group of Dhaka. Apartment size, location, activity pattern, master bedroom location and size and window specifications were determined from the data collected in three phases. Initially a questionnaire survey on five REHAB enlisted developers were done, followed by assessment of the twenty randomly selected plans of residential buildings, constructed by REHAB enlisted developers, and finally through interviewing REHAB members, developers, architects and other stake holders. The data was then assessed to identify a typical case, which would be converted to use as input of Dynamic Thermal Simulation models, constructed and simulated in Ecotect.

The second sub phase involved fieldwork, consisted of temperature measurements inside a case study and an interview of the residents of the studied building. The study was conducted inside a master bedroom, located at the south-west corner of a south facing apartment, on the topmost floor of a multi-unit residential building. This is assumed as representative of apartments for high-rise residential buildings that house the upper middle class of the city. Quantitative and qualitative data were collected from the case study building. All the information analyzed during this phase, were intended to fulfil the structure, outlined in theoretical framework formed in the first phase. Secondary sources such as articles in local newspapers, or in the internet, were also used to complement and cross-check the information. The fieldwork was done during April, the hottest month, later in May and also in January. Temperature readings inside the apartment were taken using data loggers, while outside temperature data was collected from the met office, for the same time. These readings were compared with the simulation results for subsequent validation.

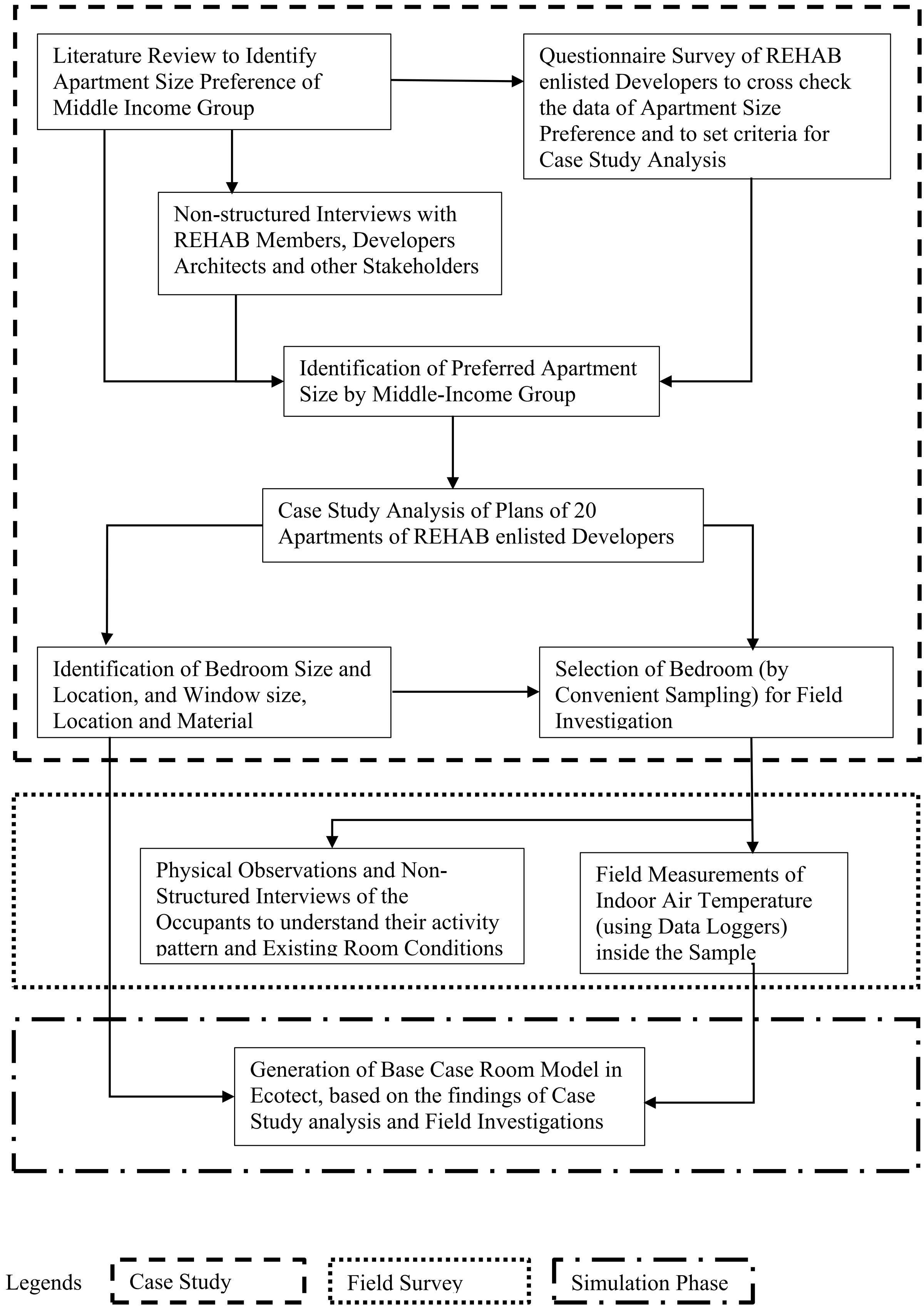


Fig. 4.1: Structure of Data Collection Phase

4.2. Case Study Analysis

The first phase of data collection for research was case study analysis, which is collective in nature. The steps of this phase are discussed in detail in Section 4.2.

4.2.1. Selection of Case Study

In this part of the research, 92.903 sqm to 148.65 sqm sized apartments (as identified in Section 3.6) of multi-unit residential apartments, that house upper middle-income groups, were the primary case of analysis. Each such apartment is representative of typical three-bedroom apartment of high-rise multi-unit residential building in Dhaka. The height of the buildings surveyed ranged between 23m to 32m (7 storeys to 10 storeys), which according to BNBC (2006), is termed as high-rise. Only those apartments were chosen which had architectural drawings available, and the apartments were accessible, with the households being cooperative.

4.2.2. Data Gathering Strategies and Issues Investigated

Twenty apartment buildings of renowned developers, enlisted in REHAB's data, comprising the identified apartment size, were randomly analyzed coupled with interviews, to identify the approximate size, location, activity pattern and the window specification of the master bedrooms (Appendix B).

Data gathering strategies were divided into a mixture of qualitative and quantitative approaches. The following different combinations of data gathering strategies were adopted:

- Qualitative and quantitative semi-structured interviews, (Appendix A) that have open and closed questions, with designated REHAB members, project architects, engineers and contractors to identify the following:
  _ Preferred size and location of the apartments, bought by the upper middle income groups.
  _ Typical master bedroom size and location in such apartments.
  _ Window and door locations and sizes inside such bedrooms.
  _ Window and door material specifications.

- Qualitative and quantitative analysis of architectural drawings (Appendix B) to identify:
  _ Typical master bedroom size and location in such apartments.
  _ Window and door location and size inside such bedrooms.
  _ Window and door material specifications

- Photographs and three dimensional images of the case study buildings (qualitative and quantitative)

4.2.3. Specifications of Typical Bedroom inside 92.903 sqm to 148.65 sqm Apartment

From the case study phase, some quantitative design aspects of the typical master bedroom of apartments, preferred by the middle-income groups, were investigated. These findings were used as the basis for choosing the specific bedroom sample for the field investigation part in Section 4.3, and also as inputs during modelling of the base case bedroom in Ecotect (Chapter 5). The specifications are as follows:

- Bed room area and height: 3.66m X 4.57m, 3.05m (clear height: 2.896m)

- Construction Material:
  _ Concrete slab (0.153m)
  _ Concrete beam (0.305m X 0.61m)
  _ Concrete column (center to center av. span: 0.56m)
  _ Plastered brick wall
  (Exterior wall: 0.25m with 0.019m to 0.025m plaster on both side;
  Interior wall: 0.127m with 0.019m to 0.025m plaster on both side)

- Door
  _ Swing Door: (Wooden door: Burma Teak and
  Flush Door: Hollow core plywood)
  _ Sliding Door: Single Glazed Aluminum Door

- Window (Fig: 4.2)
  Single Glazed Sliding Window
  _ Type: Sliding
  _ Size: 1.676m X 1.372m (economic size, as found on survey)
  _ Frame: 0.032m Aluminum Frame
  _ Glazing: 6mm Clear or Tinted Glass
  _ Location: Central (preferable, as found on survey)
  _ Sill Height: 0.153m – 0.762m
  _ Lintel Height: 2.134m – 2.439m
  _ Shading Depth: 0.508m (minimum, as mentioned in BNBC, 2006)

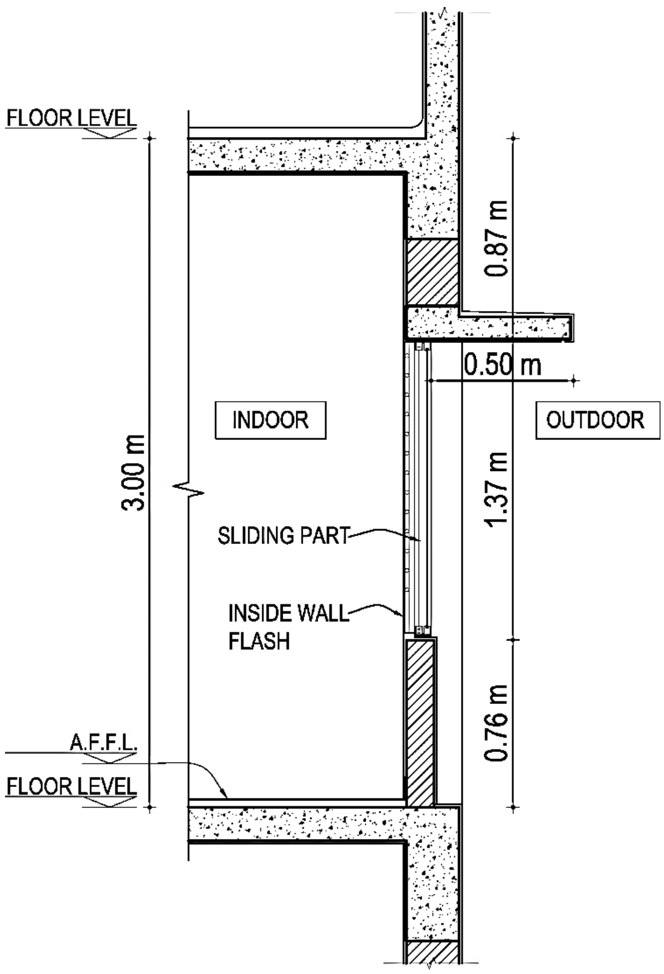


Fig. 4.2: Typical Window Section of Residential Building (Not in Scale)
Source: Survey Findings

The above identified data were assumed to be standard for a typical master bedroom, generally resided by the upper middle income group of Dhaka city. These data were then analyzed and used for convenient selection of an apartment building comprising the identified apartment size. A field investigation was conducted on the prevailing indoor air temperature inside the selected master bedroom. The data from both case study and field survey were later used as a basis for the inputs during simulation model construction, as well as the dynamic thermal simulation and computational fluid dynamics analysis.

4.3. Field Investigation

According to Ryken, et al. (2007), "field investigations of the environment involves the systematic collection of data for the purposes of scientific understanding. They are designed to answer an investigative question through the collection of evidence and the communication of results; they contribute to scientific knowledge by describing natural systems, noting differences in habitats, and identifying environmental trends and issues".

For conceptual clarity, the study of Ryken et al. (2007) have identified three types of field investigations—descriptive, comparative, and correlative. Descriptive field investigation involves describing and/or quantifying parts of a natural system. Comparative field investigations, involve collecting data on different populations/organisms, or under different conditions. Correlative field investigations involve measuring or observing two variables and searching for a relationship.

In descriptive field investigation, multiple measurements over time or location are taken in order to improve system representation (model). Individual measurement is repeated if necessary to improve data accuracy. In this type of field investigation record, data are organized into tables or other forms. The type of field investigation employed in this part of research is descriptive. The field investigation also included physical observations of the surveyed unit and one-to-one interview with the occupants of the surveyed room.

4.3.1. Objective of the Field Investigation

In the field investigation part, hourly temperature measurements of indoor air temperature, were taken inside the surveyed room, in three different months of the year, covering hot and cool dry seasons.

The field survey and subsequent analysis were carried out for the following criterion:

- To understand the living pattern and typical 24-hour activity carried out by the occupants of the surveyed room.
- To identify the existing indoor air temperature range inside the case study room during various activity state of the occupants.
- To compare the indoor air temperature and outdoor temperature in naturally ventilated state.
- To obtain a set of indoor air temperature data for comparing with the data produced in dynamic thermal simulation, during the same time period, when the field investigation was carried out, under similar indoor condition, using identical construction material.
- To validate the simulated values for the indoor air temperature of such room model, with the measured values in existing case.

4.3.2. Sample Selection

The study adopted a convenience sampling method. It is a type of nonprobability or nonrandom sampling, where members of the target population that meet certain practical criteria are included for the purpose of the study (Dörnyei, 2007). The information can be readily collected from the participants who are easily accessible to the researcher, assuming that the members of the target population are homogeneous (Saumure and Given, 2008; Palinkas, et al, 2013).

Based on the findings of the case study analysis and literature review, a residential building of height G+7 was chosen, using convenience sampling. The building is selected as a representation of the high-rise residential building, that houses upper-middle income people of the city. It is located at Lalmatia, residential area of Dhaka. Its apartment sizes range from 117.058 to 146.787 sqm approximately, which agrees with the preferable apartment size, identified in the case study section. It was easily accessible, both in terms of geographical proximity, as well as the availability and willingness of the dwellers to participate in the research work. This helped to monitor continuously the readings from data loggers, and also to avail any necessary settings needed for the readings to be accurate, according to the requirement of the research. Easy accessibility and close proximity of the surveyed building, facilitated repeated physical observations of the surveyed room and frequent interviews with the occupants, which were done prior to the field measurements of temperature were taken.

4.3.3. Overview of the Field Investigated Building

The building is located in Lalmatia residential area (Fig. 4.3 and 4.4), an upper-income neighborhood, located at the heart of the city. Lalmatia is planned residential area, and is surrounded by Mohammadpur and Sher-e-Bangla Nagar to the north, Raja Bazar to the east and Dhanmondi and Rayerbazar to the south. The area is within walking distance of Bangladesh's National Assembly Building.

Fig. 4.3 and 4.4: Location and Google Image of the Studied Building
Source: Google Map and Google Earth, 2016

Fig. 4.5: Image of the Surveyed Building

The case study building (Fig. 4.5) is a typical eight-storied, multi-unit residential building, with three apartments on each floor, housing twenty-one households. This type of multi-unit residential building is popular in Dhaka, because of the increasing pressure on land, and the dynamic changes in the urban lifestyle. Due to scarcity of land, old single-family houses are being demolished and in its place, residential buildings are being built by developers. The process of constructing a building begins as the owner of a particular plot of land gives the land to a developer under a contract. In return of the land value, the owner usually gets 30%- 60 % of the apartments, that the developer would construct on that land. The developers sell the remaining apartments to prospective clients. For reasons of profitability, both parties (developer and land owner) aim in constructing as many units / apartments per floor as possible. In this case, the owners of the land got eight apartments out of 21. Thus, apartments in this building are resided by both owners and tenants. The residents of the first floor are the owners of the building.

The three different apartments /units in the building are: Type A, Type B and Type C (Fig. 4.6 and 4.7). The sizes of apartments Type A, B and C are 146.787 sqm, 117.058 sqm and 117.058 sqm respectively. Type A is surrounded by a vacant plot on the southern side, and by residential buildings on the western and eastern side. The access road is on the northern part of the plot, along Type B and Type C. The plot is the third one from the node. The topmost apartment of the southern side of the plot, named A7, was surveyed.

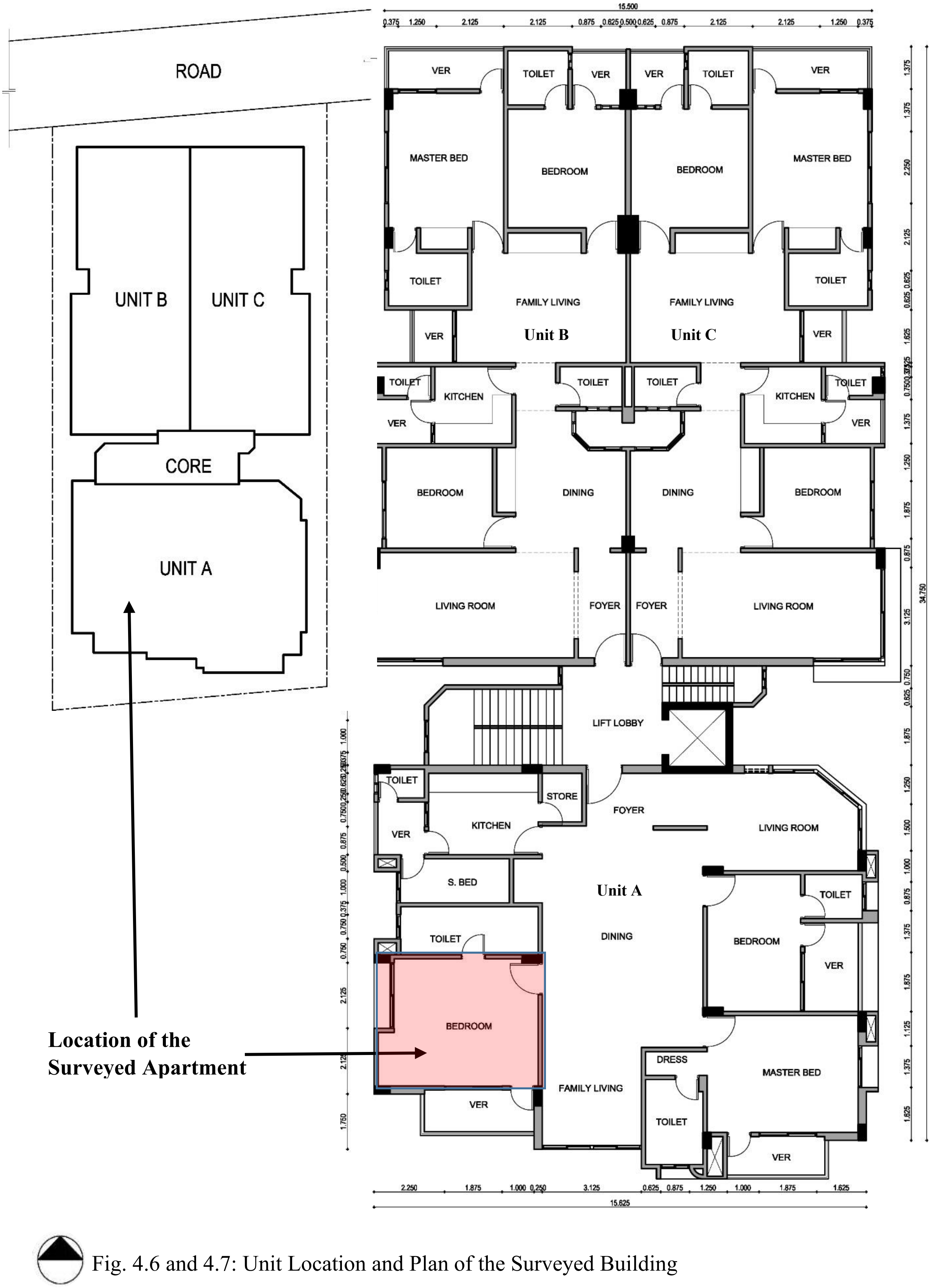


Fig. 4.6 and 4.7: Unit Location and Plan of the Surveyed Building

4.3.3.1. Features of the Surveyed Room

The master bedroom (Fig. 4.8) of interest, is located at the south-western part (as this is supposed to be the hottest corner, Section 2.5.1 and Table 3.3) of the apartment on the topmost floor (7th floor). The topmost floor was chosen as maximum direct sunlight is received on the topmost floor in tropical countries, (Section 2.5.3). It is 3.658m X 4.572m in area and 3.048m in height, the clear height being 2.896m. The room has an attached toilet at the east side, and is located beside the family living, having a verandah on the south. The room has one main entrance door of 1.016m and two 0.762m doors, one for the verandah access and the other for toilet.

There are two windows in the room, both centrally located, one on the west wall and the other at the south wall, beside the verandah. Both of the windows are of same size, 1.372m X 1.676m, and located centrally on the wall, the sill and lintel level being at 0.762m and 2.134m respectively. The room has a ceiling fan, hung centrally; a fluorescent tube light and two wall brackets (Fig. 4.9). Apart from the electrical fixtures, a 0.813m LED TV and two cell phones are usually used inside the room, mostly during the occupancy hour (7pm to 7am).

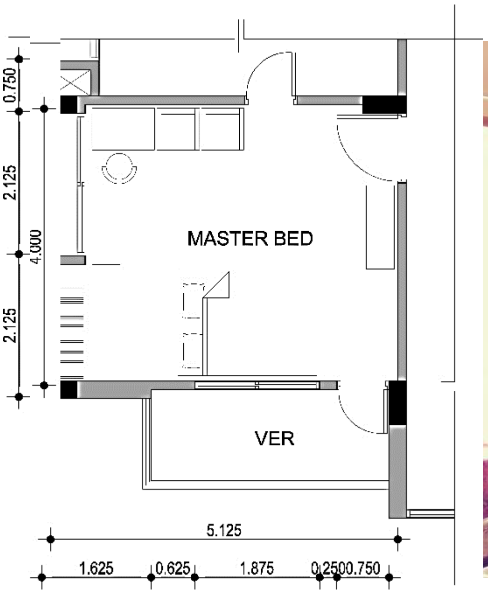


Fig. 4.8 and 4.9: Plan and Interior Image of the Surveyed Room

The room ceiling consists of 0.152m concrete casting and 0.025m plaster (approx.) cover. Typical masonry used in the room, are mainly baked clay brick of 0.121m thickness with 0.0191m plastered. The walls are coated with plastic paint of light pink color, and ceiling is painted using cream color distemper. The floor consists of 0.152m concrete casting, finished with ceramic tiles. Flush Door

(0.038m thick hollow core plywood) is used as the main entrance door of the room. The door leading to the toilet and verandah are of 0.038m thick solid core Burma Teak. The windows are single glazed, with a 6mm tinted pane surrounded by 0.032m aluminum frame and have 0.508m wide exterior horizontal shading device.

4.3.4. Instrument Used and Its Location Inside the Surveyed Room

A data logger, named iButton, was used to take the temperature measurements inside the investigated room. The specifications of the data logger are given on Appendix I. The data logger was placed in a holder, and hung across the room in a central position, using four white strings, as shown in Fig. 4.10 and 4.11.

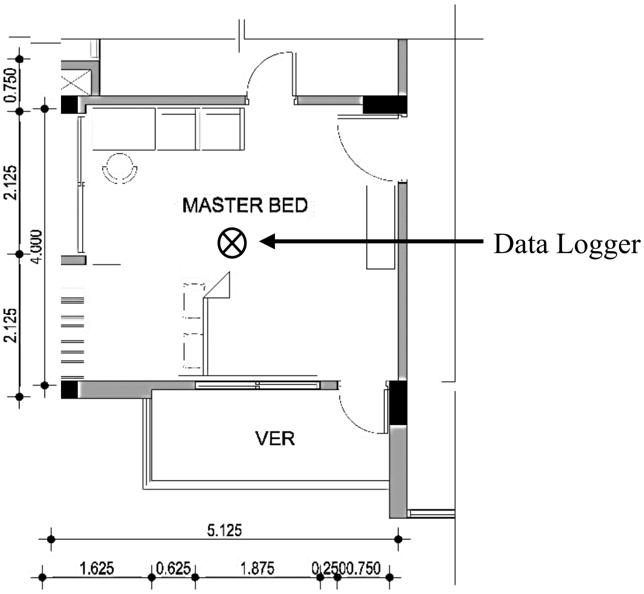


Fig. 4.10: Location of Data Logger in Plan

Fig. 4.11a: Blow-up Position of Data Logger

Fig. 4.11b: Data Logger's Position inside the Room

4.3.5. Data Gathering Strategies

A temperature data logger (available at www.maximintegrated.com), cited in Appendix I, was used to record the 24-hour temperature inside the surveyed bedroom, at intervals of 1hour, for the last ten days of April (21 to 30), first 10 days of May (1 to 10) (summer months, Section 3.2.1) in 2016 and later on, for mid-10 days January (11 to 20) in 2017 (Appendix E). Hourly readings of multiple days of the three different months were taken to improve data accuracy. The data logger was installed inside the room using thin string (Fig 4.12), hung at a height of 1.067m, the seated height, as bedrooms are mostly used for sleeping, resting, or moderate work at seated state.

Along with the detailed temperature measurements, qualitative and quantitative physical survey (Appendix C and D) of all the apartments (of identified size) of the building, selected for field measurements, were done to understand the daily activity and living pattern of the occupants.

4.3.6. Issues Identified during Physical Observations and Interview with Occupants

From the physical survey, the following issues were revealed through numerous observations and several non-structured interviews with the occupants of the room (Appendix C and D).

- Number of occupants of the room: 02
- General living pattern of the occupants of the room: Both the occupants, the husband and the wife, were service holders.
- Ventilation Type: Natural ventilation, no AC installed, but during the hotter part of the year, ceiling fan is turned on as soon as the room is occupied.
- Type of activity usually carried out inside the room: Sitting and watching TV or reading, resting, sleeping and sometimes light work.
- Room occupancy time and duration: 50% time during weekdays, that is, 7pm in the evening to 7am in the morning, and around 90% during weekends
- Common electrical appliances used inside the room: 0.813m LED TV, 1.42m Ceiling Fan, 1.219m long Fluorescent Tube Light (mostly used), two wall brackets (rarely used) and 2 Smart Phones.
- Window opening time and duration: Same as the Occupancy hour (Occupants open window just after entering the room, coming back from work place, at around 7pm, and closes before leaving for work, at approximately 7am).
- Window aperture size due to drape used (fully or partially covered drape): Mostly covers half of each window during the occupancy hour.

- Fan operation duration and tentative fan speed: Fan is usually at highest speed during the occupancy hour in summer days and at moderate to low speed, even switched off, at lower temperature period of the year.
- Door status: Mostly kept open, both during the day and night and no drape used.

4.4. Conclusion

The overall strategies for data collection phase have been described in this chapter, along with the detailed procedure for case study selection and field measurements. Twenty randomly selected buildings constructed by REHAB enlisted developers, with apartment size between 111.484 sqm to 148.65 sqm, were analyzed to determine the approximate size, location, activity pattern and window specifications, of the master bedroom of interest. The above identified data were assumed to be standard for a typical master bedroom, generally resided by the upper-middle income group of Dhaka city. These data were used for convenient selection of a similar apartment building, comprising the identified apartment size. A field investigation was conducted on the prevailing indoor air temperature inside the master bedroom. These set of data were further used as a basis for the inputs during simulation model construction as well dynamic thermal simulation (elaborated in chapter 5). The data obtained from field measurements and the simulation result for the same, were finally compared for validation of the software, used for comprehensive simulation. The description of measuring instruments, used in the field survey have also been included in this chapter.

Chapter 05: SIMULATION STUDY

5. 1. Methodology of Simulation

This phase comprises of simulation study of the existing case, and of the varied cases, changing window sizes. The simulation phase is further divided into two sub phases: Dynamic Thermal Simulation (DTS) study, in Autodesk Ecotect Analysis, and Computation Fluid Dynamics Analysis in WinAir. The steps of the simulation phase are summarized below in Fig. 5.1.

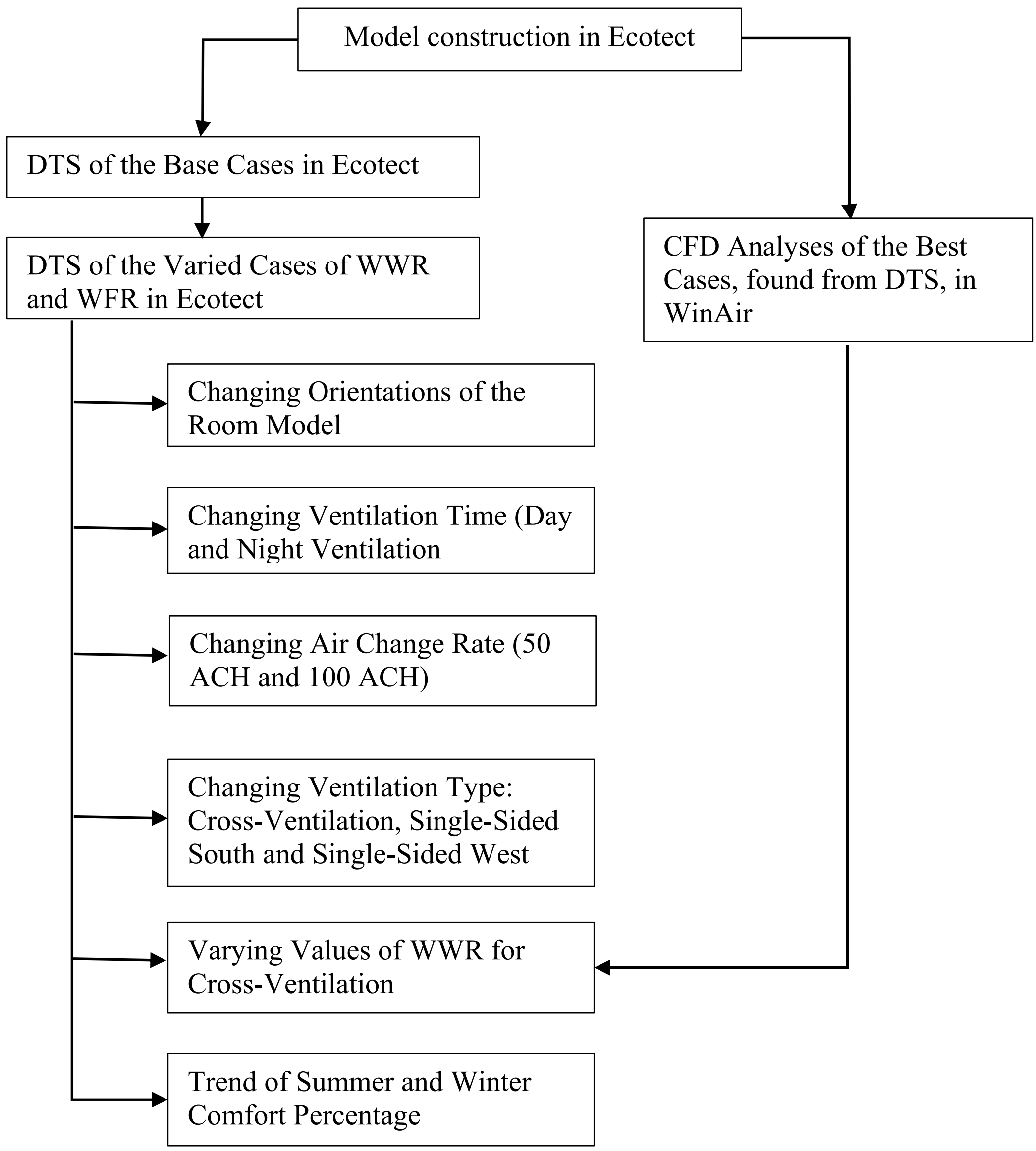


Fig. 5.1: Structure of Simulation Phase

In the DTS part, a base case model was generated in Autodesk Ecotect, with features similar to the building consisting of the surveyed room, to compare the data from field investigation with the simulated values, thus assessing the accuracy of the software used. The base case room model, at the same level as that of the surveyed room, was then simulated. The simulation varying WWR and WFR were done for four different orientations, for day and night ventilations, for different air change rate and ventilation type, to analyze and evaluate the effect of these variations on indoor air temperature in the naturally ventilated bed room. In the second part, a CFD analysis of the case, having the best combination of WWR, identified during the dynamic thermal simulations, was done in WinAIR V4.1b, to understand the wind flow pattern and direction for different window sizes inside the models.

5.2. Objective of the Simulation Study

The simulation phase consists of sequential optimizations, with the aim of minimizing thermal problems in bedroom of naturally ventilated building. The stages are mainly divided into two parts:

The model of the surveyed building with a similar sized room at the south west, having similar material and same window proportion, as that of the surveyed bedroom, was constructed in Autodesk Ecotect Analysis. Dynamic thermal simulation, was conducted on the dates exactly when the field measurements of temperature were taken. This was done to test the temperature variation between the simulated values and measured data of indoor air temperature, for subsequent validation of the software used (Section 1.3.2 and Appendix E).

The base-case bedroom model, based on the data identified in the case study part and physical survey (Section 4.2 and 4.3), was again generated in Autodesk Ecotect Analysis. A comprehensive thermal simulation was conducted, varying WFR and WWR for different orientations, day and night ventilation, changing air change rates, cross and single-sided ventilation, and finally for summer and winter seasons (Fig. 5.1). The DTS is followed by the CFD, to understand the air flow pattern in case of changes in WWR, inside the modeled bedroom. The main objective of simulating with all these varying combinations, was to understand the importance of window size and proportion, in modifying indoor air temperatures in naturally ventilated rooms of apartments, used by the middle-income group of Dhaka. This, in turn, can help to create a data source for preliminary design decisions regarding window size in a naturally ventilated building.

5.3. Simulation Tool

Among several simulation tools, Dynamic Thermal Simulation (DTS) and Computational Fluid Dynamics (DTS) are used in this part of the research. The DTS was done using Autodesk® Ecotect®

Analysis (Appendix H), to analyze the impact of variation of WFR and WWR on indoor air temperature inside typical south-west facing bedrooms in residential apartments. The CFD analysis was done using WinAIR V1.4b, a plugin on a mesh of Ecotect, to portray the internal wind flow pattern for such variations in window size.

5.4. Thermal Simulation Strategy

As mentioned above, the simulation was divided into two main steps, approach in each step was similar with slight change. In the first step, both the model construction and dynamic thermal simulation, were done using Autodesk Ecotect Analysis. The CFD analysis was done in the second step, using WinAIR V4.1b, plugins for the same software.

The first analysis was conducted on the base case, whose model was constructed to exactly represent the studied room, having window size and proportion similar to the room, used for recording temperature measurements. Since, sliding windows were found to be the most typical window used in residential buildings (Appendix B), as well as, in the surveyed room, sliding windows were used both in the base case simulation, and for the varied cases. The window closing and opening times (Fig 5.5) were scheduled, based on the findings of physical observations and interviews with the occupants, reported in Section 4.3.6. The window type being sliding, only half of the window was operable, thus, 50% of the window aperture was considered as void.

The model of the whole building was constructed in Ecotect, based on the data collected in the case study and field study part (Section 4.2 and 4.3), considering each room as individual zone (Fig 5.2). The model represents a typical high-rise apartment building, with a master bed room similar to the surveyed one. All zones inside the buildings were considered as non-thermal zones, except the master bedroom in the south-west corner of the topmost floor. This modification was done to avoid complexities in determining the exact effect of specific window parameters, like varied WWR or WFR, on indoor air temperature. Thus, for the convenience of studying the precise effect of varying window size and proportion, inter-zonal heat transfer among different zones of the building, was not considered. The weather data for Dhaka, retrieved from the website of EnergyPlus (2016), was used as the climatic input for the simulation.

Orientations, window opening time (night and day ventilation), air change rate (50 and 100 ACH) and ventilation type (cross and single-sided) were changed during the simulation, to understand their impact on indoor air temperature for different values of WWR and WFR.

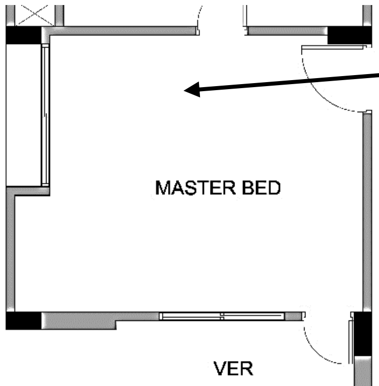


Fig. 5.3a: Plan of the Existing Bedroom used for Field Survey

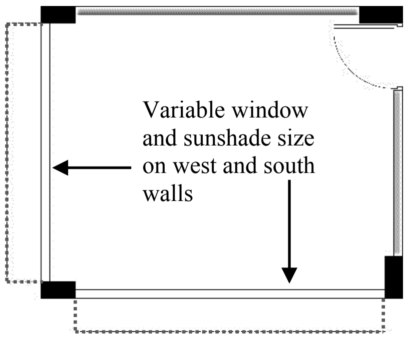


Fig. 5.3b: Simplified Plan of the Base Case Bedroom Model used in Simulation

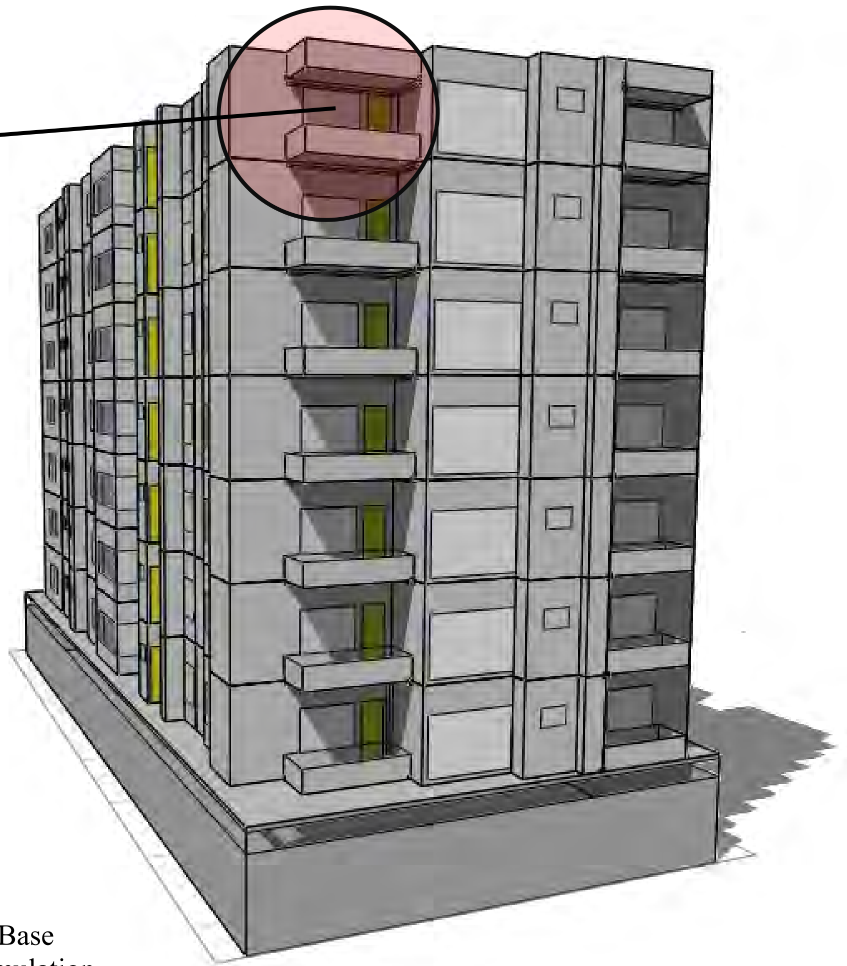


Fig. 5.2: Three-dimensional Visualization of the Surveyed Building in Autodesk Ecotect Analysis-2pm Conditions

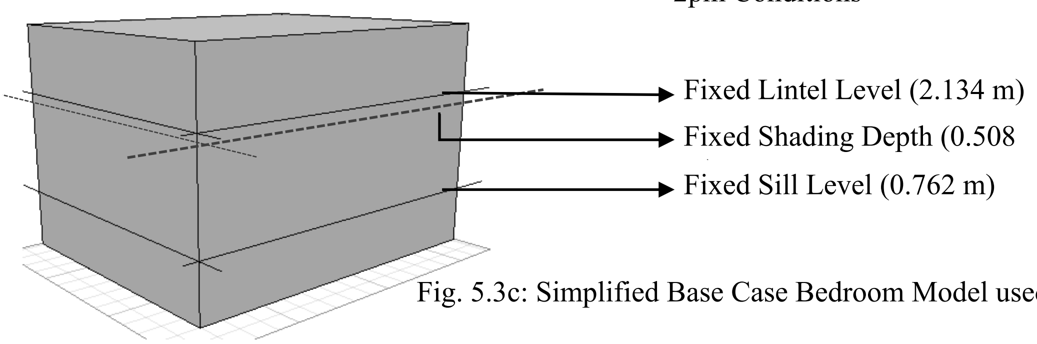
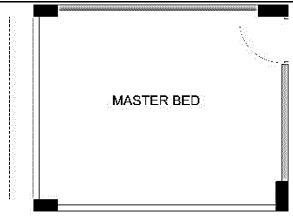
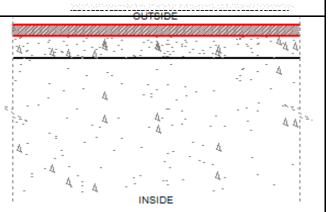
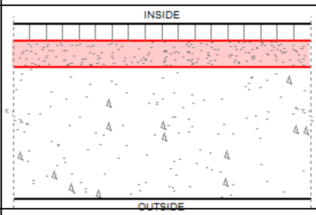
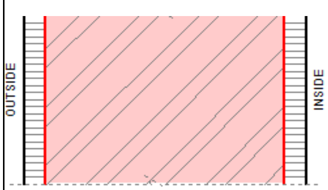
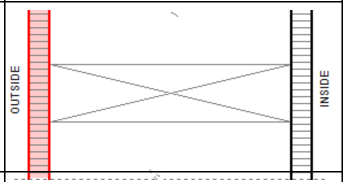
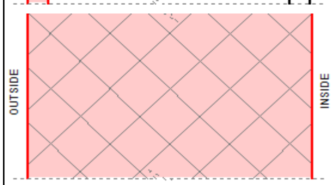
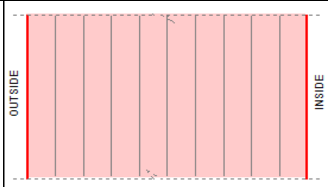
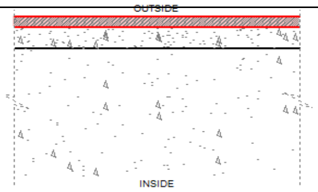


Fig. 5.3c: Simplified Base Case Bedroom Model used in Simulation

5.4.1. Inputs used during Thermal Simulation

The base case model was simplified; the projected verandah was not considered during simulation, and the walls were considered as exterior walls, with windows having the minimum shading of depth 0.457 m. This modification was done to understand the direct effect of window aperture size of exterior wall on indoor air temperature. The geometry of the modelled room (Fig 5.3) was taken as: 3.658m wide, 4.572m long and 3.048m high, the total floor area being 16.723 sqm. The window height was kept constant at 0.762m, as in bed rooms it is particularly important to keep the window-sill height at a similar height as that of the beds, thus making provision for air flow around the sleeping area (Arif and Islam, 2002). The material specification of the room is given in Table 5.1.

Table 5.1: Specification of the Base Case Room used in Ecotect Modelling

	Description	Type and Size (meter)	U-value (W/m^2.k)	Section
Room	Rectangular in shape, located at the south west corner	Rectangular; (3.658 X 4.572 X 3.048) m		
Ceiling	0.127m thick suspended concrete ceiling with 0.025m plaster underneath	Plastered Concrete Ceiling; (3.658 X 4.572) m	1.990	
Floor	0.127m thick suspended concrete floor with 0.025m plaster and 0.019m ceramic tiles	Tiled Concrete Floor; (3.658 X 4.572) m	2.080	
Wall	0.121m brick with 0.019m plaster either side.	Plastered Brick wall; (4.572m X 3.048m) 2 (3.658m X 3.048m) 2	2.200	
Internal Door	0.038m thick hollow core plywood door	Swing door; (1.016 X 2.134) m	2.980	
External Door	0.038m thick solid core oak timber door	Swing door; (0.762 X 2.134) m	2.260	
Window	6mm single pane of glass with 0.032m aluminum frame around	Sliding; (1.372 X 1.524) m	6.000	
Over-hang	0.127m thick suspended concrete ceiling with 0.025m plaster underneath	Plastered Concrete Overhang; (1.524 X 0.508) m	1.990	

(Source: Surveyed data and Autodesk Ecotect Analysis default input)

In the second step, values of WWR and WFR were varied and the hourly temperature profile inside the room were recorded for the variations. This analysis was carried out for the following combinations:

- Moving the room orientation from south-west corner to south-east, north-west and north-east corners, to assess the impact of orientations (Section 2.5.1), while varying WWR and WFR.
- Keeping the window opened at night and closed during the day and vice versa, to identify the impact of varying WWR and WFR on night cooling (Section 2.6.1).
- Varying air change rate – 50 ACH is taken for naturally cross-ventilated state and 100 ACH for moderately windy state (Section 2.7.3), to comprehend the impact of air movement on variable window sizes.
- Adopting different ventilation type – cross and single-sided ventilation (Section 2.6.2), to detect the potential ventilation type for south-west corner.
- Changing the season from summer to winter to understand seasonal shifts in indoor air temperature.

Thermal analysis was based on 50% occupancy during weekdays and 90% during the weekends, as reported during the interviews with the occupants. Based on the observation reported in Section 4.3.6., number of inhabitants were assumed to be two, the husband and the wife, and their activity pattern during their stay inside the bed room, were assumed to be light working (Table 5.3). As the building was naturally ventilated, the maximum air change rate was taken as 50 ACH, for still condition and 100 ACH for moderately windy condition in cross-ventilated state (Section 2.7.3). The zone specification used to run the simulations are illustrated in Table 5.2, 5.3 and 5.4 and Fig. 5.4 and 5.5.

Table 5.2: Occupancy and Operation Specification inside the Room used during Simulation

Occupancy			Operation				
Occu-pant No.	**Clo. Value**	**Activity Level**	**Internal Heat Gain**	**Air Change Rate**		**Window Aperture Status**	
02	0.55	80W (light work)	13W/m^2	50 ACH (cross ventilated still state)	100 ACH (moderately windy state)	Opened during day (7am to 7pm)	Opened at night (7pm to 7am)

Table 5.3: Rate of Heat Output by Body in Various Activity

Activity	Watts
Sleeping	min. 70
Sitting, moderate movement, e.g. typing	130–160
Standing, light work at machine or bench	160–190
Sitting, heavy arm and leg movements	190–230
Standing, moderate work, some walking	220–290
Walking, moderate lifting or pushing	290–410
Intermittent heavy lifting, digging	440–580
Hardest sustained work	580–700
Maximum heavy work for 30-minutes duration	max^{m}. 1100

(Source: Koenigsberger et al, 1973)

Table 5.4: Internal Heat Gain for Common Bedroom Appliances

Appliances	Values
Fluorescent Light	40 W
0.813m LED TV	110 W
Ceiling Fan	60 W
Room area (3.658m X 4.572m)	16.723 sqm
Total Internal Heat Gain	12.56 W/m^2

(Source: DESCO Appliance Calculator, 2016)

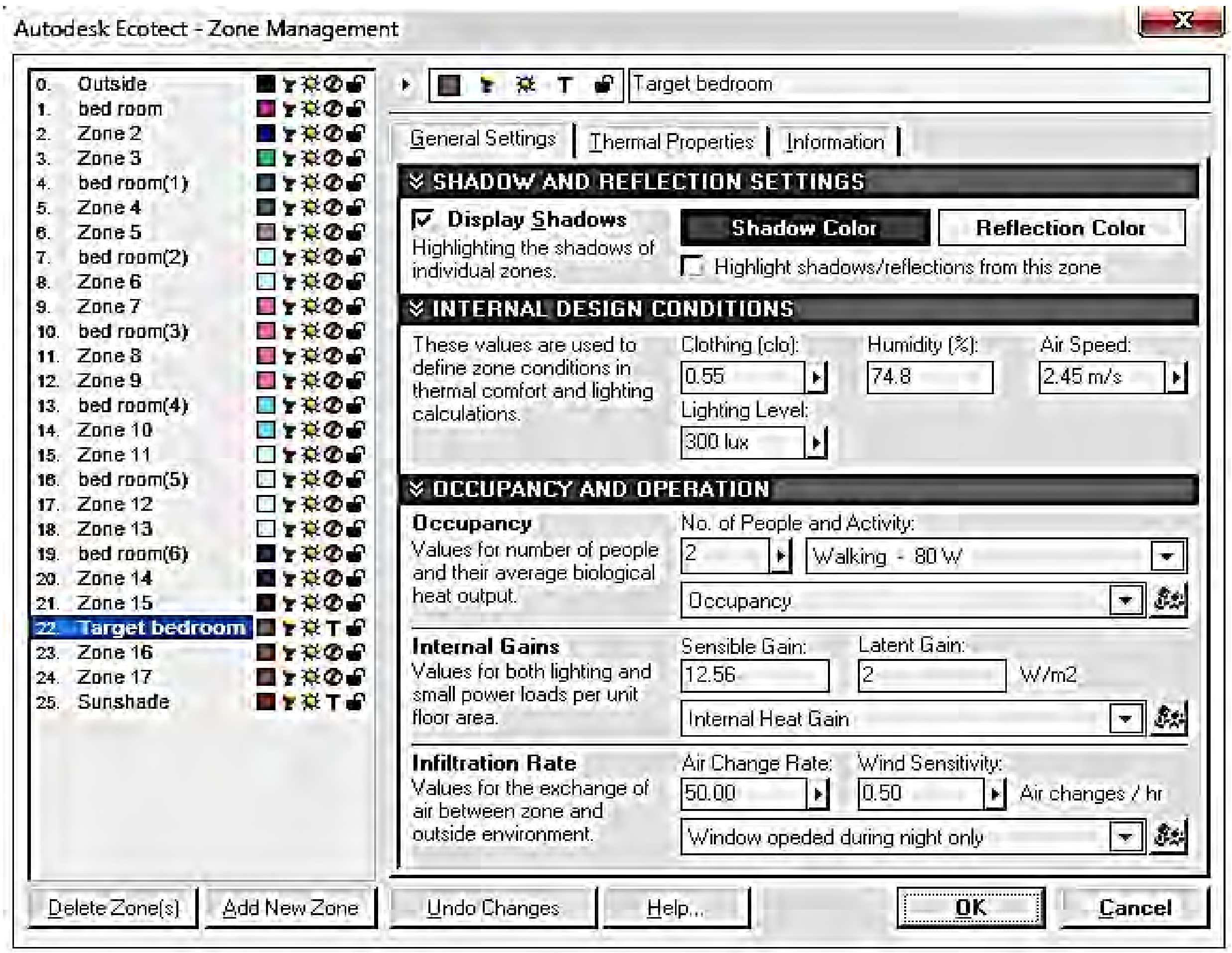


Fig. 5.4: Zone Management Specification in Autodesk Ecotect
Source: Autodesk Ecotect Analysis 2011

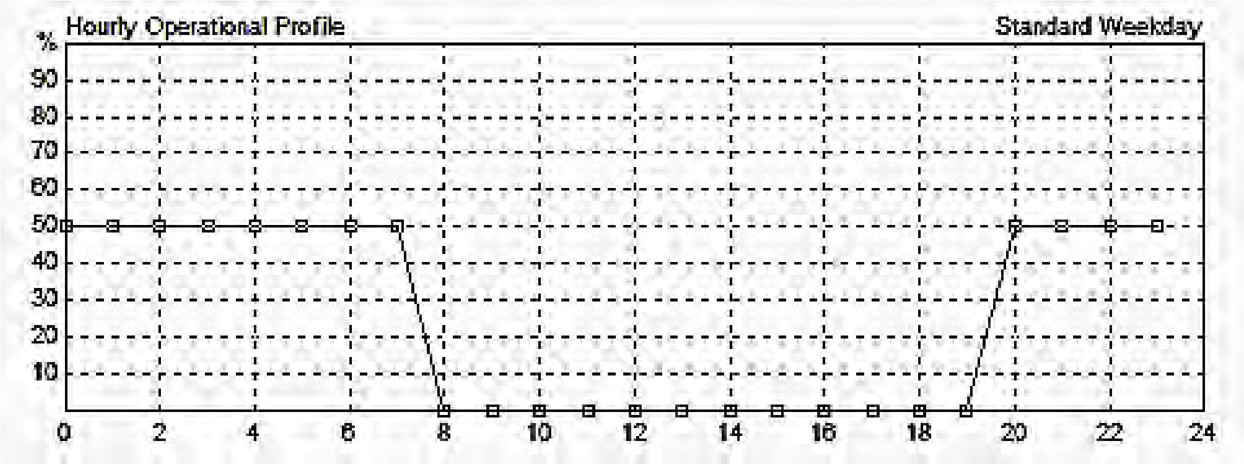


Fig. 5.5: Window Opening Schedule in Autodesk Ecotect
Source: Autodesk Ecotect Analysis 2011

5.4.2. Constant Variables

Variables that were kept constant during the dynamic thermal simulation phase are listed below:

Building geometry

- Bedroom shape, size, height and orientation (Table 5.1)
- Door and window material, size, height and location (Table 5.1)
- Overhang depth: 0.505m wide (Section 4.2.3),
- Sill and lintel levels of window (0.762m and 2.134m respectively, as found in the case study phase, Section 4.2.3)
- Floor, wall and ceiling material (Table 5.1)
- Door and drape status (door always opened and no drape used, found during field observation, Section 4.3.6.)
- Active ventilation system: Naturally ventilated, (Section 4.3.6.)
- Artificial lighting level: Set to 300 lux (default in Autodesk Ecotect Analysis)

Occupancy schedules

- Room Occupancy Hour: 7pm in the evening to 7am in the morning (Section 4.3.6)
- Zone activity state: Light work of 80W (Table 5.3)
- Clothing value: 0.55clo, summer clothing value (Tariq, 2014)
- Humidity level inside the room: 74.83% (Annual Average, Table 3.2, BMD, 2016)
- Indoor air velocity: 2.45 m/sec without ceiling fan (Table 3.2, Annual Average, BMD, 2016) and 4 m/sec with ceiling fan at maximum speed, approx. max. fan speed (calculated maximum fan speed during summer)
- Internal heat gain for common bed room appliances: 12.56W/m^2 (Table 5.4)

5.5. Calculations used in Thermal Simulation

A number of DTS and CFD simulations (approximately 150 individual Ecotect files) were run, varying the values of WWR and WFR. The values of WWR ranged from 5% to 40% (multiples of 5) for both single-sided and cross-ventilated state. Single-sided ventilated state was achieved, by placing window on south wall in one case and on west wall in the other. WFR values varied from 5% to 55% for cross ventilation, 5% to 35% for single-sided ventilation on south wall and 5% to 25% for single-sided ventilation on west wall. The calculation for WWR and WFR and the corresponding window sizes for each value of WWR and WFR, are given in detail in Appendix G.

5.5.1. Assumptions for WWR and WFR Calculations:

- Window height kept constant at 1.372m, sill level at 0.762m and lintel at 2.134m (Section 4.2.3), and located centrally, in case of both WWR and WFR.
- WWR and WFR values, more than 40% and 55% respectively, produce window width, exceeding the size of the accompanying walls, so values of WWR till 40% and WFR till 55%, were only used for calculations in cross-ventilated state.
- At 40% WWR, window width for 4.572m wall was taken to be 2.083m and for 3.658m wall, 1.575m wide window, as using windows of equal sizes were not possible, for the room being rectangular.
- For single-sided ventilations, on south wall, WFR value upto 35%, and on west wall, WFR value upto 25%, was viable to construct in the model for simulation.
- In cross-ventilated state, at 55% WFR, the window sizes were not kept equal, as in that case the window would be larger than the accompanying wall.
- At 35% WFR, in case of single-sided ventilation on south wall, window size was slightly reduced to accommodate its width in its accompanying wall.

5.6. Thermal Data Analysis Steps

A number of individual simulations were done using the above-mentioned inputs. Hourly indoor air temperature profile for March, April and May (pre-monsoon season) and December, January and February (cool dry season) were generated in several different Excel files. The data were than analyzed and compared with the comfort temperature range (summarized in Section 2.8.2, Table 2.2), to produce necessary tables and graphs. The graphs mainly consist of comfort and discomfort hour percentage graphs, percentage of hours within, above or below the identified comfort temperature range for Dhaka. Apart from the comfort graphs, average temperature profile for the worst-case scenario was produced:

the hottest month, April; hottest day, 7th April; and warmest hour of the day, 2pm temperature, were produced. All these comparisons were done while varying the values of WWR and WFR for different air change rates, and for day and night ventilations.

5.7. CFD Simulation Strategies

In the final stage of simulation, internal air flow rate and air flow vector (Section 6.5.2) were analyzed in WinAIR, for the best cases identified in the Dynamic Thermal Simulations (Section 6.5.1). The values of WWR ranging from 5% to 40%, were used for varying the window sizes, assuming cross ventilation, with windows on the south and west wall of the modelled bedroom. In each model, every window was modelled with a void, equal to half of the area of the total calculated area of respective window. This was done because the typical sliding window used in the residential buildings, are only partially operable, that is, only 50% of the window area can be kept open. The climatic data of April, being the hottest month, were used as inputs for the CFD grid analysis in Ecotect. The air flow pattern and vector were taken at 1.067m, the seated height, because, maximum activity carried out inside the bedroom, being light, were done while sitting. The apertures of both the windows were kept 50% void, being sliding, and the doors were kept closed, so that the impact of window size on indoor air flow rate and direction could be solely analyzed. The void on the window of the south wall was kept towards the east side and on the west wall, towards the north side.

5.7.1. Specifications used in CFD Analysis

The specific inputs used for the CFD analysis in Ecotect, with assistance from its plugin, WinAir, are given below and illustrated in Fig 5.6:

- The boundary condition for the CFD analysis was taken to be inside the model.
- Outdoor Wind speed: 4.21m/s for Dhaka (Section 3.2.1, Table 3.2)
- Prevailing wind direction during summer month in Bangladesh: Southwest (-45°) (Section 3.1.2)
- Air Density: 1.2kg/m3 (ISA, 1975).
- Air viscosity: 1.8e-05 (ISA, 1975).
- Monitoring cell: The value is automatically set by the software during the simulation.
- Internal Temperature: 20 °C (Average minimum temperature for April, found in the Thermal simulation part)
- External Temperature: 34.4°C (Annual Average Daily Normal Maximum Temperature for April, Appendix F, BMD, 2016)

- Iteration of the WinAir calculation is set to 500, and calculation saving interval to100, which seems to yield expectable results.

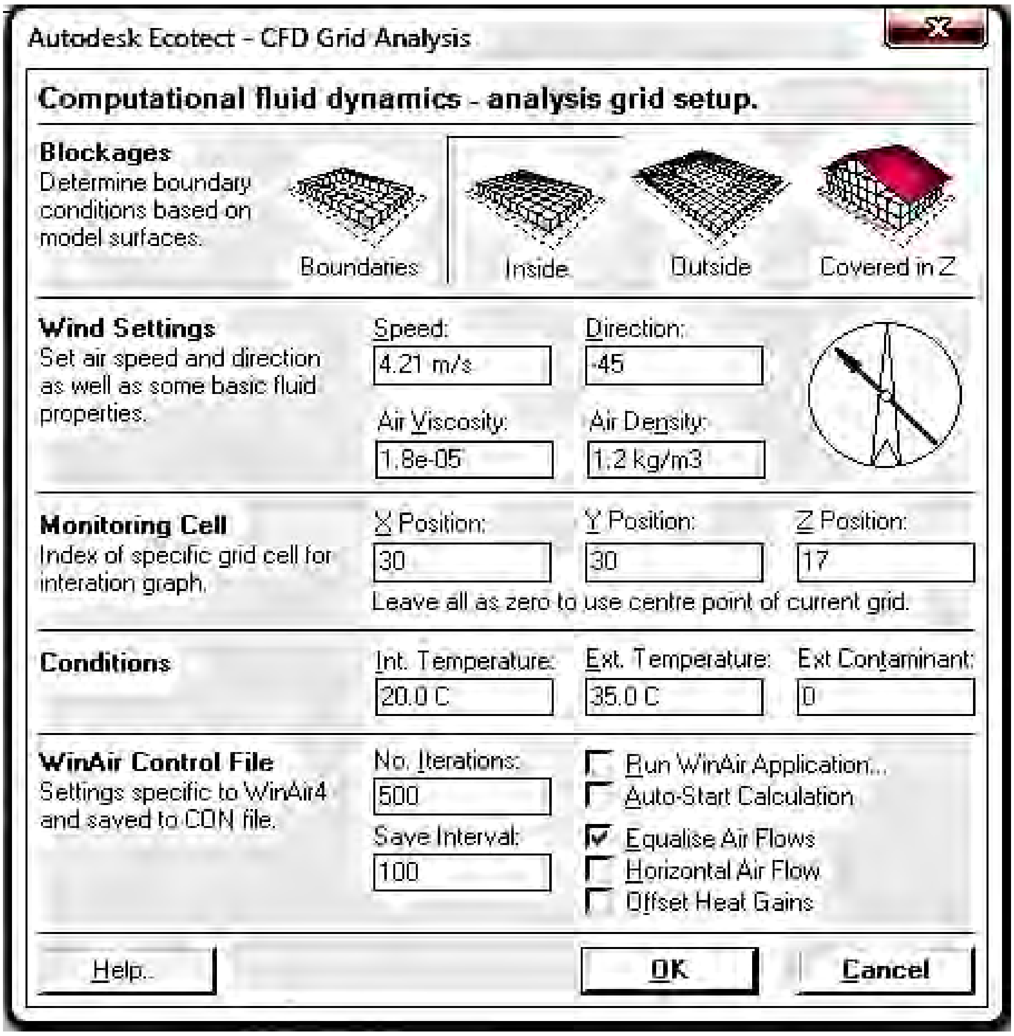


Fig. 5.6: CFD Grid Analysis in Autodesk Ecotect
Source: Autodesk Ecotect Analysis 2011

5.7.2. CFD Data Analysis Steps

Air flow plots for WWR, in cross ventilated state, were examined to understand the flow speed and direction inside the room models with window aperture size, resulting from 5% to 40% WWR. To study the air flow speed, air flow rate plots were used. To identify the direction and zone of maximum air circulation, air flow vector plots were analyzed. Thus, for each percentage of WWR, two different types of plots were examined to evaluate the air flow pattern inside the bedroom of interest, with varying window sizes, depending on the values of WWR. The results of CFD analysis are explained in detail in Section 6.5.2.

5.8. Conclusion

This chapter depicts the detailed strategies and steps underlying the simulation study. A base case model, grounded on the literature survey and data collected, was generated in Autodesk Ecotect Analysis. Comprehensive DTS varying WFR and WWR for different circumstances (mentioned in Section 5.4) of the model, were carried out to understand their impacts on varying WWR and WFR. A subsequent CFD simulation, using WinAir was also run, to understand the air flow pattern inside the model. The results generated in this chapter and findings from the previous chapters have been analyzed in the next chapter, for finding the impact of varying window size in lowering indoor air temperature of bedrooms of residential building.

Chapter 07: CONCLUSION AND RECOMMENDATIONS

7.1. Introduction

In this research, a parametric study of the indoor air temperature state of bedroom of high-rise apartment buildings, preferred by upper-middle income group of Dhaka, Bangladesh, was conducted. The findings and analysis of the research have been presented and interpreted in Chapter 6. This concluding chapter will focus on the knowledge available through this research, and suggest some recommendations for scope of future work in this arena.

7.2. Findings of the Research

The study was based on optimization of WWR and WFR, integrating variable/night ventilation, to reduce indoor air temperature in naturally ventilated bedroom of residential apartments. As, the issue has received scant attentions in previous studies on thermal comfort in Bangladesh, the indication from the study can act as an initial guideline for designing window of naturally ventilated residential building.

7.2.1. Apartment Size Preference, Typical Bedroom Size and Window Location and Size

From the literature review it was found that apartments less than 92.903 square meter are preferred by lower middle income group, 92.903 – 111.48 square meter for mid-middle income group and 111.48 – 148.65 square meter, are chosen by upper-middle income group and apartments above 148.65 square meter are considered for high income group (Section 3.6).

Another major part of the study reveals that the master bedroom size of typical 111.48 to 139.36 square meter apartments, vary between 3.048m to 4.57m in length and/width (Section 4.2.3). The apartments usually have sliding windows consisting of aluminum frame and clear or tinted glass, located centrally in most cases, with sill of 0.762m and lintel at 2.134m. The shading device of such windows usually project to 0.508m, which is in keeping with BNBC.

7.2.2. Effect of WWR and WFR on Indoor Air Temperature for different Orientations

In order to determine the critical orientation with apartments, simulations, changing the room orientations, were conducted. According to the analysis of comfort and discomfort percentage for the four corner orientations, North East, North south, South East and South West (Section 6.1), comfort percentage is found to be higher in the north-east orientation (Fig. 6.2 and 6.3), for both day and night ventilations, while varying WWR and WFR. The comfort period percentage is 73.9% for 5% WWR to 70.9% for 40% WWR. In the south-west orientation, the comfort percentage is the lowest, reaching almost 69.8% for 40% WWR, for both day and night ventilation, with variable window sizes. In the south west corner, warm period is comparatively higher, reaching almost 21% out of the total hour of the summer months (March, April and May) for 40% WWR (Fig 6.2). The comparison among the average temperature for April shows that south-west corner possesses the highest temperature, up to 30^{o}C for 5% WWR, whereas the north-east corner presents the lowest, which agrees with the comfort and discomfort percentage analysis for the same, although the variation is very less (Fig 6.3). The values of WFR show similar trend as that of for the values of WWR (Fig 6.3).

Therefore, it can be concluded that the south-west corner of the building is the warmest area of a building and presents the highest percentage of warm discomfort hours, which can be minimized decreasing the window size. These findings agree with previous studies of naturally ventilated buildings in tropical regions, which show that the south-west corner is the warmest part of a building (Section 2.5.1 and section 3.2.1).

7.2.3. Effect of WWR and WFR on Indoor Air Temperature for Day and Night Ventilation

After simulation, analysis based on various combinations of WWR and WFR were done to determine the comfort and discomfort hour percentages for day and night ventilations. Comparative analysis of comfort and discomfort hour percentages suggest that overall comfort percentage is much higher for night ventilation than day ventilation (Section 6.2). During night ventilation, the comfort period percentage range is 81.3% for 5% WWR to 78.99% for 40% WWR, whereas for the day ventilation, it is 74% for 5% WWR to 68.9% for 40% WWR (Fig 6.5). Cool period percentage increases rapidly as the value of WWR and WFR increases for ventilation during the day, but the change is almost steady for night ventilation. On the other hand, warm period percentage remains steady, ranging from 1% to 3% for 5% WWR to 40% WWR respectively, for both day and night ventilation (Fig. 6.5 and 6.6). The result shows consistency with studies (highlighted in Section 2.6.1) on naturally ventilated building in the tropics, where night flushing is used as an important ventilation strategy to reduce indoor air temperature, instead of using mechanical means to attain comfortable temperature range for indoor.

7.2.4. Effect of WWR and WFR on Indoor Air Temperature for Varied ACH

According to the findings on the impact of 50 ACH and 100 ACH on indoor air temperature (Section 6.3), the cool period percentages are higher and the warm period percentages are lower at 100 ACH for night ventilation, but the comfort period percentages are lower with 100 ACH than at 50 ACH. The comfort period percentage with 50 ACH, ranges from 81.1% for 5% WWR to 78.8% for 40% WWR, whereas with 100 ACH, comfort period percentage ranges from 78.5% for 5% WWR to 76.5% for 40% WWR (Fig. 6.7). The cool period percentage with 100 ACH, ranges from 17.66% for 5% WWR to 19.2% for 40% WWR, which is almost 3% to 4% higher than the cool period percentage with 50 ACH (Fig 6.7 and 6.9). The results for average temperature range for the hottest day, 7th April, is lower at 100 ACH, than at 50 ACH (Fig. 6.11). This finding indicates that at 100 ACH, the air exchange rate with the outdoor is higher compared to at 50 ACH (Fig 6.7 to 6.11). The minimum temperature with 100 ACH is constant, at approximately 22^{o}C, for all values of WWR, which is almost 1.5^{o} less than the minimum temperature with 50 ACH. Likewise, the maximum temperature at 100 ACH is less than the maximum temperature at 50 ACH, ranging from 29.8^{o}C to 30.1^{o}C for 5% to 40% WWR, respectively, although the difference is very little. The similar trend is noticed for varying values of WFR (Fig 6.8 and 6.10). Therefore, if the outdoor air is warmer than the inside and the air exchange rate is high, initially the indoor air temperature might increase to neutralize the temperature difference. Similarly, in case of cool outdoor, indoor air temperature cools down quickly due to increased air exchange rate. The result agrees with the findings of Section 2.7.3, that increased air exchange rate helps to decrease indoor air temperature in naturally ventilated building, when there is an outside wind nearby.

7.2.5. Effect of WWR and WFR on Indoor Air Temperature in Cross-Ventilation and Single-Sided Ventilation on South and West Wall

The investigation on cross-ventilated state, and single-sided south and west ventilation (Section 6.4) confirms that the cool period percentage (temperature < 24^{o}C) is highest and warm period percentage (temperature > 32^{o}C) is lowest in cross ventilated spaces. At cross-ventilated state, comfort period percentage ranges from 78.6% for 5% WWR to 76.6% for 40% WWR, and warm period percentage lies between 0.23% for 5% WWR to 0.68% for 40% WWR, whereas the cool period percentage ranges from 21.2% for 5% WWR to 22.7% for 40% WWR (Fig. 6.12). Conversely, for single sided ventilation on west wall, the cool period percentage is the lowest and warm period percentage is the highest. The average hourly indoor air temperature for April (Fig. 6.13) for the three states of ventilation, also agrees with this fact, showing that the highest temperature range of 27.11^{o}C for 5% WWR to 27.15^{o}C for 40% WWR, is found in case of single sided ventilation on west wall, though the temperature difference, induced by the smallest window size to the largest window size, is very little. The similar trend is noticed in case of variations in WFR (Fig. 6.14 and 6.15). This indicates that cross-ventilation can help to reduce indoor air temperature, compared to the single sided ventilation, yet, ventilation on south wall produces better result than ventilation on west wall.

7.2.6. Influence of Window Size on Indoor Air Temperature during Summer and Winter

The comparison between indoor air temperature for winter and summer suggests that the winter is less comfortable compared to the pre-monsoon summer months (March, April and May) in Bangladesh, for all values of WWR, even if the windows are kept open during the day (Fig. 6.27). However, there is very little change of indoor air temperature for the winter season, even with increased window sizes. The discomfort percentage during winter, though higher, can be overlooked as winter in Bangladesh lasts for only three months (December, January and February).

7.2.7. Influence of WWR on Indoor Air Temperature in Cross-Ventilated State

The effect of varying WWR on indoor air temperature and air flow were studied using DTS and CFD analysis (Section 6.5). The analysis were done for the cross ventilated state, having windows on the south and west wall and opened during the night, throughout the summer months (March, April and May).

The DTS and CFD analysis (Section 6.5.1 and 6.5.2) confirmed that larger window size is preferable for night ventilation, but during the day time, radiant heat through large window opening heats up the indoor, increasing the indoor air temperature, even if the windows are kept closed and a minimum shading device of depth 0.508m is used.

Although the results show that 5% WWR is responsible for the maximum hours (1791 hrs) of comfort, the hours with temperature below 24^{o}C (cool period hour) is highest for 40% WWR, the number of hours being 424 hours (Table 6.2). During the daytime, 40% WWR is accounting for maximum indoor air temperature, reaching the peak value of 29.8^{o}C at around 2pm, whereas during the night, 40% WWR is responsible for the lowest indoor air temperature, the minimum temperature being 23.2^{o}C. Smaller sized windows seem to keep the indoor cooler during the day, whereas during the night, larger window widths help to cool down the indoor air temperature rapidly. However, window sizes resulting from 25% to 35% WWR, produce better consequence in terms of air flow distribution and can help to reduce indoor air temperature by increasing the air exchange rate.

7.3. Recommendations

Based on the findings, this research recommends some guidelines to achieve lower indoor air temperature for naturally ventilated bedroom of high-rise apartment buildings, ideal for upper middle-income group of Dhaka, Bangladesh. The recommendations are as follows:

- Rooms in south-west corner of a building should have the provision of cross-ventilation.

- Increased air change rate helps to reduce indoor air temperature of naturally ventilated spaces, when there is an outside wind nearby.
- Cross-ventilations is more preferred for rooms in the south-west orientation, instead of single sided ventilations.
- Variations in window sizes, based on WWR and WFR, behaves almost similarly in inducing indoor air temperature.
- Larger window size is ideal for night ventilation to cool down the indoor rapidly, but larger window aperture also increases radiant heat gain during the day.
- Natural ventilation cannot reduce indoor air temperature to a significant level, so mixed mode ventilation may be an option to achieve comfortable indoor air temperature, instead of relying completely on mechanical means.
- Window sizes resulting from 25% to 35%, allow high speed wind to flow across naturally cross-ventilated room of high-rise apartments. Thus, air exchange rate with the surroundings increases, and helps to reduce the indoor air temperature, provided the outdoor temperature is comparatively lower than the indoor.

7.4. Suggestion for Further Studies

Though the scopes of this investigation were limited to the hot-dry season, south-west orientation and indoor air temperature, the objective, to find the appropriate window size and proportion for bedroom of high-rise residential building of Dhaka, was fulfilled. However, during the course of this research, it was evident, that there were gaps in knowledge about some major issues that may help to design naturally ventilated buildings more contextually. The research can be further extended for all seasons, taking account of daylighting and humidity content of indoor air, in addition to the choice of window materials, to inquire for the optimum window size and proportion for reducing indoor air temperature of bedrooms in high-rise residential buildings in the tropics.

REFERENCE

Chapter 1

Bastide, A., Lauret, P., Garde, F., Boyer, H., (2006). Building energy efficiency and thermal comfort in tropical climates. Presentation of a numerical approach for predicting the percentage of well-ventilated living spaces in buildings using natural ventilation. Energy Build, vol. 38, no. 9, pp. 1093–103.

Henly J., (2015). World set to use more energy for cooling than heating, Climate Change, The Guardian, available at www.theguardian.com, accessed on 22nd November, 2016.

Perez-Lombard L., Ortoiz J., Pout C., (2008). A review on buildings energy consumption information, Energy and Building, Elsevier Journal, vol. 40, pp. 394 – 398.

Mohanty, P. O., Ford, B., Lau, B., (2013). Effectiveness of natural ventilation in tall residential building in tropical climate - A critical analysis and design review, 29th PLEA Conference, Sustainable Architecture for a Renewable Future, Munich, Germany.

Rofail T. (2006). Natural Ventilation in Buildings. NEERG Seminar.

Peddie, K., and Rofail. A., (2011). Designing for natural ventilation in tall residential buildings, CTBUH 2011, World Conference, Seoul, Korea.

Daly, A., (2002). Operable windows and HVAC system. Heating/Piping/Air Conditioning Engineering, December 1.

Gross, S., and Hu, H., (2011). A feasibility study of natural ventilation in a midrise student dormitory building, Proceedings of Building Simulation, 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November.

Mahdavi, A., and Bellahy, S.E., (2005). Effort and effectiveness considerations in computational design evaluation: a case study, Building and Environment, Elsevier Journal, vol. 40, pp. 1651–1664.

Attia, S. (2010). Building performance simulation tools: Selection criteria and user survey; Université Catholique de Louvain: Louvain La Neuve, Belgium.

US GSA, Statsbygg and Senate, (2010), Information Delivery Manual (IDM) for BIM Based Energy Analysis as part of the Concept Design BIM. accessed on November 23, 2015, available online: www.blis-project.org/IAIMVD/IDM/BSA-002/PM_BSA-002.pdf.

JICA, (2015). Energy Efficiency and Conservation Master Plan up to 2030, Final Report Annex of The Project for Development of Energy Efficiency and Conservation Master Plan in Bangladesh.

Ahmed, Z.N., (1994), Assessment of residential sites in Dhaka with respect to solar radiation gain, Ph.D. thesis (Unpublished), De Montfort University, in collaboration with the University of Sheffield.

Mourshed, M., (2011). The impact of the projected changes in temperature on heating and cooling requirements in buildings in Dhaka, Bangladesh, Applied Energy, vol. 88, issue 11, pp. 3737 – 3746.

Ahmed, Z.N., Ahmed, F., and Mazumder, S., (2011). Climate Change: Comparing effects on coastal and urban regions of Bangladesh; International Conference on Climate Change and Social Issues, CCSI 2011, Colombo, Sri Lanka; 14-15 December.

Tariq, S. H., (2016). An investigation on energy consumption for thermal comfort with respect to plan layout of residential apartment buildings in Dhaka, unpublished Masters Thesis, Department of Architecture, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

Johansson, R., (2003). Case study methodologies (Lecture III B). Stockholm: Royal Institute of Technology, Built Environment Analysis.

Stake, R. E., (1995), The Art of Case Study Research. Thousand Oaks, California: Sage.

Patton, M.Q., (1990). Qualitative Evaluation and Research Methods. 2nd Edition. Newbury Park, California: Sage.

Chapter 2

Corbis, (2011). Creative Research Mini Brief, H1.

IEA (2008). Worldwide Trends in Energy Use and Efficiency, Key Insights from IEA Indicator Analysis, In support of the G8 Plan of Action, International Energy Agency.

IEA (2007c). Energy Balances of OECD Countries, 2004-2005, IEA/OECD, Paris. http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1931

IEA (2007d). Energy Balances of Non-OECD Countries, 2004-2005, IEA/OECD, Paris. http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1077

IEA (2007e). CO2 Emissions from Fuel Combustion 1971-2005, IEA/OECD, Paris. http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1825

Tariq, S. H., (2016). An Investigation on Energy Consumption for Thermal Comfort with Respect to Plan Layout of Residential Apartment Buildings in Dhaka, unpublished Masters thesis, Department of Architecture, Bangladesh University of Engineeering and Technology, Dhaka, Bangladesh.

IEO (2016). International Energy Outlook 2016, With Projections to 2040, May 2016, U.S. Energy Information Administration, Office of Energy Analysis, U.S. Department of Energy Washington, DC 20585.

Hossain, M. S., Li, B., Chakraborty S., Hossain M. R., Rahm M. T., (2015). A comparative analysis on China's energy issues and CO2 emissions in global perspectives, Journal of Sustainable Energy, vol. 3, No. 1, pp. 1-8

Safirova, E., Houde, S., and Harrington, W., (2007). Spatial Development and Energy Consumption (Washington, DC: Resources for the Future, December).

Cheok-Chan, G., (2008). Proposed legislative framework on environmental sustainability for buildings. T.D. Division, Editor, Building and Construction Authority, Singapore.

AL-Najem, A.A., (2002). The architectural category and its importance to measure the electrical energy demand and to identify effective conservation measures, Symposium on Energy Conservation and Management in Buildings Conference; Saudi Arabia.

Lam, J.C., and Li, D.H.W., (1999). An analysis of daylighting and solar heat for cooling-dominated office buildings, Solar Energy, Mar, vol. 65, no. 4, pp. 251–62.

IEA, (2007). Energy Efficiency of Air Conditioners in Developing Countries and the role of CDM, IEA Information Paper, International Energy Agency, Paris, September.

CETDEM, (2006). Center for Environment, Technology and Development of Malaysia, Working with the community on energy efficiency at household level in Petaling, Jaya. A CETDEM Study on Energy Efficiency.

GRPH, (2010). General Report of the Population and Housing Census. Department of Statistics Malaysia.

GRPH, (2000), General Report of the Population and Housing Census, Department of Statistics Malaysia.

Mahlia, M.I., et al., (2004). Viewpoint: Mitigation of emissions through energy efficiency standards for room air conditioners in Malaysia. Energy Policy. Nov, vol. 32, no. 16, pp. 1783–7.

Michel, A., Bush, E., Nipkow, J., Brunner, C.U., Bo, H., (2011). Energy efficient room air-conditioners – Best available technology (BAT), EEDAL Conference, Copenhagen.

Lin, J., and Rosenquist, G., (2006). China cools with tighter RAC Standards, Proceedings of 2006 International Conference on Energy Efficiency in Domestic Appliances and Lighting, London.

Sangsawang, V., (2010). Energy Efficiency Standards and labeling Measures in Thailand: Air Conditioner, Dept. of Alternative Energy Development and Energy Efficiency, Ministry of Energy, Bangkok, March 2010.

Song W. Q., (2010). Research on air environmental impact of urbanization development strategy in Shandong Province, Ph.D. Dissertation, Shandong University:

Sivak, M., (2013). Will AC Put a Chill on the Global Energy Supply?" Journal of American Scientist, vol. 101, issue 5, pp. 330.

Hossain, I., (2013), Energy efficiency and energy security, Daily star, March 19, 2013

Kamal, M. A, (2012). An overview of passive cooling techniques in buildings: Design concepts and architectural interventions, Acta Technica Napocensis: Civil Engineering and Architecture, vol. 55, issue 1, pp. 84-97, 2012.

Quarmby, S.S., (2013). Passive design strategies applied to office buildings in Gauteng, unpublished Bachelor Thesis, Faculty of Engineering, Built Environment and Information Technology, Department of Construction Economics, University of Pretoria.

Quarmby, S.S., (2013). Passive design strategies applied to office buildings in Gauteng, unpublished Bachelor Thesis, Faculty of Engineering, Built Environment and Information Technology, Department of Construction Economics, University of Pretoria.

PHIUS, (2016). Passive House Institute US, accessed on March, 2016, available at http://www.phius.org.

Ochoa, C.E., and Capeluto, I.G., (2008). Strategic decision-making for intelligent buildings: Comparative impact of passive design strategies and active features in a hot climate, Building and Environment, vol. 43, pp. 1829-1839.

Holm, D., and Viljoen, R., (1996). Primer for Energy Conscious Design', Department of Minerals and Energy, Pretoria.

Ralegaonkar, R.V., and Gupta, R., (2010). Review of intelligent building construction: A passive solar architecture approach, Renewable and Sustainable Energy Reviews, vol. 14, pp. 2238-2242.

Ahmed, Z.N., (2003). Creating low-energy architecture: Reducing dependency on conventional energy sources in urban buildings, Symposium on Renewable Energy, Institution of Engineers, Dhaka, Bangladesh

Haase, M. and Amato, A., (2009). An investigation of the potential for natural ventilation and building orientation to achieve thermal comfort in warm and humid climates, Solar Energy, vol. 83, pp. 389-399.

Sadineni, S.B., Madala, S. and Boehm, R.F., (2011). Passive building energy savings: A review of building envelope components', Renewable and Sustainable Energy Reviews, vol. 15, pp. 3617-3631.

Hawkes, D., McDonald, J. and Steemers, K., (2002). The Selective Environment: An Approach to Environmentally Responsive Architecture, Spon Press, London.

Koenigsberger, O.H., Ingersoll, T.G., Mayhew, A., Szokolay, S.V., (1973), Manual of Tropical Housing and Building: Climatic Design, first published by Orient Blackswan Private Limited, India.

Givoni, B., (1997). Climate Considerations in Building and Urban Design. USA: Van Nostrand Reinhold, pp. 109.

Lauber, W., (2005). Tropical Architecture: Sustainable and humane building in Africa, Latin America and South-East Asia. New York: Prestel Publishing.

Rajapaksha, I., Nagai, H., and Okumiya, M., (2002). Indoor Thermal Modification of a Ventilated Courtyard House in the Tropics, Journal of Asian Architect. Building Engineering, vol. 1, no.1, pp. 87–89.

Ahmed, Z. N., and Ahmed K. I., (1997). Poverty alleviation in Bangladesh: Any scope for architects? Role of Engineers in Poverty Alleviation in Developing Countries, Palok Publishers and Institution of Engineers, Bangladesh, pp. 101-106.

Zaki, W. R. M., Nawawi, A. H. and Ahmad, S., (2007). Case study in passive architecture: Energy savings benefit in a detached house in Malaysia, Proceedings in the 24th Conference on Passive and Low Energy Architecture, University of Singapore, pp. 259-266.

Zaki, W. R. M., Nawawi, A. H. and Ahmad, S., (2008). Energy savings benefit from passive architecture, Journal of Canada Centre of Science Education, vol. 3, pp. 51-63

La Roche, P., Liggett, R. (2001). A web based assistant for the design of climate responsive buildings, Architectural Science Review, vol. 44, pp. 437-448.

Thomas, R., and Garnham, T., (2007). The environments of architecture: Environmental design in context. Great Britain: Taylor & Francis.

Belgaid, B. (2011). Building thermal performance in Saharan climate, International Journal of Energy and Environment, vol. 2, issue 2, pp. 261-266.

Ling, C. S., Ahmad, M. H., Ossen, D. R., (2007). The Effect of geometric shape and building orientation on minimizing solar insolation on high-rise buildings in hot humid climate, Journal of Construction in Developing Countries, vol. 12, issue 1, pp. 27 – 38.

Fadzil, S.F.S., and Sia S-J. (2004). Sunlight control and daylight distribution analysis: The KOMTAR case study. Building and Environment, vol. 39, issue 6, pp. 713-717.

Konya, A. (1980). Design Primer for Hot Climates. London: published bt The Architectural Press.

Tombazis, A.N., and Preuss, S. A., (2001). Design of passive solar buildings in urban areas. Journal of Solar Energy, vol. 70, no. 3, pp. 311-318.

Koch-Nielsen, H., (2007). Stay cool: A design guide for the built environment in hot climates. London: The Cromwell Press.

Tariq, T., and Ahmed, Z. N., (2013), Effects of roof treatment on thermal performance of residential buildings in Dhaka, PLEA 2013 – 29th Conference, Sustainable Architecture for a Renewable future, Munich, Germany.

Ahmed, Z.N., (2002). The effects of room orientation on indoor air movement in the warm-humid tropics: Scope for energy savings, Journal of Energy and Environment, Centre for Energy Studies, Bangladesh University of Engineering and Technology, vol. 2, pp. 73-82.

Ahmed, Z. N., (1987), The effects of climate on design and location of windows for building in Bangladesh, unpublished M. Phill Thesis, Department of Building, Sheffield City Polytechnic.

Santamouris, M., and Asimakoupolos, D., (1996). Passive Cooling of Buildings (1st ed.), William Road, London NW1 3ER, UK: James & James (Science Publishers) Ltd.

Samuel, D.G. L, Nagendra, S.M. S., Maiya, M.P., (2013), Passive alternatives to mechanical air conditioning of building: A review. Building and Environment, vol. 66, pp. 54–64.

Limb, M.J., (1998). Passive Cooling Technologies for office buildings. An Annotated Bibliography". Air Infiltration and Ventilation Centre (AIVC), 1998.

Niles, P., and Kenneth., (1980). Passive Solar Handbook. California Energy Resources Conservation. ASIN B001UYRTMM.

DeKay, M., and Brown, C., (2013). Sun, Wind, and Light: Architectural Design Strategies. John Wiley & Sons.

Givoni, B., (1991). Performance and applicability of passive and low-energy cooling systems". Energy and Buildings, vol. 17, no. 3, pp. 177–199.

Finn, D., Connolly, D., Kenny, P., (2007). Sensitivity analysis of a maritime located night ventilated library building. Solar Energy, vol. 81, no. 6, pp. 697–710.

Grondzik, W. T., Kwok, A.G., Stein, B., Reynolds, John S., (2010). Mechanical and Electrical Equipment for Building (11th ed.), 111 River Street, Hoboken, NJ 07030, USA: John Wiley & Sons.

Artmann, N., Manz, H., Heiselberg, P., (2008). Parameter study on performance of building cooling by night-time ventilation, Renewable Energy, vol. 33, no. 12, pp. 2589–2598.

Allard F., (1998). Natural Ventilation in Buildings: A Design Handbook, James and James Ltd., London, England.

Aynsley R., (1999). Estimating summer wind driven natural ventilation potential for indoor thermal comfort, J Wind Eng Ind Aerodyn, vol. 83, no. 1–3, pp. 515–525.

Ahmed K. S., Haq A., Moniruzzaman M., (2006). Potentials of window design in inducing air-change in still air condition, PLEA2006, The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland.

Linden P.F., (1999). The fluid mechanics of natural ventilation, Annu Rev Fluid Mech, vol. 31, pp. 201–238.

Venkatachalam, L. J. and Amirtham, L. R., (2011). Thermal comfort conditions in naturally ventilated low-rise apartment units of Chennai, The 5th International Conference of the International Forum on Urbanism (IFoU), National University of Singapore, Department of Architecture Global Visions: Risks and Opportunities for the Urban Planet.

Brown G.Z. and DeKay M., (2001). Sun, Wind, and Light, published by Wiley.

Hassan, M. A., and Guirguis, N. M., (2007). Investigation of effects of window combinations on ventilation characteristics for thermal comfort in buildings. Desalination 209, vol. 1, issue 3, pp. 251-260.

El-Agouz, S. A. (2008). The effect of internal heat source and opening locations on environmental natural ventilation, Energy and Buildings 40(4): 409-418.

Evola, G. and V. Popov (2006). Computational analysis of wind driven natural ventilation in buildings, Energy and Buildings 38(5): 491-501.

Jiang, Y. and Chen, Q., (2001). Study of natural ventilation in buildings by large eddy simulation, Journal of Wind Engineering and Industrial Aerodynamics, vol. 89, issue 13, pp. 1155-1178.

Wei, Y., Zhang, G., Xiao, W. and Xia San-xian, X., (2010). Potential model for single-sided naturally ventilated buildings in China, Elsevier Journal of Solar Energy, vol. 84, issue 9, pp. 1595-1600

Roulet C. A., and. Ghiaus C., (2005). Specific Devices for Natural Ventilation, Natural Ventilation in the Urban Environment: Assessment and Design, book, first published by Earthscan in the UK and USA in 2005.

Carmody, J., Selkowitz, S., and Heschong, W. W. L., (1996). Residential Windows: A Guide to New Technologies and Energy Performance, published by Norton and Company.

Szokolay, S., (2004). Introduction to Architectural Science: The Basis of Sustainable Design, First Edition, Architectural Press, Oxford, UK.

Al-Tamimi, N.A., and Syed F.S.F., (2011). Thermal performance analysis for ventilated and unventilated glazed rooms in Malaysia (Comparing simulated to field data), Indoor and Built Environment; vol. 20, no. 5, pp. 534–542.

Al-Tamimi, N. A., S. F. Syed Fadzil, and Harun, W.M.W., (2011), The effects of orientation, ventilation, and varied WWR on the thermal performance of residential rooms in the tropics, Journal of Sustainable Development, vol. 4, no. 2, pp. 142-149.

Edwards L., and Torcellini, P., (2002). A literature review of the effects of natural light on building occupants technical report, National Renewable Energy Laboratory.

Kukreja, C.P., (1978). Tropical architecture. New Delhi, Tata McGraw-hill publishing company limited.

Allard F., (1998), Natural ventilation in buildings: a design handbook, James and James Ltd., London, England.

Dascalaki E. and Santamouris M., (1998). The AIOLOS Software. In F. Allard, ed. Natural Ventilation of Buildings—A Design Handook, London: James and James Ltd, pp. 327–350.

Heiselberg P., Dam H., Sorensen L. C., Nielsen P. V. and Svidt K. (1999). Characteristics of air flow through windows, presented at the First International One Day Forum on Natural and Hybrid Ventilation, HybVent Forum'99, Sydney, Australia.

Holm, D., and Viljoen, R., (1996), Primer for Energy Conscious Design, Department of Minerals and Energy, Pretoria.

Menzies, G.F., and Wherrett, J.R., (2005). Windows in the workplace: examining issues of environmental sustainability and occupant comfort in the selection of multi-glazed windows', Energy and Buildings, vol. 37, pp. 623-630.

Aflaki, A., Mahyuddin, N., Awad Z.A.M., Baharum M.R., (2014). Relevant indoor ventilation by windows and apertures in tropical climate: a review study, E3S Web of Conference 3, published by EDP Sciences.

CABRi (2010). China Academy of Building Research, JGJ134-2010, Design standard for energy efficiency of residential buildings in hot summer and cold winter zone, China Architecture and

Building Press, Beijing, China.

Sadineni, S.B., Madala, S. and Boehm, R.F., (2011), Passive building energy savings: A review of building envelope components, Renewable and Sustainable Energy Reviews, vol. 15, pp. 3617-3631.

Gratia, E., Bruyere, I., De Herde, A., (2004). How to use natural ventilation to cool narrow office buildings, Building and Environment, vol. 39, no. 1), pp. 1157–1170.

Kim S.-H., Kim S.-S., Kim K.-W., and Cho Y.-H., (2014). A study on the proposes of energy analysis indicator by the window elements of office buildings in Korea, Energy and Buildings, vol. 73, pp. 153–165.

Wang, H. H., Rui, G., and Xiao, Q. L., (2012). Energy saving effect of building envelope in summer, Journal of Central South University of Technology (English Edition), vol. 19, no. 5, pp. 1370–1376.

Kontoleon, K.J. and Bikas, D.K., (2002). Modelling the influence of glazed openings percentage and type of glazing on the thermal zone behavior. Energy and Buildings, vol. 34, pp 389-399.

Bostancioglu E., and Telatar B., (2013). Effect of window size on residential buildings' energy costs, World Applied Science Journal, vol. 21, issue. 4, pp. 631-640.

Feng, Y., and Yang, H., (2001). Defining the area ratio of window to wall in 'design standard for energy-efficiency of residential buildings in hot summer and cold winter zone, Journal of Xi'an University of Architecture and Technology, vol. 33, pp. 348–351.

Al-Homoud, M. S., (1997). Optimum thermal design of office buildings, International Journal of Energy Research, vol. 21, no. 10, pp. 941–957.

Goia, F., Haase, M., and Perino, M., (2013). Optimizing the configuration of a facade module for office buildings by means of integrated thermal and lighting simulations in a total energy perspective, Applied Energy, vol. 108, pp. 515–527.

Yang, Q., Liu, M., Shu, C., Mmereki, D., Hossain, M.U and Zhan, X., (2015). Impact analysis of window-wall ratio on heating and cooling energy consumption of residential buildings in hot summer and cold winter zone in China, Journal of Engineering, Hindawi Publishing Corporation, vol. 2015, pp. 1-17.

Johnson, C. A., Besant R. W., and Schoenau, G. J. (1990). Economic preferred window orientation and optimum fenestration design.

Bokel, R. M. J., (2007). The effect of window position and window size on the energy demand for heating, cooling and electric lighting, Proceedings of Building Simulation.

Lam J.C., (2000). Residential Sector Air Conditioning Loads and Electricity Use in Hong Kong. Energy Conversion and Management. Vol. 41, no. 16, pp. 1757-68.

Persson, M.L., Roos A., Werner, A., Wall, M., (2004). Window size and orientation in a low energy house, Proceedings of the CIB World Building Congress, Toronto, Canada.

Binarti F., (2009). Energy-efficient window for classroom in warm tropical area, Eleventh International IBPSA Conference Glasgow, Scotland, pp. 1655 – 1662.

Nasrollahi F., (2010). Window Area in office buildings from the viewpoint of energy efficiency, BauSIM 2010 (Building Performance Simulation in a Changing Environment, Third German-Austrian IBPSA Conference, Vienna University of Technology.

Muhaisen A S., Dabboor H. R, (2015). Studying the impact of orientation, size, and glass material of windows on heating and cooling energy demand of the Gaza Strip buildings, Journal of Architecture and Planning, Vol. 27, issue 1, pp. 1-15.

Liping, W., Hien,W.N and Shuo, L., (2007). Facade design optimization for naturally ventilated residential buildings in Singapore. Energy and Buildings, vol. 39, no. 8, pp. 954-961.

Koranteng, C., Essel, C., Nkrumah, J., (2015). Passive analysis of the effect of window size and position on indoor comfort for residential rooms in Kumasi, Ghana, International Advanced Research Journal in Science, Engineering and Technology, vol. 2, issue 10, pp. 114-120.

Longo T. A., Melo A. P., Ghisi E., (2011). Thermal comfort analysis of a naturally ventilated building, Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, pp. 2004-2010.

Atolagbe, A.M.O., and Ajayi, O.O., (2015). Natural ventilation and body heat comfort: An evaluation of residents' satisfaction in Ogbomoso, Nigeria, International Journal of Civil Engineering, Construction and Estate Management, vol. 3, no.2, pp. 7-15.

Ishwar C., (1976). Design Aids for Natural Ventilation in Buildings. Lecture Program in Functional Aspects of Building Design, pp. 24 - 26, CBRI, Ronkie India.

Goncalves, J., and Bhatla, S., (2012). Environmental performance of the TTDI, Journal of CTBUH (Council on Tall Building and Urban Habitat), issue. 2.

Ahsan T., Soebarto V., Williamson T., (2014). Key predictors of annual electricity use in high-rise residential apartments in Dhaka, Bangladesh, Across: Architectural research through to practice: 48th International Conference of the Architectural Science Association, The Architectural Science Association and Genova, University Press. pp. 517–528.

Capeluto, I.G., (2003). The influence of the urban environment on the availability of daylighting in office buildings in Israel. Building and Environment, vol. 38, pp. 745-752.

Smith, P.F., (2005). Architecture in a Climate Change. 2nd Edition, Architectural Press, Elsevior, Oxford.

Ibrahim, N.L.N., (2009). Daylighting rule of thumb and typology, Faculty of Architecture, Design and Planning, University of Sydney, New South Wales, Australia.

Wu, W. and E. Ng, (2003). A review of the development of daylighting in schools. Light. Res. Technol., vol. 35, pp. 111-124.

Nedhal, A.T., Syed, F. S. F., and Adel A., (2016). Relationship between window-to-floor area ratio and single-point daylight factor in varied residential rooms in Malaysia, Indian Journal of Science and Technology, vol 9, issue. 33.

Neufert, E., (2000). Neufert Architects Data, Toronto, Sydney, New York, London.

Gutherie, P., (1995). The Architect's Portable Handbook: First Step Rules of Thumb for Building Design. Mc-Graw-Hill, New York.

LBA (1894-1909), London Building Acts.

BNBC, (2006). Bangladesh National Building Code.

ASHRAE Standard 62.2 (2013). Ventilation and acceptable indoor air quality in low-rise residential buildings. Atlanta, GA: American society of heating, refrigerating and air-conditioning engineers.

de Jong T.; Bot G. P. A., (1992). Air exchange caused by wind effects through (window) openings distributed evenly on a quasi-infinite surface. Energy and Buildings, vol. 19, issue 2, pp. 93–103.

Johnson, T., Myers, J., Kelly, T., Wisbith, A. and Ollison, W., (2004). A pilot study using scripted ventilation conditions to identify key factors affecting indoor pollutant concentration and air exchange rate in a residence. J. of Exposure Analysis and Environmental Epidemiology, 14, pp. 1–22.

Howard-Reed, C., Wallace L.A., and Ott, W.R., (2002). The effect of opening windows on air change rates in two homes. J. Air and Waste Manage. Assoc., 52, pp. 147-159.

Jordan, R.C., Erickson, G.A. and Leonard, R.R., (1963). Infiltration measurements in two research houses. ASHRAE Jounal, vol. 5, pp. 344–350.

Chandrashekaran, D., (2010). Air flow through louvered openings: Effect of louver slats on air movement inside a space, University of Southern California: United States, California, p. 141.

La Roche, P., and Milne, M., Automatic Sunshades, (2004). An experimental study, Proceedings of ASES 2004, American Solar Energy Society.

Cicelsky A., (2010). Parametric analysis of environmentally responsive (energy conserving) strategies for building envelopes specific for the southern Arava Valley, Unpublished Master's Thesis, Institute for Desert Research, Albert Katz International School for Desert Studies, Ben-Gurion University of the Negev Jacob Blaustein

USGBC Guide, (2016). U.S. Green Building Council's Green Home Guide. "10 Ways to Beat the Heat," available at http://greenhomeguide.com/know-how/article/10-ways-to-beat-the-heat, accessed December 14, 2016).

Givoni, B., (1997). Climate considerations in building and urban design. USA: Van Nostrand Reinhold, pp. 109.

Sreshthaputra A., (2003). Building design and operation for improving thermal comfort in naturally ventilated buildings in a hot-humid climate, unpublished PhD thesis, Texas A&M, May 2003.

ASHRAE Standard 55 (2004), American Society of Heating, Refrigerating and Air-Conditioning Engineers, Thermal Environmental Conditions for Human Occupancy, Inc. 1791 Tullie Circle NE, Atlanta, GA 30329 www.ashrae.org

Owen, M.S., and Kennedy, H.E. (Eds.), (2009). 2009 ASHRAE handbook: Fundamentals (SI Edition). Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Lomas, K. J., Cook, M.J., Short, C.A., (2008). Commissioning hybrid advanced naturally ventilated buildings: A US case study, 5th Windsor Conference of the Network for Comfort and Energy Use in Buildings on air Conditioning and the low Carbon Cooling Challenges, Cumberland Lodge, Windsor, UK.

Givoni, B. (1992). Comfort climate analysis and building design guidelines. Energy and Building, vol. 18, issue 1, pp. 11-23.

Olgyay V. (1963). Design with climate, bioclimatic approach and architectural regionalism. Princeton (NJ): Princeton University Press

Olesen, B.W., and Brager, G.S., (2004). A better way to predict comfort: The new ASHRAE standard 55-2004. ASHRAE Journal, vol. 46, no. 8, pp. 20-28.

Taleghani, M., Martin, T., Stanley, K., and Andy, V. D. D., (2013). A review into thermal comfort in buildings, Renewable and Sustainable Energy Reviews, vol. 26, pp. 201-215.

Humphreys, M.A., and Nicol, J.F., (2002). The validity of ISO-PMV for predicting comfort votes in every-day thermal environment, Energy and Buildings, vol. 34, pp. 667-684.

Fountain, M., Brager, G., de Dear R., (1996). Expectations of indoor climate control, Energy and Buildings, vol. 24, pp 179-182.

de Dear, Richard J., and Gail S. B., (2002), "Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55." Energy and buildings, vol. 34, no. 6 (2002), pp. 549-561.

Feriadi, H. and Wong, N.H., (2004). Thermal comfort for naturally ventilated houses in Indonesia, Energy and Building, vol. l, pp. 614-626.

Wong, N. H., Feriadi, H., Lim, P. Y., Tham, K. W., Sekhar, C., and Cheong, K. W., (2002). Thermal comfort evaluation of naturally ventilated public housing in Singapore, Building and Environment, vol. 37, issue 12, pp. 1267-1277.

Brager, G.S., and de Dear, R., (1998). Developing an adaptive model of thermal comfort and preference, ASHRAE Transactions, vol. 104, pp. 145-167.

Busch, J.F., (1990). Thermal sensation to the Thai office environment, ASHRAE Transactions, vol. 96, pp. 17-35.

de Dear, R. and Auliciems, A., (1985), "Validation of the predicted mean vote model of thermal comfort in six Australian field studies", ASHRAE Transactions, vol. 91, pp 452-468.

Fanger, P.O. and Toftum, (2002). Extension of the PMV model to non-air conditioned buildings in warm climates, Energy and Buildings, vol. 34, pp. 533-536.

Nicol, J.F., (2004). Adaptive thermal comfort standards in the hot humid tropics, Energy and Buildings, vol. 36, pp. 628-637.

Nicol, F., Humphreys, M., Roaf, S., (2012). Adaptive Thermal Comfort: Principles and Practice, Routledge, Abingdon, pp. 2012.

Zheng. X., (2015). Thermal comfort research in naturally ventilated high- rise residential building, unpublished Master Thesis of Science in Building Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands, December 3th 2015.

Lin, Z., and Shiming, D., (2006). A questionnaire survey on sleeping thermal environment and bedroom air conditioning in high-rise residences in Hong Kong, Energy and Buildings, vol. 38, no. 11, pp. 1302-1307.

Dahlan, N. D., Phillip, J. J., Donald, K. A., Salleh, E., and Dylan D., (2008). Field measurement and subjects' votes assessment on thermal comfort in highrise hostels in Malaysia, Indoor and Built Environment, vol. 17, no. 4, pp. 334-345.

Madhavi, I., (2010). Thermal comfort in naturally ventilated apartments in summer: findings from a field study in Hyderabad, India, Applied Energy, vol. 87, no. 3, pp. 866- 883.

Kr"uger, E., and Givoni, B., (2008). Thermal monitoring and indoor temperature predictions in passive solar building in an arid environment, Building and Environment, vol. 43, issue 11, pp. 1792 – 1804.

Nicol, J.F., and Humphreys, M. A., (2010). Derivation of the equation for comfort in free-running buildings in CEN Standard, EN 1521, Building and Environment, vol. 45, issue 1, pp. 7 -11.

Tanabe, S. (1988). Thermal Comfort Requirement in Japan. Tokyo, Japan: Waseda University.

Nicol, J.F., (1974) An analysis of some observations of thermal comfort in Roorkee, India and Baghdad, Iraq. Annals of Human Biology, vol. 1, issue 4, pp. 411–426.

Humphreys M.A., and Nicol, J.F., (1970). An investigation into the thermal comfort of office workers, Journal of Institute of Heating and Ventilation Engineers, (now CIBSE), vol. 38. pp. 181-189.

Ahmed, Z.N., (1994), Assessment of residential sites in Dhaka with respect to solar radiation gain, Ph.D. thesis (Unpublished), De Montfort University in collaboration with the University of Sheffield.

Mallick, F. H., (1996). Thermal comfort and building design in the tropical climates, Energy and Buildings, vol. 23, pp. 161-167.

Mallick, F. H., (1994). Thermal Comfort for Urban Housing in Bangladesh, unpublished PhD Thesis, EESP, Architecture Association, London.

Hong, T., Chou, S.K., Bong, T.Y., (2000). Building simulation: An overview of developments and information sources, Elsevier Journal of Building and Environment, vol. 35, no. pp. 347 – 361.

Nguyen, A. T., Reiter, S., Rigo, P., (2014). A review on simulation-based optimization methods applied to building performance analysis, Applied Energy, vol. 113, pp. 1043–1058.

Mahdavi, A. and El-Bellahy, S. (2005). Efforts and effectiveness considerations in computational design evaluation: A case study, Elsevier Journal of Building and Environment, vol. 40, Issue 12, pp. 1664- 1651.

McElroy L., and Clarke, J.A., (1999). Embedding simulation within energy sector business, Proceedings of the 6th IBPSA Conference, Building Simulation, vol. 99, pp. 262-268, Kyoto.

Holm, D., (1993). Building thermal analysis: What the industry needs: The architectural perspective" Building and Environment, Building and Environment, vol. 28, no. 4, pp 405-407.

Augenbroe, G., (1992). Integrated building performance evaluation in the early design stages, Elsevier Journal of Building and Environment, vol. 27, no. 2, pp 149-161.

Lawson, B., (1990). How designers think – The design process demystified, Butterworth Architecture, pp 15-17.

Banks, J., Carson, J., Nelson, B., Nicol, D., (2001). Discrete-event system simulation. Published by Prentice Hall, Pearson.

Attia, S. (2010). Building performance simulation tools: Selection criteria and user survey; Université Catholique de Louvain, Louvain La Neuve, Belgium.

US GSA U.S. (2010). General Services Administration, Statsbygg and Senate, Information Delivery Manual (IDM) for BIM Based Energy Analysis as Part of the Concept Design BIM, Available online: www.blis-project.org/IAI-MVD/IDM/BSA-002/PM_BSA-002.pdf, accessed on 12th January 2013.

Wang L, Wong N.H, (2009). Coupled simulations for naturally ventilated rooms between building simulation (BS) and computational fluid dynamics (CFD) for better prediction of indoor thermal environment, Elsevier Journal of Building and Environment, vol. 44, issue 1, pp. 95–112.

Wang L, Wong N.H, (2006). The impact of façade designs: orientations, window to wall ratios and shading devices on indoor environment for naturally ventilated residential buildings in Singapore, PLEA 2006 - The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland.

Wang L, Wong N.H, (2008). Coupled simulations for naturally ventilated residential buildings", Elsevier Journal of Automation in Construction, vol. 17, pp 386–398.

Chapter 03

Ahmed, R., (2006). Climate, BANGLAPEDIA, National Encyclopedia of Bangladesh, [online], accessed in 11 November, 2016, available in http://www.banglapedia.org/httpdocs/HT/C_0288.HTM

BBS, (2011). Bangladesh Bureau of Statistics (BBS), Monthly Statistical Bulletin – February, 2011, Bangladesh Bureau of Statistics, Ministry of Planning.

BBS, (1984). Bangladesh Bureau of Statistics (BBS), Bangladesh population census, 1981, National series, analytical findings and national tables, Bangladesh Bureau of Statistics, Ministry of Planning.

BBS, (2012). Bangladesh Bureau of Statistics (BBS), Population and housing census, 2011, Community series - Dhaka, Gazipur, Narayangang, Bangladesh Bureau of Statistics, Ministry of Planning.

UN, (2012). United Nations, World Urbanization Prospects - The 2011 revision, Department of Economic and Social Affairs, Population Division, New York.

Dewan, A., Corner, R., (2014). Dhaka Megacity, Geospatial Perspectives on Urbanization, Environment and Health, Springer Geography.

World Atlas Travel [online], accessed on: 16 November, 2016, available at www.worldatlas.com

Ahmed, Z.N., (1987), The Effects of climate on the design and location of windows in Bangladesh, MPhil thesis, Sheffield City Polytechnic.

Rashid, H., (1991), Geography of Bangladesh, 2nd edition, The University Press Limited, Dhaka

Mridha, A. M. M. H., (2002). A Study of thermal performance of operable roof insulation, with special reference to Dhaka, unpublished M. Arch. Thesis, Department of Architecture, Bangladesh University of Engineering and Technology, BUET, Dhaka.

Ahmed, K. S., (1995). Approaches to bioclimatic urban design for the tropics with special reference to Dhaka, unpublished Bangladesh, PhD Thesis, EESP, Architecture Association, London.

Hossain, M.E., and Nooruddin, M., (1993). Global solar rdiation on horizontal surface in Dhaka, Proceedings of International Technical Conference on Tropical Urban Climates, Dhaka.

Khatun, M. A., Rashid, M. B. and Hygen, H. O., (2016). Climate of Bangladesh, Met Report, Norwegian Meteorological Institute.

Khan M.J., Iqbal, M.T. and Mahboob, S. (2004). A wind map of Bangladesh, Elsevier Journal of Renewable Energy, vol. 29, pp. 643–660.

Hasan, A.B.M. S. U., and Rahman, M. Z., (2013), Change in Temperature over Bangladesh Associated with Degrees of Global Warming, Asian Journal of Applied Science and Engineering, Vol 2, No 2, pp. 62 – 75.

Asaduzzaman and Rob, (1997). Environmental control over urbanization of Dhaka City (Dhaka: The Mappa).

Islam, M. S., Shahabuddin, A. K. M, Kamal, M. M., and Ahmed, R., (2012). Wetlands of Dhaka city: Its past and present scenario, Journal of Faculty of Life and Earth Science, University of Rajshahi, Bangladesh, Vol. 7, pp. 83-90.

Koenigsberger, O. H., Ingersoll, T. G., Mayhew A., and Szokolay, S. V., (1973). Manual of Tropical Housing and Building Design: Climatic Design, published by Orient Longman Private LTD., London.

Rashid, H., (1991), Geography of Bangladesh, 2nd edition, The University Press Limited, Dhaka

BMD (2016). Bangladesh Meteorological Department, Climate Division, (online), accessed on January 2016, available at www.bmd.gov.bd.

Mohiuddin, H., Bhuiya, M. M. R. and Mamun, M. M. A, (2014). An analysis of the temperature change of Dhaka city, Proceedings of 5th International Conference on Environmental Aspects of Bangladesh [ICEAB 2014], pp. 46-48.

Ahmed, Z.N., (1994) Assessment of Residential sites in Dhaka with respect to solar radiation gain, unpublished Ph.D. Thesis, De Montfort University, in collaboration with the University of Sheffield.

Roy, G.S., (2010). Thermal environment in residential areas of Metropolitan Dhaka: Effects of densification, unpublished Master's Thesis, Department of Architecture, BUET. pp-23-34.

BMD (2012). Bangladesh Meteorological Department, Climate Division, Agargoan, Dhaka.

Rashid, R., (2008). Thermal performance of Bangladesh traditional house during winter and summer seasons, unpublished Master's Thesis, Faculty of Built Environment, Universiti Teknologi Malaysia, Malaysia.

Tariq, T., (2014). Investigation of perception of thermal condition of naturally ventilated classroom environment during warm periods in Dhaka, unpublished MASTERs Thesis, Department of Architecture, Bangladesh University of Engineering and Technology, (BUET), Dhaka, Bangladesh.

Shahjahan, A., (2012). An investigation of indoor thermal comfort range for rural houses of Dhaka region, unpublished Master's Thesis, Bangladesh University of Engineering and Technology, (BUET), Dhaka, Bangladesh.

Mourshed, M, (2011). The impact of the projected changes in temperature on heating and cooling requirements in buildings in Dhaka, Bangladesh. Applied Energy, vol. 88, issue 11, pp. 3737 – 3746.

Ishrat, A. K., Matin I. and Banu D.A. (2013). Recent climatic trends in Bangladesh, Daffodil International University Journal of Science and Technology, vol. 8, issue 2, pp. 43-50.

Wyon, D., (2000). Enhancing productivity while reducing energy use in buildings, Proceedings of the conference, the Ronald Reagan Buildings and International Trade Centre, Washington D.C, U.S.A.

Seppänen, O., W.J. Fisk, and D. Faulkner, (2004). Control of temperature for health and productivity in offices, ASHRAE Transactions, Vol. 111, part 2, pp. 680 – 686.

Wan, K.K.W., Li, D.H.W., Pan, W., Lam, J.C., (2012). Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications, Applied Energy, vol. 97, pp. 274-282.

Xu, P., Huang, Y.J., Miller, N., Schlegel, N., Shen, P., (2012). Impacts of climate on heating and cooling energy patterns in California. Energy, vol. 44, pp. 792–804.

Wang, X., Chen D., Ren, Z., (2010). Assessment of climate change impact on residential building heating and cooling energy requirement in Australia, Building and Environment, vol. 45, pp. 1663-1682.

Lebassi, B., Gonnzález, J. E., Fabris, D., Bornstein, R., (2010). Impacts of climate change in degree days and energy demand in coastal California, J. of Solar Energy Engineering, vol. 132, pp. 0310051-0310059.

Collins, L., Natarajan, S., Levermore, G., (2010). Climate change and future energy consumption in UK housing stock, Building Service. Eng. Res. Technol., vol. 31, no. 1, pp. 75–90.

Lam, T.N.T., Wan, K.K.W., Wong, S.L., Lam, J.C., (2010). Impact of climate change on commercial sector air conditioning energy consumption in subtropical Hong Kong, Applied Energy 87, pp. 2321-2327.

Papakostas, K.T., Zagana-Papavasileiou, P., Mavromatis T., (2014). Analysis of 3 decades temperature data for Athens and Thessaloniki, Greece - Impact of Temperature Changes on Energy Consumption for Heating and Cooling of Buildings, Proceedings' of the International Conference ADAPTtoCLIMATE, Nicosia, Cypris, 27-28, March.

Ahmed, B., Raj, M. R. H., Maniruzzaman, K. M. (2009). Morphological change of Dhaka city over a period of 55 years: A case study of two wards, Journal of Bangladesh Institute of Planners, vol. 2, pp. 30-38.

BBS, (2008). Bangladesh Bureau of Statistics (BBS), Bangladesh population census, 2001, vol.3, National series, Urban Area Report, Bangladesh Bureau of Statistics, Ministry of Planning.

UN, (2011). United Nations, World Urbanization Prospects, Department of Economic and Social Affairs, Population Division, New York.

Rahman, I., (2014). Necessity and benefits of FAR: A proposal for Dhanmondi residential Area of Dhaka City, unpublished Masters thesis, Department of Architecture, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

Begum A., (2007). Urban housing as an issue of redistribution through planning? The case of Dhaka city. International Journal of Social Policy and Administration, vol. 41, issue. 4, pp- 410 -418, John Wiley & Sons Ltd.

Mourshed M., and Mallick F. H., (2012). Adapting buildings to climate change, Journal of Open House International Association, vol. 37, issue. 4, 5pp, Loughborough University Institutional Repository.

Alam, M. and Rabbani, M.G., (2007). Vulnerabilities and responses to climate change for Dhaka, Environment and Urbanization, vol, 19, issue. 1, pp. 81-98.

JICA, (2015). Energy Efficiency and Conservation Master Plan up to 2030, Final Report Annex of the Project for Development of Energy Efficiency and Conservation Master Plan in Bangladesh, March 2015.

Moushumi A., (2010). Energy efficiency of residential buildings in Dhaka city; Implications for sustainable urban planning, unpublished Master Thesis, Department of Urban and Regional Planning, Bangladesh University of Engineering and Technology.

UNEP, (2009). Summary for Decision-Makers, Buildings and Climate Change, Sustainable Buildings and Climate Initiative.

Tariq, S. H., (2016). An investigation on energy consumption for thermal comfort with respect to plan layout of residential apartment buildings in Dhaka, unpublished Masters thesis, Department of Architecture, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

Ali, Z. F., (2007). Comfort with courtyards in Dhaka apartments, BRAC University Journal, vol. 4, no.2, pp. 1–6.

Rattia, C., Bakerb, N., and Steemers, K. (2005). Energy consumption and urban texture, Energy and Buildings, vol. 37, pp. 762-776.

Rahman K.M.M, (2011). Electricity Scenario in Bangladesh, The Innovators, Center for Research and Development, November 2011.

PSMP (2011). Power System Master Plan 2010; Power Division, Ministry of Power, Energy and Mineral Resources (MPEMR); February 2011.

Power Cell, (2014). Ministry of Power, Energy and Mineral Resources (MPEMR).

REHAB, (2012). A comprehensive study on the real estate sector of Bangladesh. Retrieved from www.rehabbd.org.

Haque, M. M., (2008). Provision of housing finance for middle income people of Dhaka City: Application of government policies, unpublished BURP Thesis, Department of Urban and Regional Planning, Jahangirnagar University, Savar, Dhaka.

Barua, S., Mridha, A. H. A. M., and Khan, R. H., (2010). Housing real estate sector in Bangladesh present status and policies implications, ASA University Review, vol. 4, issue 1.

BNBC, (2006). Bangladesh National Building Code.

Kamruzzaman, M and Ogura, N.: 2007, Apartment Housing in Dhaka City: Past, Present and Characteristic Outlook, Session A-1: Residential Building/Young Researchers Award, Department of Civil Engineering and Architecture, Faculty of Engineering, University of the Ryukyu's, 1 Senbaru, Nishihara, Okinawa 903-0213, Japan.

Begum, T. (2010). A Study on Trend Analysis of Apartment Housing by Private Developers in DCC Area, unpublished MURP Thesis, Bangladesh University of Engineering and Technology (BUET), Dhaka.

Zahur, M. (2008). Private apartment housing for middle income people: A study on affordability, unpublished MURP thesis, Bangladesh University of Engineering and Technology, Dhaka.

Gomes, C.D., (2015). Visibility effecting gender aspects in middle income group apartments in Dhaka, Proceedings of the 10th International Space Syntax Symposium (SSS10), pp. 104:1 – 104:15, July, 2015.

REHAB, (2016). Real Estate and Housing Association of Bangladesh, available at www.rehab-bd.org, accessed on 22nd, March, 2016.

Hasan, M. (1991). Land development policy for low-income housing in Dhaka Metropolitan Area, Unpublished MURP thesis, Bangladesh University of Engineering and Technology, Dhaka.

Labib, S.M., Bhuiya M. M. R. and Rahaman M. Z, (2013). Location and size preference for apartments in Dhaka and prospect of real estate market, Bangladesh Research Publications Journal, vol 9, issue 2, pp. 87-96.

Seraj, T. M., (2012). Private Sector Housing, Parl Publication, Dhaka.

Seraj, T. M., (2011). Real Estate Development in Dhaka. In: Roxena, H. and Rabbani, A.K.M.G., ed. 2011. 400 Years of Capital Dhaka and Beyond: Urbanization and Urban Development, vol-III. Dhaka: The Asiatic Society of Bangladesh.

Chapter 04

REHAB, (2015). Real Estate and Housing Association of Bangladesh, [online], accessed on 22nd January, 2015, available at www.rehab-bd.org

BNBC, (2006). Bangladesh National Building Code.

Ryken, A. E., Otto, P., Pritchard, K., Owens, K., (2007). Field investigations: Using outdoor environments to foster student learning of scientific processes, A Project of the Association of Fish and Wildlife Agencies' North American Conservation Education Strategy; Developed by the Pacific Education Institute Funded by a Multistate Grant of the Sport Fish and Wildlife Restoration Program.

Dörnyei, Z., (2007). Research methods in applied linguistics, New York: Oxford University Press.

Saumure, K., and Given, L. (2008). Convenience Sample. In L. Given (Ed.), The SAGE Encyclopedia of Qualitative Research Methods, Thousand Oaks, CA: SAGE Publications.

Palinkas LA, Horwitz SM, Green CA, Wisdom JP, Duan N, Hoagwood K., (2013). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research, Administration and Policy in Mental Health and Mental Health Services Research.

www.maximintegrated.com, Maxim Integrated, (2016), accessed on February, 2016

Chapter 05

EnergyPlus, (2016), Wheather Data, EnergyPlus, accessed on 25th august, 2015, available at https://energyplus.net/weather location/asia_wmo_region_2/BGD//BGD_Dhaka.419230_SWERA

Arif, Q. A and Islam, I., (2002). Urban dwelling in tropical climate of Dhaka: Guidelines for energy conscious and contextual architecture, PLEA 2005, 22nd International Conference on Passive and Low Energy Architecture, pp. 522 – 528.

Koenigsberger, O. H., Ingersoll, T. G., Mayhew A., and Szokolay, S. V., (1973). Manual of Tropical Housing and Building Design: Climatic Design, published by Orient Longman Private Ltd., London.

DESCO Appliance Calculator, (2016). Dhaka Electric Supply Company Limited, Nikunja Dhaka, accessed on 12th March, 2016, available in https://www.desco.org.bd/index.php?page=bill-calculator

Tariq, T., (2014). Investigation of perception of thermal condition of naturally ventilated classroom environment during warm periods in Dhaka, unpublished MASTERs Thesis, Department of Architecture, Bangladesh University of Engineering and Technology, (BUET), Dhaka, Bangladesh.

BMD (2016). Bangladesh Meteorological Department, Climate Division, (online), accessed on January 2016, available at www.bmd.gov.bd.

ISA (1975). International Standard Atmosphere, published by International Organization for Standardization, Geneva, Switzerland.

Appendix H

Wang, E., Shen, Z., Barryman, C., (2011). A building LCA case study using Autodesk Ecotect and BIM model, 47th Associated Schools of Construction (ASC), Annual International Conference Proceedings: Construction Systems: Papers in Construction Management.

Crawley, D.B., Hand, J.W., Kummert, M., Griffith, B.T., (2008). Contrasting the capabilities of building energy performance simulation programs, Building and Environment, vol. 43, pp. 661–673.

Marsh, A. J., (2006). Thermal Modelling: The AUTODESK ECOTECT Way. Natural frequency, July 04(002).

Abdullah, A.H., Bakar, S.K.A., Rahman, I.A., (2013). Simulation of office's operative temperature using Ecotect model. International Journal of Construction Technology and Management, vol. 1, issue 1, pp. 33–37

Attia S. and Herde, A. D., (2011). Early design simulation tools for net zero energy buildings: A comparison of ten tools, Proceedings of the 12th International Building Performance Simulation Association, Sydney, Australia.

Vangimalla, P.R., Olbina, S.J., Issa, R.R., Hinze, J., (2011). Validation of Autodesk Ecotect^{TM} accuracy for thermal and daylighting simulations, Simulation Conference (WSC), Proceedings of the 2011 Winter. IEEE, pp. 3383–3394.

Ibarra, D.I. and C.F. Reinhart, (2009). Daylight factor simulations-how close do simulation beginners 'Really' Get? Proceedings of the 11th International IBPSA Conference, Jul. 27-30, Glasgow, Scotland. pp: 1-8.

Neslihan, T., Bayraktar, K. E., Omondi, O. S., (2013). Analysis of zoning strategies of dynamic thermal simulations on an existing structure, Conference: SB13 Munich: Implementing Sustainability, At Munich.

Kheiri, F., (2013). The relation of orientation and dimensional specifications of window with building energy consumption in four different climates of Köppen classification, Researcher Science Journal, vol. 5, issue 12, pp. 107 – 115

Bakar, S. K. B. A., (2013). An evaluation of passive cooling strategies on indoor thermal performance of an office space, unpublished Master thesis, Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn, Malaysia.

Madhumathi A., Vishnupriya J., Vignesh S, (2014). Sustainability of traditional rural mud houses in Tamilnadu, India: An analysis related to thermal comfort, Journal of Multidisciplinary Engineering Science and Technology (JMEST), vol. 1, issue 5.

Dhanasekaran, M. and Jayasudha, P., (2014). Thermal Performance Assessment of a Vernacular Residence in Thanjavur Region, Journal of Innovative Research and Solution (JIRAS)- A unit of UIIRS, vol. 1, issue 1, pp. 376 – 388.

Trisha, S. H., (2015). Assessment of HVAC Load in the Light Zones to Determine Energy Efficient Shading for Tall Office Buildings of Dhaka, unpublished Masters thesis, Department of Architecture, Bangladesh University of Engineeering and Technology, Dhaka, Bangladesh.

Suxian Z. and Bo F. (2016). Analysis of thermal environment of existing residential building envelope energy-saving in ECOTECT simulation, Proceedings of the 3rd International Conference on Materials Engineering, Manufacturing Technology and Control, pp 442 – 446.

Tariq, S. H., (2016). An Investigation on Energy Consumption for Thermal Comfort with Respect to Plan Layout of Residential Apartment Buildings in Dhaka, unpublished Masters thesis, Department of Architecture, Bangladesh University of Engineeering and Technology, Dhaka, Bangladesh.

Autodesk, (2015). Autodesk Ecotect Analysis, accessed on 10th August, 2015, available at http://www.autodesk.com.au.

Beattie, K.H., and Ward, I. C., (2012). The advantages of building simulation for building design engineers, available at: http://www.ibpsa.org/proceedings/BS1999/BS 99_PB-16.pdf

Gado, T., and Mohamed, M. (2014). Investigating the process of exporting Autodesk Ecotect models to detailed thermal simulation software*,* Environment and Ecology Research*,* vol. *2*, issue 5, pp. 209-220.

Appendix A: QUESTIONNAIRE FOR DEVELOPERS

		RANGS PROPERTIES LTD.	AMIN MOHAMMAD LTD.	SUVASTU DEVELOPMENTS LTD.	SOUTH BREEZE HOUSING LTD.	SHELTECH (PVT) LTD
1	**What is the % of people interested to buy apartments**	20	30	80	40	30
2	**What is the % of people interested to build their own houses?**	80	70	20	60	70
3	**What can be the possible demand percentage for buying flats in the next 3/5/10 years?**	(10)-(25)-(75)	(10)-(25)-(40)	(30)-(20)-(30)	0)-(30(15)-(25)-(50)	(30)-(2
4	**Which areas of Dhaka city have the highest preference for buying flat and why?[Please mark the areas by numbers according to preference (Ex. 1: most preferred, 14: least preferred)]**					
	Mirpur	1	7	2	1	3
	Dhanmondi	5	5	3	9	2
	Uttara	1	13	4	1	4
	Khilgaon	5	12	10	5	10
	Mohammadpur	1	6	1	1	1
	Bashundhara	5	8	11	5	12
	DOHS	5	3	12	6	11
	Gulshan	1	1	7	8	8
	Baridhara	5	4	8	7	7
	Mogbazar	5	11	3	5	3
	Farmgate	1	10	13	1	14
	Banani	1	2	5	10	5
	Shegunbagicha	5	9	6	5	6
	Others		14	14		13
5	**Which age groups of buyers are most interested to buy flat?[Please mark by numbers according to preference (Ex. 1: most preferred, 5: least preferred)]**					
	30 or less	5	5	5	5	5
	30 to 40	2	3	3	2	3
	40 to 50	1	1	1	1	1
	50 to 60	3	2	2	4	2
	60+	4	4	4	3	4

6	**What are the possible occupation ranges of buyers to buy flat?[Please mark by numbers according to preference (Ex. 1: most preferred, 5: least preferred)]**					
	Doctor	1	2	5	1	3
	Engineer	2	3	6	2	2
	Banker	1	4	3	1	4
	Teacher	4	5	7	3	5
	Business	1	1	1	1	1
	Lawyer	2	6	2	2	6
	Service	4	7	4	4	8
	Others		8	8		7
7	**Area wise average size ranges of apartments in different areas of the city:**					
RANGE 01	**Mirpur**	600-800	1000-1200	800-1300		800-1300
	Dhanmondi	1200-1500	2000-2500	1500-2200	1200-1500	1500-2200
	Uttara	1000-1200	1200-1400	1500-1800	1000-1200	1500-1800
	Khilgaon	1000-1200	1200-1400			1000-1200
	Mohammadpur	600-800	1200-1400	1200-2200	600-800	1200-2200
	Bashundhara	1200-1500	1500-2000	1500-1800	1200-1500	1500-1800
	DOHS	1200-1500		1500-2000	1200-1500	1500-2000
	Gulshan	1200-1500	3000-4000	2200-4000	1200-1500	2200-4000
	Baridhara	1200-1500	2500-3500	3000+	1200-1500	3000+
	Mogbazar	4000-5000	1200-1500			4000-5000
	Farmgate	600-800			600-800	600-800
	Banani	1200-1500	1500-3000	2000-3000	1200-1500	2000-3000
	Shegunbagicha	1000-1200	1200-1500			
RANGE 02	**Mirpur**	800-1200	1200-1400			
	Dhanmondi	1500-2000	2500-3500		1500-2000	
	Uttara	1200-1500	1400-1500		1200-1500	
	Khilgaon	1200-1500				
	Mohammadpur	800-1200	1400-1600		800-1200	
	Bashundhara	1500-2000	2000-2500		1500-2000	
	DOHS	1500-2000			1500-2000	
	Gulshan	1500-2000	4000-5000		1500-2000	
	Baridhara	1500-2000			1500-2000	
	Mogbazar	800-1200				
	Farmgate	800-1200			800-1200	
	Banani	1500-2000			1500-2000	
	Shegunbagicha	1200-1500				

8	**Area wise average price ranges of apartments in different areas of the city:**							
		RANGE 01	**Mirpur**	3500-4000	4000-5000	4500		4500
			Dhanmondi	7000-8000	10000-12000	10000	7000-8000	10000
			Uttara	4000-5000	6500-7500	6000	4000-5000	6000
			Khilgaon	6000-7000	4500-5000			7000
			Mohammadpur	4000-5000	6500-8500	6000	4000-5000	6000
			Bashundhara	7000-8000	6500-7500	6000	7000-8000	6000
			DOHS	7000-8000		8000-10000	7000-8000	10000
			Gulshan	10000-12000	18000-22000	15000	10000-12000	15000
			Baridhara	7000-8000	25000-28000	18000	7000-8000	18000
			Mogbazar	4000-5000	5000-6000			5000
			Farmgate	4000-5000			4000-5000	5000
			Banani	10000-12000	12000-14000	10000-12000	10000-12000	10000
			Shegunbagicha	6000-7000	10000-12000			
		RANGE 02	**Mirpur**	4000-5000	4500-5000			
			Dhanmondi	8000-9000	10000-12000		8000-9000	
			Uttara	4000-5000	6500-7500		4000-5000	
			Khilgaon	7000-8000				
			Mohammadpur	5000-6000	6500-8500		5000-6000	
			Bashundhara	8000-9000	6500-7500		8000-9000	
			DOHS	8000-9000			8000-9000	
			Gulshan	15000-20000	18000-22000		15000-20000	
			Baridhara	8000-9000			8000-9000	
			Mogbazar	5000-6000				
			Farmgate	5000-6000			5000-6000	
			Banani	15000-20000			15000-20000	
			Shegunbagicha	7000-8000				
9	**Which size range of apartments do the buyers prefer most?[Please mark by numbers according to preference (Ex. 1: most preferred, 12: least preferred)]**							
			>700	1	11	11	12	3
			700 – 1000	2	10	10	11	2
			1000 – 1200	3	2	6	5	1
			1200 – 1600	4	1	4	2	4
			1600 – 1800	6	3	1	1	6
			1800 – 2000	8	4	2	3	8
			2000 – 2400	10	5	3	4	10
			2400 – 2600	12	6	5	4	11
			2600 – 2800	12	7	7	6	11
			2800 – 3000	11	9	8	11	12
			3000 +	8	11	9	7	8
			Others	13	12	12	10	12

10	**Which orientation of flats have the highest demand and which has the lowest demand and why?[Please mark by numbers according to preference (Ex. 1: most preferred, 4:**					
	North	2	2	2	2	2
	South	1	1	1	1	1
	East	3	3	3	3	3
	West	4	4	4	4	4
11	**Which issues mainly guide the window size and location in an apartment?**					
	Size	Natural air ventilation, Direct Sun light, View towards streets or surroundings.	Natural air ventilation, Direct Sun light, View towards streets or surroundings.	Natural air ventilation, Direct Sun light, View towards streets or surroundings.	Natural air ventilation, Direct Sun light, View towards streets or surroundings.	Natural air ventilation, Direct Sun light, View towards streets or surroundings.
	Location	View towards streets or surroundings, Natural air ventilation, Direct Sun light	View towards streets or surroundings, Natural air ventilation, Direct Sun light	View towards streets or surroundings, Natural air ventilation, Direct Sun light	View towards streets or surroundings, Natural air ventilation, Direct Sun light	View towards streets or surroundings, Natural air ventilation, Direct Sun light
	Type	Slit type window for controlled light & elevation beauty, Full height for viewing & Elevation beauty, light & ventilation., Box window for basic ventilation & light.	Slit type window for controlled light & elevation beauty, Full height for viewing & Elevation beauty, light & ventilation., Box window for basic ventilation & light.	Slit type window for controlled light & elevation beauty, Full height for viewing & Elevation beauty, light & ventilation., Box window for basic ventilation & light.	Slit type window for controlled light & elevation beauty, Full height for viewing & Elevation beauty, light & ventilation., Box window for basic ventilation & light.	Slit type window for controlled light & elevation beauty, Full height for viewing & Elevation beauty, light & ventilation., Box window for basic ventilation & light.
12	**What is the typical type of window in the master bedroom?**					
	Single glass sliding	1	1	1	1	1
	Single glass sliding + mosquito net	1	1	1	1	1
	Double glass sliding				1	
	Double glass sliding + mosquito net					
	Others	1				
13	**What is the typical size of window in the master bedroom and living room of an apartment?**					
	Window Size	8'x5'x1'8"	7'x6'x10"	7'x6'x10"	8'x8'x1'8"	7'x6'x10"

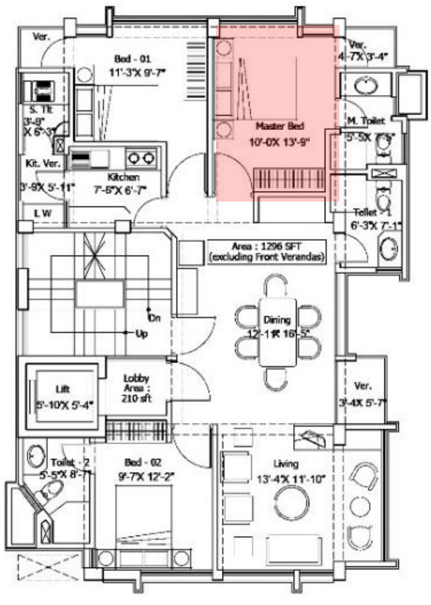
14	**Preference of window location [Please mark by numbers according to preference (Ex. 1: most preferred, 3: least preferred)]**					
	Corner alignment	2	1	1	2	1
	Central	3	3	3	3	3
15	**On which orientation is the window of master bedroom placed mostly? [Please mark by numbers according to preference (Ex. 1: most preferred, 4: least preferred)]**					
	North	3	3	2	2	2
	South	1	1	1	1	1
	East	2	2	3	3	3
	West	4	4	4	4	4
16	**What is the typical sill height in master bedroom and living room?**	2'-6"	2'-6"	0'-6" to 1'-0"	0'-6"	0'-6" to 1'-0"
17	**What is the typical lintel height in master bedroom and living room?**	7'-0"	7'-0"	7'-0"	8'-0"	7'-0"
18	**What is the typical window frame material used in master bedroom and living room?**	Matt Black Anodized Aluminum section		Aluminum swing	Matt Black or Silver Aluminum section	Silver Aluminum section
19	**What is the typical window glass specification used in master bedroom and living room?**	Single glazed 5mm non tempered clear white glass.		Double glazed	Single glazed 5mm non tempered clear white glass.	Single glazed 5mm non tempered tinted glass.

Appendix B: CASE STUDIED BUILDINGS

B.1

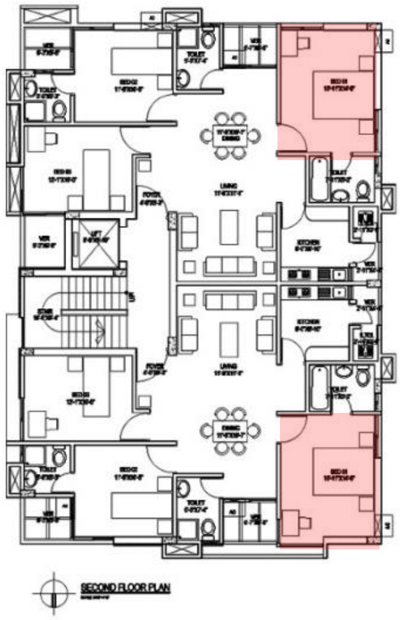
Location: Banani
Developer: SHELTECH
Unit Size: 102.19 sqm.
Master Bedroom Size: 3.05m x 4.57m
Window type: Sliding
Sill Height: 0.76m; Lintel Height: 2.13m

B.2.

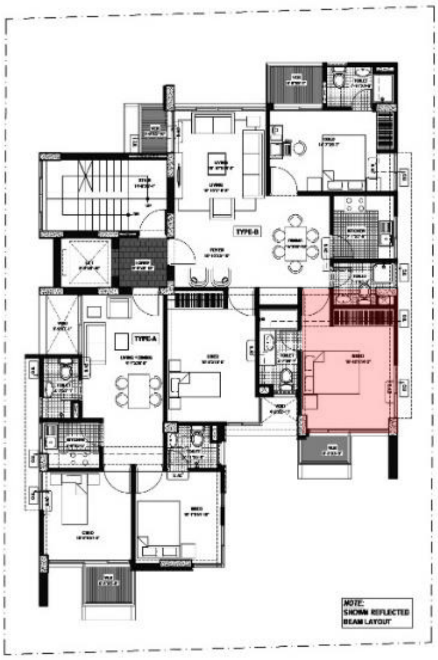


TYPICAL FLOOR PLAN

Location: Uttara
Developer: KEYSTONE PROPERTIES
Unit Size: 120.40 sqm.
Master Bedroom Size: 3.05m x 4.19m
Window Type: Sliding
Sill Height: 0.76m; Lintel Height: 2.13m



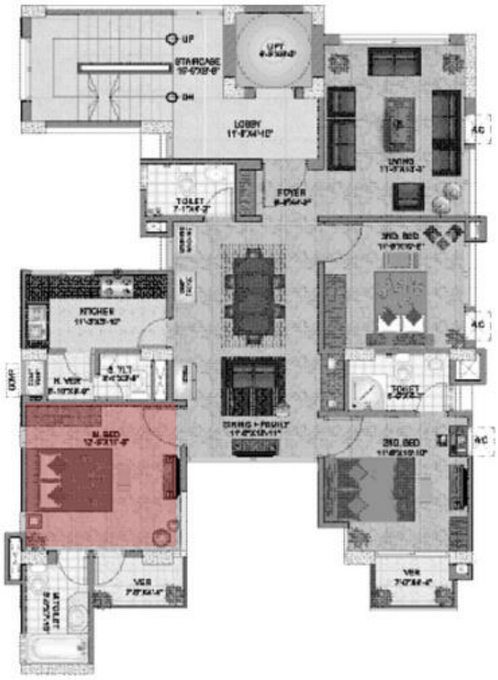
Location: Baridhara DOHS
Developer: ABODE PROPERTIES
Unit Size: 120.77 sqm.
Master Bedroom Size: 3.35m x 4.27m
Window Type: Sliding
Sill Height: 0.15m Lintel Height: 2.13m



3RD FLOOR PRESENTATION PLAN

Location: Uttara
Developer: AWR REAL ESTSTE
Unit Size: 130.06 sqm.
Master Bedroom Size: 3.30m x 4.32m
Window Type: Sliding
Sill Height: 0.15m; Lintel Height: 2.44m

B.5.



Location: Bashundhara
Developer: UNIMASS PROPERTIES
Unit Size: 120.77 sqm.
Master Bedroom size: 3.81m x 3.35m
Window Type: Sliding
Sill Height: 0.15m; Lintel Height: 2.13m

B.6.

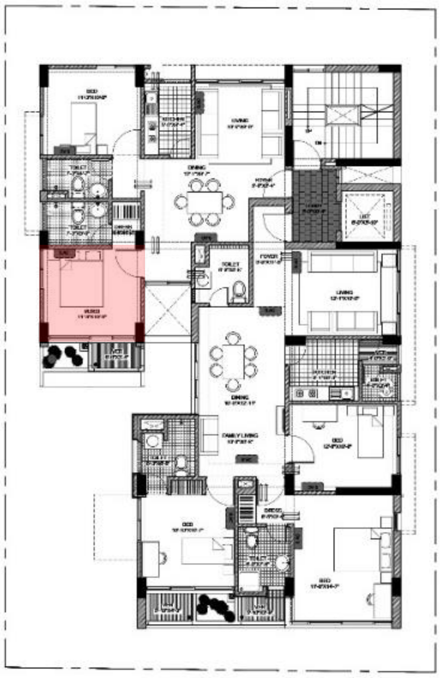
2ND TO 4TH FLOOR PLAN
NOT IN SCALE

Location: Mohammadpur
Developer: ASTER PARK
Unit Size: 139.35 sqm.
Master Bedroom Size: 3.66 x 4.44m
Window Type: Sliding
Sill Height: 0.15m; Lintel Height: 2.44m

B.7.

Location: Kathalbagan
Developer: SHELTECH LTD.
Unit Size: 139.35 sqm.
Master Bedroom Size: 4.83m x 3.43m
Window Type: Sliding
Sill Height: 0.76m; Lintel Height & 2.13m

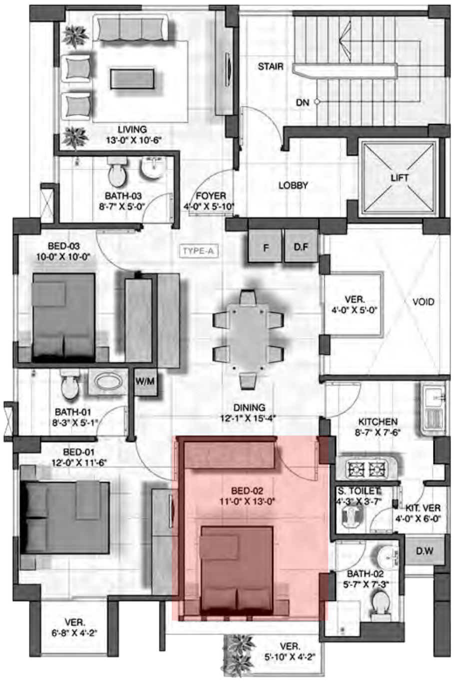
B.8.



TYPICAL FLOOR PLAN
SCALE: NOT IN SCALE

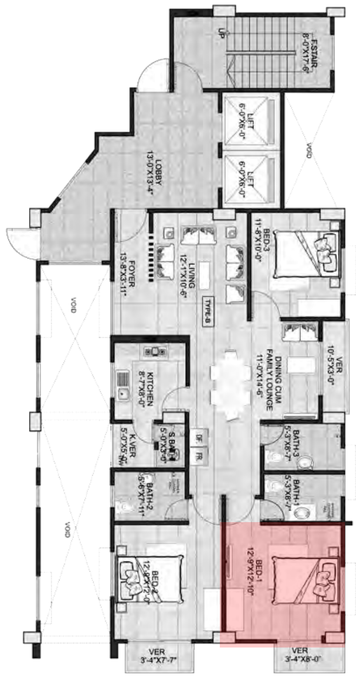
Location: Uttara
Developer: EPILION
Unit Size: 139.35 sqm.
Master Bedroom Size: 3.50m x 4.44m
Window Type: Sliding
Sill Height: 0.15m; Lintel Height & 2.44m

B.9.



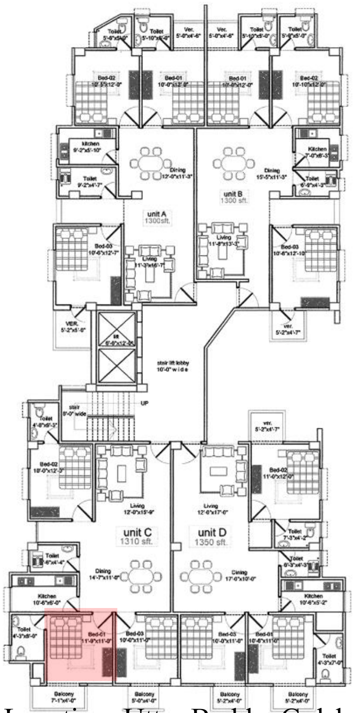
Location: Bashundhara R/A
Developer: Building Technology & Ideas Ltd.
Unit Size: 140.75 sqm.
Master Bedroom Size: 3.35m x 3.96m
Window Type: Sliding
Sill Height: 0.15m; Lintel Height: 2.13m

B.10.



Location: Aftabnagar
Developer: Building Technology & Ideas Ltd.
Unit Size: 111.48 sqm.
Master Bedroom Size: 3.89m x 3.91m
Window Type: Sliding
Sill Height: 0.76m; Lintel Height: 2.13m

B.11.

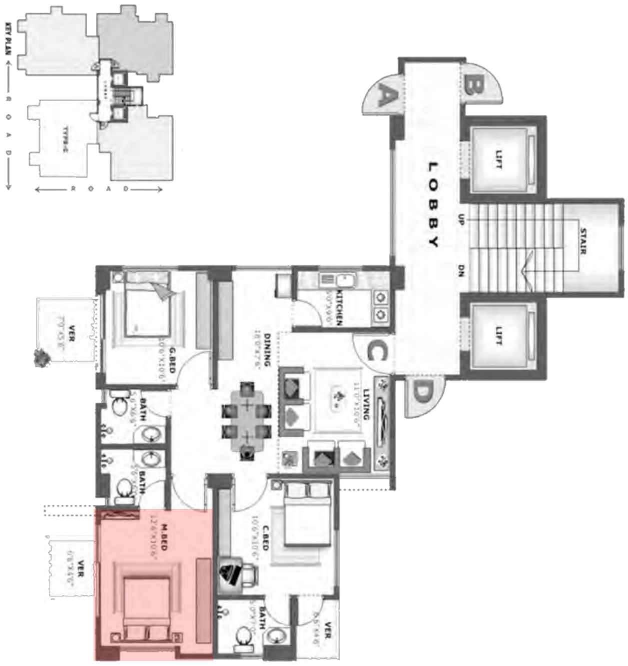


Location: Uttar Badda, Gulshan
Developer: Biswas Builders Limited
Unit Size: 120.77- 125.42 sqm.
Master Bedroom Size: 3.58m x 3.35m
Window Type: Sliding
Sill Height: 0.76m; Lintel Height: 2.13m

B.12.

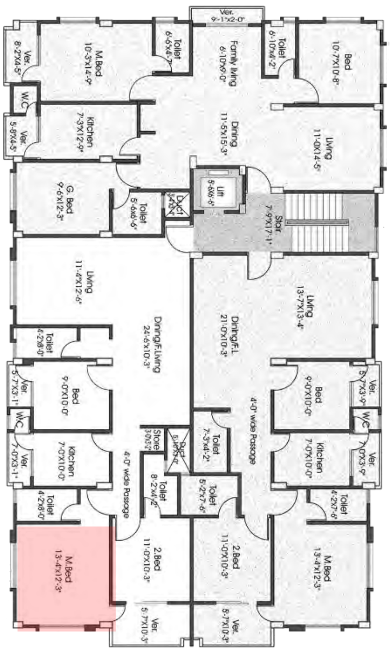
Location: Kalabagan, Dhanmondi
Developer: The Structural Engineers Ltd. (SEL)
Unit Size: 141.40 sqm.
Master Bedroom Size: 4.83m x 3.71m
Window Type: Sliding
Sill Height: 0.15m; Lintel Height: 2.13m

B.13.



Location: Mohakhali
Developer: Biswas Builders Ltd.
Unit Size: 111.48 sqm.
Master Bedroom Size: 3.81m x 3.20m
Window Type: Sliding
Sill Height: 0.76m; Lintel Height: 2.13m

B.14.



Location: West Dhanmondi
Developer: The Structural Engineers Ltd.
Unit Size: 131.92 sqm.
Master Bedroom Size: 4.06m x 3.73m
Window Type: Sliding
Sill Height: 0.76m; Lintel Height: 2.13m

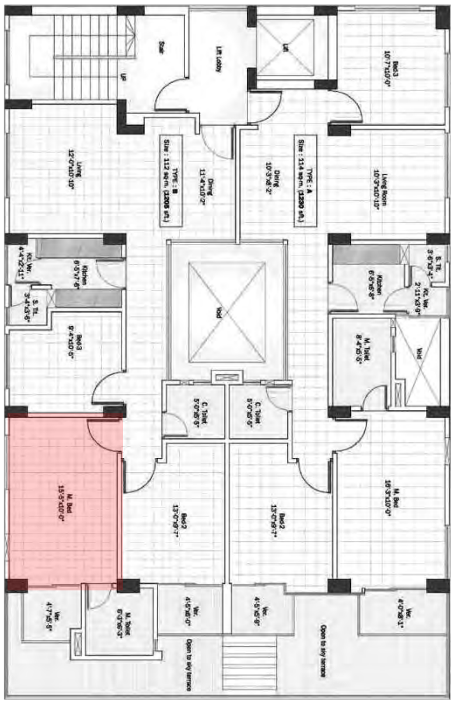
B.15.

Location: Kalabagan
Developer: The Structural Engineers Ltd.
Unit Size: 127.28 sqm.
Master Bedroom Size: 3.86m x 3.20m
Window Type: Sliding window
Sill Height: 0.15m; Lintel Height: 2.13m

B.16.

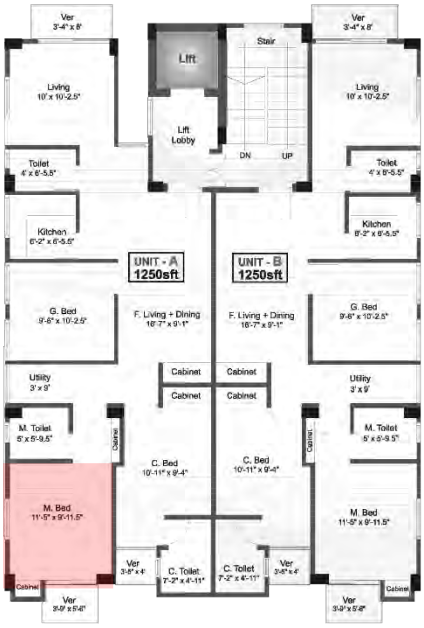
Location: West Dhanmondi
Developer: SHELTECH
Unit Size: 121.70 sqm.
Master Bedroom Size: 4.57m x 3.43m
Window Type: Sliding
Sill Height: 0.15m; Lintel Height: 2.44m

B.17.



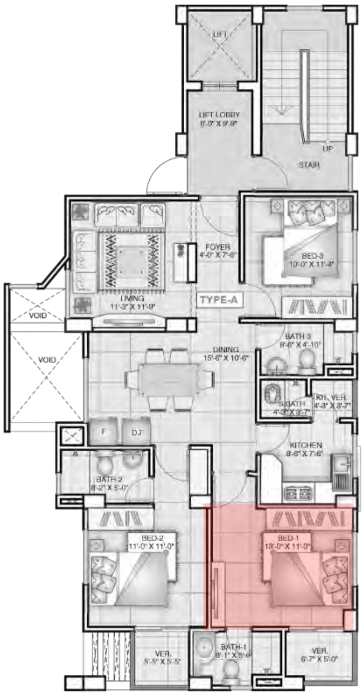
Location: Uttara
Developer: SHELTECH
Unit Size: 114.27 sqm.
Master Bedroom Size: 4.70m x 3.04m
Window Type: Sliding
Sill Height: 0.15m; Lintel height & 2.44m

B.18.



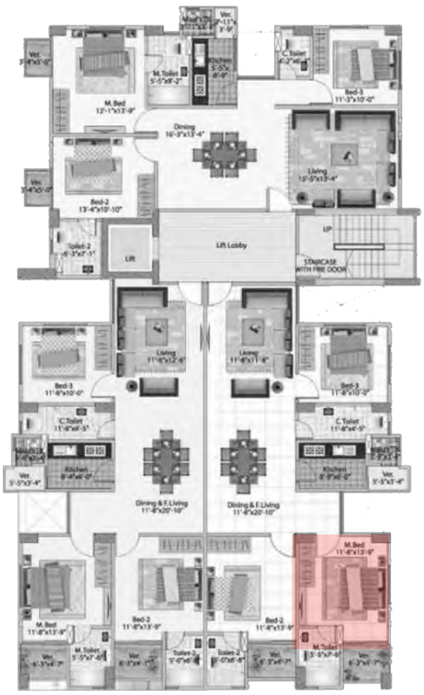
Location: Uttara
Developer: Bio Properties Ltd.
Unit Size: 116.13 sqm.
Master Bedroom Size: 3.48m x 3.48m
Window Type: Sliding window
Sill Height: 0.76m; Lintel Height: 2.13m

B.19.



Location: Aftabnagar
Developer: Building Technology & Ideas Ltd.
Unit Size: 133.59 sqm.
Master Bedroom Size: 3.96m x 3.35m
Window Type: Sliding
Sill Height: 0.15m; Lintel Height: 2.13m

B.20.



Location: Central Road
Developer: SHELTECH
Unit Size: 136.10 sqm.
Master Bedroom Size: 3.56m x 4.19m
Window Type: Sliding
Sill Height: 0.76m; Lintel Height: 2.13m

Appendix C: QUESTIONNAIRE FOR INTERVIEWING OCCUPANTS

1. Date & Time:

2. Name:

3. Age:

4. Sex:

5. No. of Occupants:

6. Daily activity pattern of each occupants:

Occupants	**Activity Pattern**				
	6am to 9am	**9am to 12noon**	**12noon to 3pm**	**3pm to 6pm**	**6pm to 9pm**
Husband					
Wife					

		6am to 9am	**9am to 12noon**	**12noon to 3pm**	**3pm to 6pm**	**6pm to 9pm**	**6am to 9am**
10.	**Clothing type**						
11.	**Appliances used**						
(a)	TV						
(b)	Fan (with speed)						
(c)	Tube light						
(d)	Wall bracket						
(e)	Mobile						
(f)	Others						
12.	**Door status (open / Close / partially open)**						
(a)	On East wall						
(b)	On South wall (towards verandah)						

(c)	On north wall (towards toilet)						
13.	**Window status (open / Close / partially open)**						
(a)	On West wall						
(b)	On South wall						
14.	**Drape status (covered / uncovered / partially covered)**						
(a)	On West wall						
(b)	On South wall						
15.	**When and at which point was the ceiling fan switched on (if used)?**						
16.	**What is the most common fan speed throughout the study period?**						
	1						
	2						
	3						
	4						
	5						

Appendix D: OBSERVATION CRITERIONS

1. Date:

2. Room dimension:

Subject	**Length**	**Width**	**Height**	**Area**	**Volume**
Bedroom					

3. Appliances Found Inside the Room:

4. No of Windows, Location and Size:

No.	**Orientation**	**Location on wall**	**Type**	**Size (Length X Height)**	**Sill height**	**Lintel height**	**Material**
1.	South Wall						
2.	West Wall						

5. Sunshade Location and Size:

Location	**Length**	**Width**	**Depth**	**Height**	**Material**

6. No. of Doors, Location and Size:

No.	**Orientation**	**Location on wall**	**Type**	**Size (Length X Height)**	**Material**
1.	East Wall				
2.	South wall				
3.	North Wall				

Appendix E: **COMPARISON BETWEEN MEASURED VALUE AND SIMULATED VALUE OF INDOOR AIR TEMPERATURE**

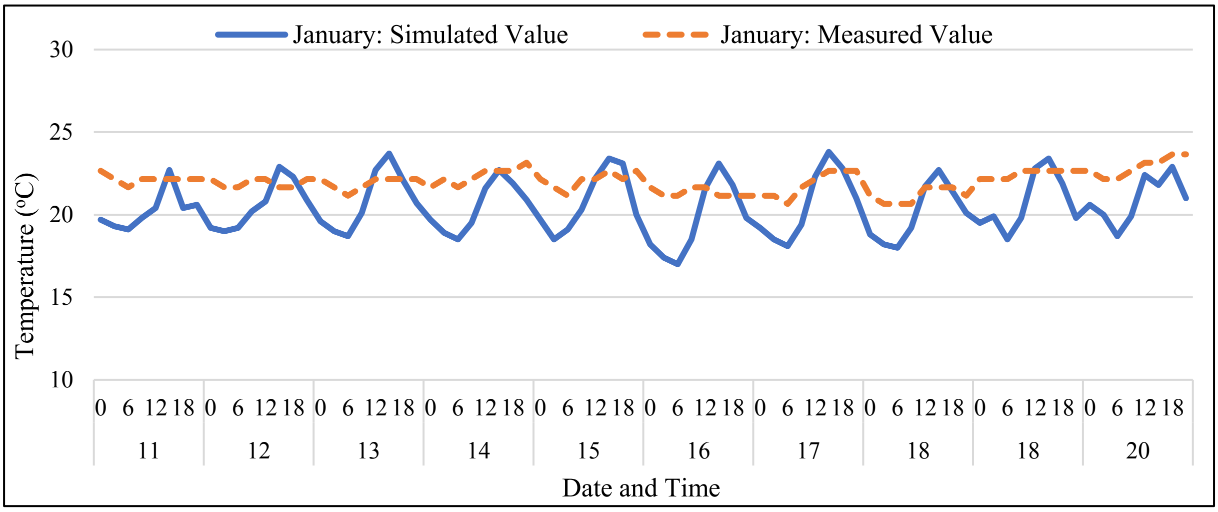
The indoor conditions of the modelled room were setup exactly the same way as it was in the surveyed room (Section 4.3). The results of Ecotect were authenticated by comparing the data obtained from field investigation and the simulated value for the same case. A temperature data logger, cited in Section 4.4.4, was used to record the 24-hour temperature, at intervals of 1hour, for the last ten days of April (21 to 30), first 10 days of May (1 to 10) (summer months, Section 3.2.1) in 2016 and later on, for mid-10 days January (11 to 20) in 2017. Hourly readings, of multiple days of three different months, were taken to improve data accuracy. Using Eq. E.1 and E.2, the difference and the percentage difference between the measured and simulated value of temperature are calculated. The temperature variation between the simulated values and measured data of indoor air temperature, showed a minor degree of variation, of around 6.57%, which is within the acceptable

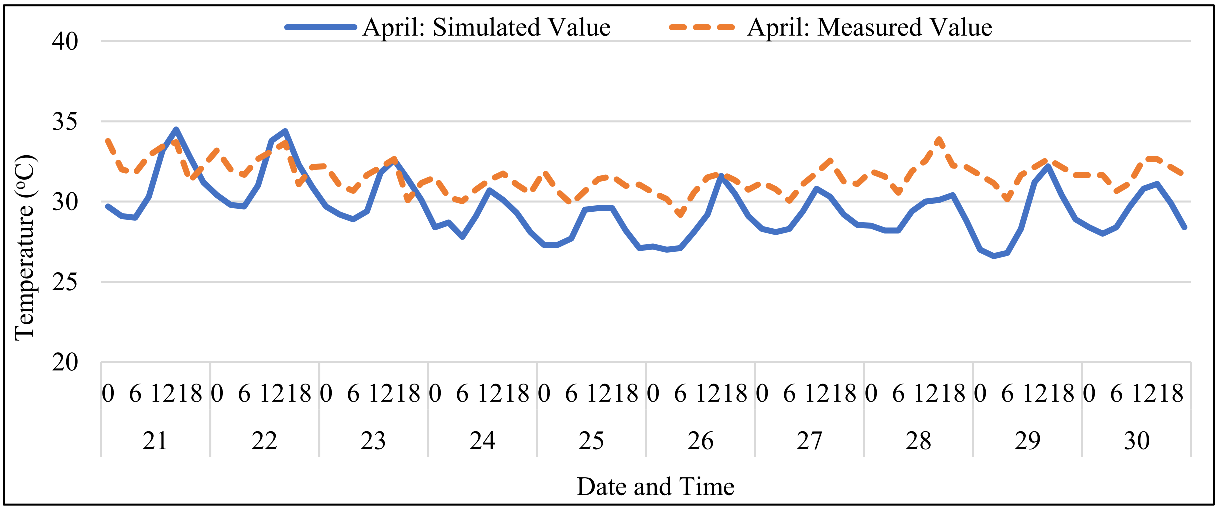
Difference = Measured Value – Simulated Value …………………………………… Eq. E.1

$$\text{Percentage Difference} = \frac{\text{Measured Value} - \text{Simulated Value}}{\text{Measured Value}} \times 100 \quad \text{.……… Eq. E.2}$$

$$= 1.832^{o}C = \mathbf{6.57\%} \text{ (within the acceptable range of 5 to 10\%)}$$

The data are plotted in temperature graphs, to visualize the difference between the measured and the simulated values of temperature. A time interval of three hours, starting from 12 midnight, was used to plot the data. Three individual graphs (Fig E.1, E.2 and E.3 and Table E.1) for ten days of January, April and May were plotted. The fluctuations in hourly temperature of indoor air are more pronounced for simulated values than the measured values. The raw data for the comparison between measured and simulated values are given in Table E.1.





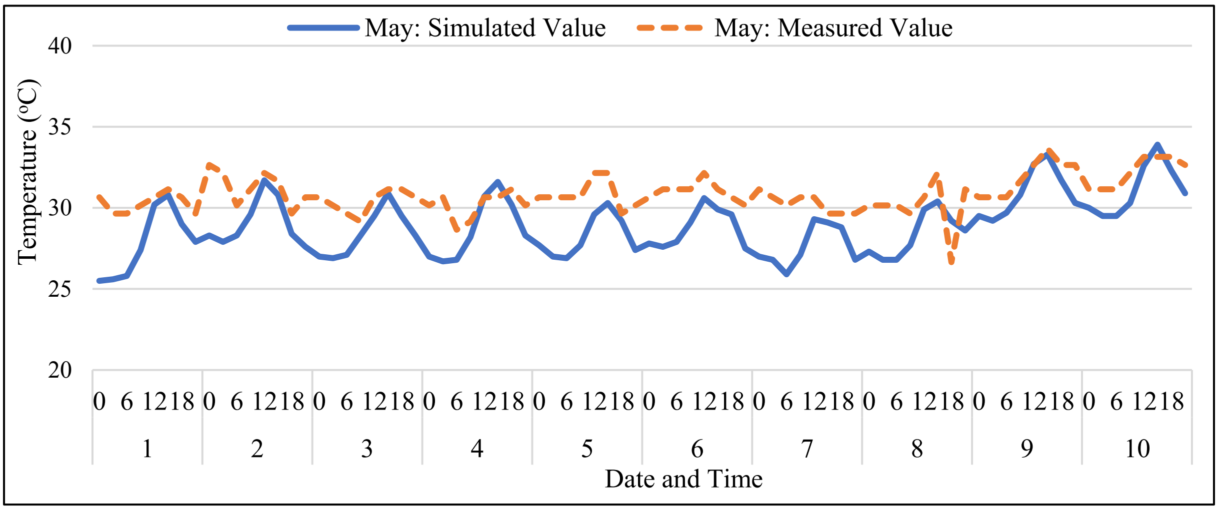


Fig. E.1, E.2 and E.3: Comparison between Measured and Simulated Value of Indoor Air Temperature for January, April and May

Table E.1: Raw Data used in Comparison between Measured and Simulated Value of Indoor Air Temperature for January, April and May

January				April				May			
Date (11-20)	Time	Simulated Value	Measured Value	**Date (20-30)**	Time	Simulated Value	Measure d Value	**Date (1-10)**	Time	Simulated Value	Measured Value
11	0	19.7	22.65	**21**	0	29.7	33.78	**1**	0	25.5	30.65
	3	19.3	22.15		3	29.1	32.01		3	25.6	29.65
	6	19.1	21.65		6	29	31.78		6	25.8	29.65
	9	19.8	22.15		9	30.3	32.87		9	27.4	30.15
	12	20.4	22.15		12	33.2	33.44		12	30.2	30.65
	15	22.7	22.15		15	34.5	33.71		15	30.8	31.15
	18	20.4	22.15		18	32.8	31.29		18	29	30.65
	21	20.6	22.15		21	31.2	32.21		21	27.9	29.65
12	0	19.2	22.15	**22**	0	30.4	33.21	**2**	0	28.3	32.65
	3	19	21.65		3	29.8	32.01		3	27.9	32.15
	6	19.2	21.65		6	29.7	31.67		6	28.3	30.15
	9	20.2	22.15		9	31	32.66		9	29.6	31.15
	12	20.8	22.15		12	33.8	33.14		12	31.7	32.15
	15	22.9	21.65		15	34.4	33.66		15	30.8	31.65
	18	22.3	21.65		18	32.3	31.08		18	28.4	29.65
	21	20.9	22.15		21	30.9	32.16		21	27.6	30.65
13	0	19.6	22.15	**23**	0	29.7	32.21	**3**	0	27	30.65
	3	19	21.65		3	29.2	31.01		3	26.9	30.15
	6	18.7	21.15		6	28.9	30.67		6	27.1	29.65
	9	20.1	21.65		9	29.4	31.66		9	28.3	29.15
	12	22.7	22.15		12	31.8	32.14		12	29.5	30.65
	15	23.7	22.15		15	32.6	32.66		15	30.9	31.15
	18	22.1	22.15		18	31.4	30.08		18	29.5	31.15
	21	20.7	22.15		21	30.1	31.16		21	28.3	30.65
14	0	19.7	21.65	**24**	0	28.4	31.51	**4**	0	27	30.15
	3	18.9	22.15		3	28.7	30.26		3	26.7	30.65
	6	18.5	21.65		6	27.8	30.02		6	26.8	28.65
	9	19.5	22.15		9	29.1	30.75		9	28.2	29.15

	12	21.6	22.65		12	30.7	31.35		12	30.7	30.65
	15	22.7	22.65		15	30.1	31.76		15	31.6	30.65
	18	21.9	22.65		18	29.3	31.06		18	30.2	31.15
	21	20.9	23.15		21	28.1	30.51		21	28.3	30.15
15	0	19.7	22.15	**25**	0	27.3	31.89	**5**	0	27.7	30.65
	3	18.5	21.65		3	27.3	30.64		3	27	30.65
	6	19.1	21.15		6	27.7	29.85		6	26.9	30.65
	9	20.3	22.15		9	29.5	30.66		9	27.7	30.65
	12	22.2	22.15		12	29.6	31.41		12	29.6	32.15
	15	23.4	22.65		15	29.6	31.58		15	30.3	32.15
	18	23.1	22.15		18	28.2	30.98		18	29.2	29.65
	21	20	22.65		21	27.1	31.06		21	27.4	30.15
16	0	18.2	21.65	**26**	0	27.2	30.56	**6**	0	27.8	30.65
	3	17.4	21.15		3	27	30.16		3	27.6	31.15
	6	17	21.15		6	27.1	29.17		6	27.9	31.15
	9	18.5	21.65		9	28.1	30.57		9	29.1	31.15
	12	21.6	21.65		12	29.2	31.52		12	30.6	32.15
	15	23.1	21.15		15	31.6	31.76		15	29.9	31.15
	18	21.8	21.15		18	30.5	31.35		18	29.6	30.65
	21	19.8	21.15		21	29.1	30.75		21	27.5	30.15
17	0	19.2	21.15	**27**	0	28.3	31.19	**7**	0	27	31.15
	3	18.5	21.15		3	28.1	30.77		3	26.8	30.65
	6	18.1	20.65		6	28.3	30.05		6	25.9	30.15
	9	19.4	21.65		9	29.4	31.09		9	27.1	30.65
	12	22.3	22.15		12	30.8	31.79		12	29.3	30.65
	15	23.8	22.65		15	30.3	32.56		15	29.1	29.65
	18	22.8	22.65		18	29.2	31.25		18	28.8	29.65
	21	21	22.65		21	28.55	31.1		21	26.8	29.65
18	0	18.8	21.15	**28**	0	28.5	31.89	**8**	0	27.3	30.15
	3	18.2	20.65		3	28.2	31.57		3	26.8	30.15
	6	18	20.65		6	28.2	30.55		6	26.8	30.15
	9	19.2	20.65		9	29.4	31.89		9	27.7	29.65

	12	21.7	21.65		12	30	32.55		12	29.9	30.65
	15	22.7	21.65		15	30.1	33.89		15	30.4	32.15
	18	21.4	21.65		18	30.4	32.25		18	29.2	26.65
	21	20.1	21.15		21	28.8	32.15		21	28.6	31.15
18	0	19.5	22.15	**29**	0	27	31.65	**9**	0	29.5	30.65
	3	19.9	22.15		3	26.6	31.15		3	29.2	30.65
	6	18.5	22.15		6	26.8	30.15		6	29.7	30.65
	9	19.8	22.65		9	28.3	31.65		9	30.8	31.65
	12	22.8	22.65		12	31.2	32.15		12	32.7	32.65
	15	23.4	22.65		15	32.2	32.65		15	33.3	33.65
	18	21.9	22.65		18	30.4	32.15		18	31.7	32.65
	21	19.8	22.65		21	28.9	31.65		21	30.3	32.65
20	0	20.6	22.65	**30**	0	28.4	31.65	**10**	0	30	31.15
	3	20	22.15		3	28	31.65		3	29.5	31.15
	6	18.7	22.15		6	28.4	30.65		6	29.5	31.15
	9	19.9	22.65		9	29.7	31.15		9	30.3	32.15
	12	22.4	23.15		12	30.8	32.65		12	32.6	33.15
	15	21.8	23.15		15	31.1	32.65		15	33.9	33.15
	18	22.9	23.65		18	29.9	32.15		18	32.3	33.15
	21	21	23.65		21	28.4	31.65		21	30.9	32.65

Appendix F: ANNUAL AVERAGE DAILY NORMAL MAXIMUM TEMPERATURE (°C) OF DHAKA

Source: BMD 2016.

Table F.1. Annual Average Daily Normal Maximum Temperature (°C) of Dhaka

Daily Normal Maximum Temperature (°C) of Each Month forDhaka																															
Months	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
January	24.6	24.8	24.5	24.5	24.9	24.8	24.8	25.0	25.1	25.0	25.1	25.1	25.6	25.2	25.4	25.5	25.1	25.1	25.1	25.1	24.9	25.4	25.4	25.7	25.9	26.2	26.6	26.7	26.4	26.4	26.7
February	26.3	26.4	26.7	26.5	26.2	26.7	26.6	26.9	26.8	27.3	27.7	27.9	28.1	28.3	28.4	28.3	29.0	28.8	29.1	29.0	29.2	28.8	28.4	29.1	29.0	29.8	29.7	29.7	29.5		
March	29.7	29.9	30.1	30.7	31.1	31.2	31.3	31.5	31.6	32.2	32.5	32.2	32.2	32.0	32.6	33.0	33.6	33.8	34.0	34.1	34.1	34.1	33.5	33.6	32.7	33.6	33.4	33.5	33.8	33.3	33.7
April	33.7	34.4	34.4	34.5	34.5	34.4	**34.8**	34.2	33.8	34.3	34.5	34.1	34.3	34.3	33.7	33.1	33.5	33.6	33.5	33.5	33.5	33.7	33.6	33.2	33.4	32.7	32.9	32.4	32.5	32.8	
May	33.2	32.4	32.7	33.6	33.1	32.1	32.0	32.3	33.4	33.0	33.0	33.0	32.8	33.2	32.3	32.8	32.8	33.1	33.3	33.1	32.8	32.9	33.3	33.5	32.7	32.7	32.3	32.3	33.0	32.8	33.1
June	32.9	33.1	32.9	32.8	32.6	33.1	32.7	32.7	32.6	32.3	32.3	32.7	32.5	32.2	32.0	31.5	31.5	31.6	31.9	32.0	32.1	31.9	31.6	31.8	31.1	31.3	31.5	31.6	31.5	31.8	
July	31.5	31.8	31.7	31.7	31.5	31.6	31.2	31.5	31.5	31.6	31.0	31.3	31.8	31.7	31.4	31.2	31.3	31.2	31.4	31.2	31.1	30.9	31.1	31.4	31.9	31.6	31.3	31.3	31.7	31.5	31.6
August	31.7	31.2	31.0	31.7	31.2	31.5	31.5	31.8	31.4	31.8	31.6	32.1	31.5	31.1	31.0	31.5	31.9	31.8	32.1	31.8	31.9	31.3	31.7	31.6	31.6	31.9	31.9	31.7	31.8	31.7	31.4
September	31.8	31.8	31.2	31.1	31.0	31.5	32.0	32.4	31.9	31.5	31.5	31.4	31.9	31.9	32.1	32.0	32.1	32.3	32.5	32.3	32.4	31.7	31.8	31.7	32.1	31.5	31.5	31.5	31.5	31.7	
October	32.2	31.9	32.4	31.9	32.1	31.6	32.0	31.7	31.6	31.8	31.8	32.4	32.1	31.9	31.8	32.1	32.0	31.1	31.3	31.1	31.3	31.5	31.8	31.4	31.6	31.7	31.3	31.0	30.7	29.9	30.4
November	30.7	31.1	30.9	30.7	30.7	30.4	30.5	30.3	29.7	29.7	29.7	29.9	29.8	29.8	29.9	29.7	29.5	29.5	29.4	29.3	29.3	29.1	29.1	28.7	28.6	28.7	28.6	28.0	27.8	27.7	
December	27.6	27.8	27.9	27.8	27.6	27.5	27.4	27.1	26.8	26.6	26.7	26.7	26.5	26.6	26.0	26.4	26.2	26.2	26.3	26.2	26.0	26.3	26.0	26.0	26.0	25.5	25.7	25.1	25.0	25.2	25.2

Hottest Month and Hottest Day

Appendix G: WWR AND WFRCALCULATIONS USED TO SET WINDOW SIZE FOR SIMULATION

1. WWR Calculations

WWR: Window-to-Wall Area Ratio = (Total Window Area / Total Exterior Wall Area) X 100

No. of Exterior Wall: 2

Room Size: 3.658m X 4.572m X 3.048m

Area of 4.572m wall: 4.572m X 3.048m = 13.936 sqm

Area of 3.658m wall: 3.658m X 3.048m = 11.148 sqm

Total Exposed (Exterior) Wall area: 25.084 sqm

Cross Ventilated State:

WWR: Window-to-Wall Area Ratio = (Total Window Area / Total Exterior Wall) X 100

$$\text{Total Window area} = \text{WWR} \times \frac{\text{Total Exterior Wall Area}}{100}$$

$$\text{Total Window Area} = \text{WWR} \times \frac{25.084 \text{ sqm}}{100}$$

Therefore, Total Window Area = WWR X 0.25 sqm

Single-Sided Ventilation on South Wall:

For 4.572m Wall,

$$\text{Total Window Area} = \text{WWR} \times \frac{\text{Total Exterior Wall area}}{100}$$

$$\text{Total Window Area} = \text{WWR} \times \frac{13.936 \text{ sqm}}{100}$$

Therefore, Total Window Area = WWR X 0.14 sqm

Single-Sided Ventilation on West Wall:

For 3.658m wall,

$$\text{Total Window Area} = \text{WWR} \times \frac{\text{Total Exterior Wall area}}{100}$$

$$\text{Total Window Area} = \text{WWR} \times \frac{11.148 \text{ sqm}}{100}$$

Therefore, Total Window Area = WWR X 0.11 sqm

Table G.1.1: WWR Values and Corresponding Window Size used in Simulation in Cross-Ventilated State (window in south and west wall) for both 10 and 50 ACH

WWR (%)	**Total Win. Area (m^2)**	**Each Win. Area (m^2)**	**Each Window size (m)**	**Operable Sash Width (m)**
5	5 x 0.25 = 1.25	1.25 / 2 = 0.63	0.63 / 1.37 = 0.45 (0.45 x 1.37) x 2	0.45 / 2 = 2.23
10	10 x 0.25 = 2.50	2.50 / 2 = 1.25	1.25 / 1.37 = 0.91 (0.91 x 1.37) x 2	0.91 /2 = 0.46
15	15 x 0.25 = 3.75	3.75 / 2 = 1.87	1.87 / 1.37 = 1.36 (1.36 x 1.37) x 2	1.36 / 2 = 0.68
20	20 x 0.25 = 5.00	5.00 / 2 = 2.50	2.50 / 1.37 = 1.82 (1.82 x 1.37) x 2	1.82 / 2 = 0.91
25	25 x 0.25 = 6.25	6.25 / 2 = 3.13	3.13 / 1.37 = 2.28 (2.28 x 1.37) x 2	2.28 / 2 = 1.14
30	30 x 0.25 = 7.50	7.50 / 2 = 3.75	3.75 / 1.37 = 2.74 (2.74x 1.37) x 2	2.74 / 2 = 1.37
35	35 x 0.25 = 8.75	8.75 / 2 = 4.38	4.38 / 1.37 = 3.20 (3.20 x 1.37) x 2	3.20 / 2 = 1.60
40	40 x 0.25 = 10.00	10.03 = 5.71 + 4.32	4.16 x 1.37 = 5.70 (for 4.57m wall) (3.15 x 1.37 = 4.32 (for 3.65m wall)	4.16 / 2 = 2.08 (for 4.57m wall) 3.15 / 2 = 1.57 (for 3.65m wall)

Table G.1.2: WWR Values and Corresponding Window Size used in Simulation in Single-sided Ventilated State (window on 4.57m long south wall) for both 10 and 50 ACH

WWR (%)	**Win. Area (m^2)**	**Window Size (m)**	**Operable Sash Width (m)**
5	5 x 0.14 = 0.70	0.70 / 1.37 = 0.51 (0.51 x 1.37)	0.51 / 2 = 0.26
10	10 x 0.14 = 1.40	1.40 / 1.37 = 1.02 (1.02 x 1.37)	1.02 / 2 = 0.51
15	15 x 0.14 = 2.10	2.10 / 1.37 = 1.53 (1.53 x 1.37)	1.53 / 2 = 0.76
20	20 x 0.14 = 2.80	2.80 / 1.37 = 2.04 (2.04 x 1.37)	2.04 / 2 = 1.02
25	25 x 0.14 = 3.50	3.50 / 1.37 = 2.55 (2.55 x 1.37)	2.55 / 2 = 1.27
30	30 x 0.14 = 4.20	4.20 / 1.37 = 3.06 (3.06 x 1.37)	3.06 / 2 = 1.53
35	35 x 0.14 = 4.90	4.90 / 1.37 = 3.57 (3.57 x 1.37)	3.57 / 2 = 1.78
40	40 x 0.14 = 5.60	5.60 / 1.37 = 4.08 (4.08 x 1.37)	4.08 / 2 = 2.04

Table G.1.3: WWR Values and Corresponding Window Size used in Simulation in Single-sided Ventilated State (window on 3.66m long west wall) for both 10 and 50 ACH

WWR (%)	**Win. Area (m^2)**	**Window Size (m)**	**Operable Sash Width (m)**
5	5 x 0.11 = 0.55	0.55 / 1.37 = 0.40 0.40 x 1.37	0.40 / 2 = 0.20
10	10 x 0.11= 1.10	1.10 / 1.37= 0.81 0.81 x 1.37	0.81 / 2 = 0.40
15	15 x 0.11= 1.65	1.65 / 1.37= 1.20 1.20 x 1.37	1.20/ 2 = 0.60
20	20 x 0.11= 2.20	2.20 / 1.37= 1.60 1.60 x 1.37	1.60 / 2 = 0.80
25	25 x 0.11= 2.75	2.75 / 1.37= 2.01 2.01 x 1.37	2.01 / 2 = 1.00
30	30 x 0.11= 3.30	3.30 / 1.37= 2.41 2.41 x 1.37	2.41 / 2 = 1.20
35	35 x 0.11 = 3.85	3.85 / 1.37= 2.81 2.81 x 1.37	2.81 / 2 = 1.40
40	40 x 0.11= 4.40	4.40 / 1.37= 3.21 3.21 x 1.37	3.21 / 2 = 1.60

2. WFR Calculations

WWR: Window-to-Floor Area Ratio = (Total Window Area / Total Floor Area) X 100

Room Size: 3.658m X 4.572m

Total Floor Area: 3.658m X 4.572m = 16.723 sqm

Cross Ventilated State:

WWR: Window-to-Floor Area Ratio = (Total Window Area / Total Floor Area) X 100

$$\text{Total Window Area} = \text{WWR} \times \frac{\text{Total Room Area}}{100}$$

$$\text{Total Window Area} = \text{WWR} \times \frac{16.723 \text{ sqm}}{100}$$

Therefore, Total Window Area = WWR X 0.167 sqm

Single-Sided Ventilation on South Wall:

For 4.572m Wall,

$$\text{Total Window Area} = \text{WWR} \times \frac{\text{Total Room Area}}{100}$$

$$\text{Total Window Area} = \text{WWR} \times \frac{13.936 \text{ sqm}}{100}$$

Therefore, Total Window Area = WWR X 0.139 sqm

Single-Sided Ventilation on West Wall:

For 3.658m Wall,

$$\text{Total Window Area} = \text{WWR} \times \frac{\text{Total Room Area}}{100}$$

$$\text{Total Window Area} = \text{WWR} \times \frac{11.148 \text{ sqm}}{100}$$

Therefore, Total Window Area = WWR X 0.111 sqm

Table G.2.1: WFR Values and Corresponding Window Size used in Simulation in Cross-Ventilated State (window on south and west wall) for both 10 and 50 ACH

WFR (%)	**Total Win. Area (m^2)**	**Each Win. Area (m^2)**	**Each Window size (m)**	**Operable Sash Width (m)**
5	5 x 0.17 = 0.85	0.85 / 2 = 0.42	0.42 / 1.37 = 0.31 (0.31 x 1.37) x 2	0.31 / 2 = 0.15
10	10 x 0.17 = 1.70	1.70 / 2 = 0.85	0.85 / 1.37 = 0.62 (0.62 x 1.37) x 2	0.62/ 2 = 0.31
15	15 x 0.17 = 2.55	2.55 / 2 = 1.27	1.27 / 1.37 = 0.93 (0.93 x 1.37) x 2	0.93 / 2 = 0.46
20	20 x 0.17 = 3.40	3.40 / 2 = 1.70	1.70 / 1.37 = 1.24 (1.24 x 1.37) x 2	1.24 / 2 = 0.62
25	25 x 0.17 = 4.25	4.25 / 2 = 2.12	2.12 / 1.37 = 1.55 (1.55 x 1.37) x 2	1.55 / 2 = 0.77
30	30 x 0.17 = 5.10	5.10 / 2 = 2.55	2.55 / 1.37 = 1.86 (1.86 x 1.37) x 2	1.86 / 2 = 0.93
35	35 x 0.17 = 5.95	5.95 / 2= 2.97	2.97 / 1.37 = 2.17 (2.17 x 1.37) x 2	2.17 / 2 = 1.08
40	40 x 0.17= 6.80	6.80 / 2 = 3.40	3.40 / 1.37 = 2.48 (2.48 x 1.37) x 2	2.48 / 2 = 1.24
45	45 x 0.17 = 7.65	7.65 / 2 = 3.82	3.82 / 1.37 = 2.79 (2.79 x 1.37) x 2	2.79 / 2 = 1.39
50	50 x 0.17 = 8.50	8.50 /2 = 4.25	4.25 / 1.37 = 3.10 (3.10 x 1.37) x 2	3.10 / 2 = 1.55
55	55 x 0.17 = 9.35	4.74 + 4.61 = 9.35	4.74m^2 / 1.37 = 3.46 (for 4.57m wall) 4.61m^2 / 1.37 = 3.36 (for 12' wall)	3.44 / 2 = 1.72 (for 4.57m wall) 3.36 / 2 = 1.68 (for 3.66m wall)

Table G.2.2: WFR Values and Corresponding Window Size used in Simulation in Single-sided Ventilated State (window on 4.57m long south wall) for both 10 and 50 ACH

WWR (%)	**Win. Area (m^2)**	**Window size (m)**	**Operable Sash Width (m)**
5	5 x 0.17 = 0.85	0.85 / 1.37 = 0.62 0.62 x 1.37	0.62 / 2 = 0.31
10	10 x 0.17 = 1.70	1.70 / 1.37 = 1.24 1.24 x 1.37	1.24 / 2 = 0.62
15	15 x 0.17 = 2.55	2.55 / 1.37 = 1.86 1.86 x 1.37	1.86 / 2 = 0.93
20	20 x 0.17 = 3.40	3.40 / 1.37 = 2.48 2.48 x 1.37	2.48 / 2 = 1.24
25	25 x 0.17 = 4.25	4.25 / 1.37 = 3.10 3.10 x 1.37	3.10 / 2 = 1.55
30	30 x 0.17 = 5.10	5.10 / 1.37 = 3.72 3.72 x 1.37	3.72 / 2 = 1.86
34.4	34.4 x 0.17 = 5.84	5.84 / 1.37 = 4.26 4.26 x 1.37	4.26 / 2 = 2.13

Table G.2.3: WFR Values and Corresponding Window Size used in Simulation in Single-sided Ventilated State (window on 3.66m long west wall) for both 10 and 50 ach

WWR (%)	**Win. Area (m^2)**	**Window size (m)**	**Operable Sash Width (m)**
5	5 x 0.17 = 0.85	0.85 / 1.37 = 0.62 0.62 x 1.37	0.62 / 2 = 0.31
10	10 x 0.17 = 1.70	1.70 / 1.37 = 1.24 1.24 x 1.37	1.24 / 2 = 0.62
15	15 x 0.17 = 2.55	2.55 / 1.37 = 1.86 1.86 x 1.37	1.86 / 2 = 0.93
20	20 x 0.17 = 3.40	3.40 / 1.37 = 2.48 2.48 x 1.37	2.48 / 2 = 1.24
25	25 x 0.17 = 4.25	4.25 / 1.37 = 3.10 3.10 x 1.37	3.10 / 2 = 1.55

Appendix H: REVIEW ON ECOTECT

H.1. Introduction

Ecotect analysis is compatible with BIM (Building Information Management) software, such as Autodesk Revit Architecture, and is used to perform comprehensive preliminary building energy performance analysis (Wang et al., 2011). It integrates a relatively simple and intuitive 3D modelling interface with a range of analysis functions. These comprise thermal, lighting and acoustic analyses, including overshadowing and solar reflection; sun penetration and shading device design; solar access and photovoltaic/heat collection; hourly thermal comfort and monthly space loads; natural and artificial lighting levels; acoustic reflections and reverberation times; project cost and environmental impact. (Crawley et al., 2008; Marsh, 2006). Various studies have demonstrated that Ecotect simulations are highly accurate (Abudallah et al., 2013; Attia and Herde, 2011; Vangimalla et al., 2011; Ibarra and Reinhart, 2009).

The most significant feature of ECOTECT is its interactive approach to performance analysis. In the modelling phase, Ecotect approaches building spaces into separate zones according to their location, orientation, dimension and functions - of which surfaces are planar and single layered - as closed zones bounded by floors, walls, ceilings or roofs without any restrictions of surface area, containing prismatic homogeneous air distribution aiming at particularly at heat loss and gain and thermal comfort analysis. Each thermal zone can be modelled separately. However, the zones which have similar heat flux might be united and accepted as a combined zone. Thermal zones characteristics of existing building are defined by interior conditions, such as lighting, equipment load, the number of users, thermostat set points and comfort limits and fabric elements of flooring, walls and openings. In addition, some parameters of volume configuration, users' activities related to spaces, dimensions, and orientation of building, can also be specified (Neslihan et al, 2013).

In addition to standard graph and table-based reports, analysis results can be mapped over building surfaces or displayed directly within the spaces. This includes visualization of volumetric and spatial analysis results, including imported 3D CFD data. Real-time animation features are provided along with interactive acoustic and solar ray tracing that updates in real time with changes to building geometry and material properties.

H.2. Research based on Autodesk Ecotect Analysis

Autodesk Ecotect Simulation is used in a varying range of parametric research. The major types of analysis used in research, include whole-building energy consumption, thermal performance (thermal, ventilation and wind flow analysis), resource and material cost evaluation, solar radiation and daylighting estimation, and shadows and reflections pattern. Some studies are mentioned below:

In a research to investigate the impact of orientation and dimensional specifications of window on building energy consumption, Kheiri (2013) used Ecotect to model and simulate all the variations. The result showed that 20-32% WWR, for total exterior walls, is an efficient ratio for reducing HVAC and lighting systems loads.

In a study of the evaluation of passive cooling strategies on indoor thermal performance of office space, the modelling and simulating of the existing office building was done using Ecotect, to evaluate the indoor operative temperature and indoor comfort condition of the office space. A parametric study, using the same software, was conducted to investigate indoor thermal condition in response to the passive cooling strategies, changing wall material and allowing night cooling (Bakar, 2013).

Madhumathi et al. (2014) studied the thermal comfort conditions inside vernacular rural house by simulating different thermal conditions, using Autodesk Ecotect Analysis. On-site measurements were used to validate the building simulation results and to draw inferences about the thermal behavior of dwelling units.

A thermal performance analysis, using ECOTECT 2011, simulation software was carried out to identify and understand the passive solar techniques adopted in the vernacular residences of Thanjavur region, India. The result contributed to the possibility of decreasing the dependence on fossil energy as much as possible to attain sustainability (Dhanasekaran and Jayasudha, 2014).

In the study of assessment of HVAC load for tall office building of Dhaka (Trisha, 2015), Ecotect along with raytrace based Radiance was used to evaluate luminous and thermal performance of shading devices. The result revealed that the performance of aluminum louvers cornice type sunshade in south, is significantly superior to other tested shading device in this orientation.

ECOTECT was used in an analysis of thermal environment of existing residential building. Five different modifications on the building façade were done with the same software to analyze the thermal environment of each case, which include in-depth analysis of energy consumption, temperature distribution throughout the building and thermal comfort circumstances, to provide the basis of design guidelines for existing residential buildings energy-saving Scheme (Suxian and Bo, 2016).

In a study of energy consumption for thermal comfort with respect to residential buildings' plan layout of Dhaka, Tariq (2016) used WinAir, a plugin of Ecotect, to compare the wind flow patterns through different selected plan layouts.

H.3. Limitations of Autodesk Ecotect

Thermal performance analysis in Autodesk Ecotect is based on the Chartered Institution of Building Services Engineers (CIBSE) admittance method (Autodesk, 12015). Autodesk Ecotect uses this method to calculate internal temperatures and heat loads, using idealized (sinusoidal) weather and thermal response factors (admittance, decrement factor and surface factor) that are based on a 24-hour frequency. The admittance method was originally intended to calculate peak internal temperatures in buildings to ensure that it would not become uncomfortably hot during sunny periods (Beattie and Ward, 2012).

Admittance method is a pseudo-dynamic method based on variation about the mean value. It has the disadvantage of not taking in consideration the effect of solar radiation when it enters the space. Autodesk Ecotect's thermal simulation results, thus are not fully representative of reality, although this perhaps, is not an issue in case of parametric studies investigating the relative effectiveness of design options (Gado and Mohamed, 2014).

Appendix I: SPECIFICATIONS OF THE DATA LOGGER USED

The data logger used to record the indoor air temperature inside the room is known as iButton. The iButton® device is a computer chip, enclosed in a 16mm thick stainless steel can. Information can be carried anywhere without hampering the logged data, as the data logger is enclosed closely inside a water-resistant container and can withstand harsh environments, indoors or outdoors. It has all the features of a larger temperature data logger, with a lifetime of 5-7 years. The data logging intervals may be set from 1 second to 4.5 hours, while the device can store up to 2,048 logs at empty state. Its readings are accurate to ±1 °C between -40 to + 70 °C. The OneWireViewer is a Java™ demonstration application for exploring iButton features from PC. It can be used to store temperature and humidity data, analog-to-digital conversion, and has memory features. The numerical outputs can be exported to excel sheet or can be obtained as graphs (Fig 4.11) (www.maximintegrated.com).

Fig. I.1: iButton Data Logger

Fig. I. 2: iButton Data Logger Holder

Fig. I.3: USB Adapter for Data Conversion

Source: www.maximintegrated.com

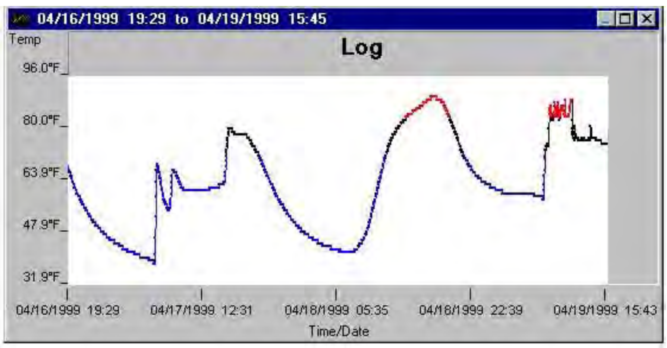


Fig. I.4: Typical Log Graph for Tracked Temperature
Source: www.maximintegrated.com

Appendix J: THREE-DIMENSIONAL VISUALIZATIONS OF THE CFD PLOTS FROM NORTH-WEST CORNER

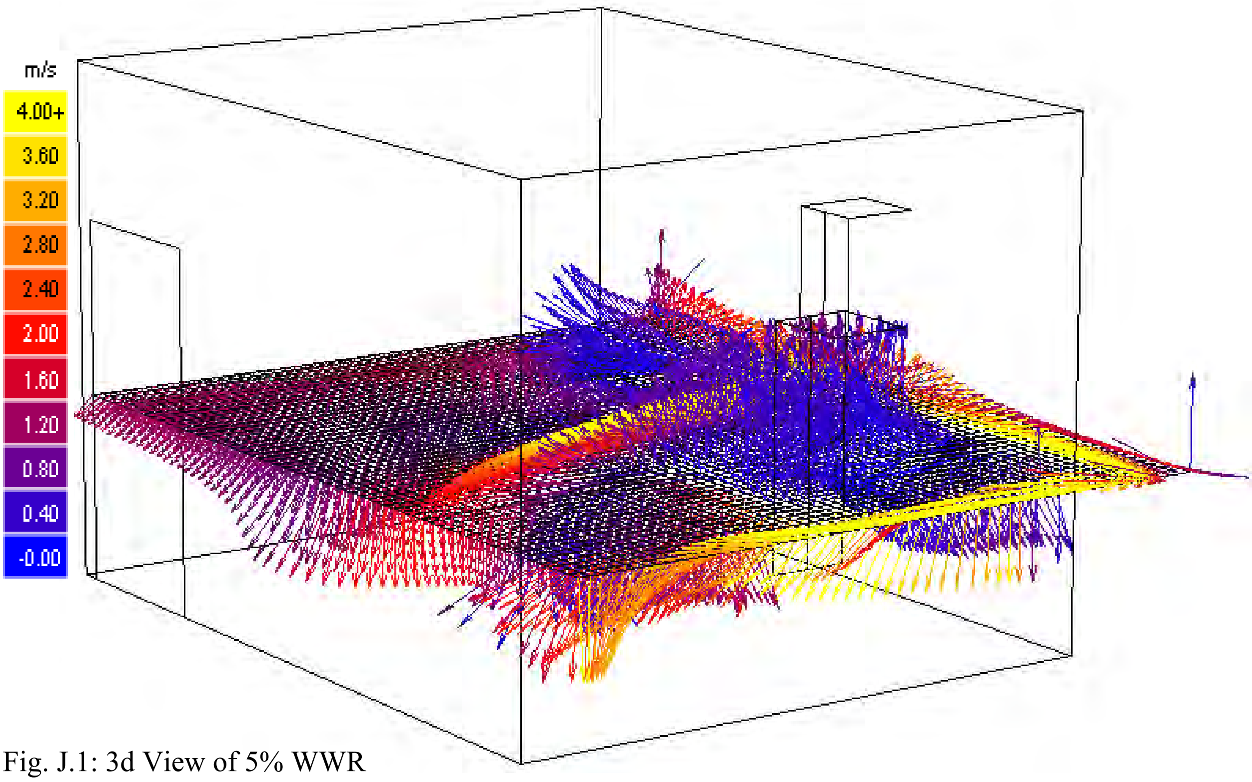


Fig. J.1: 3d View of 5% WWR

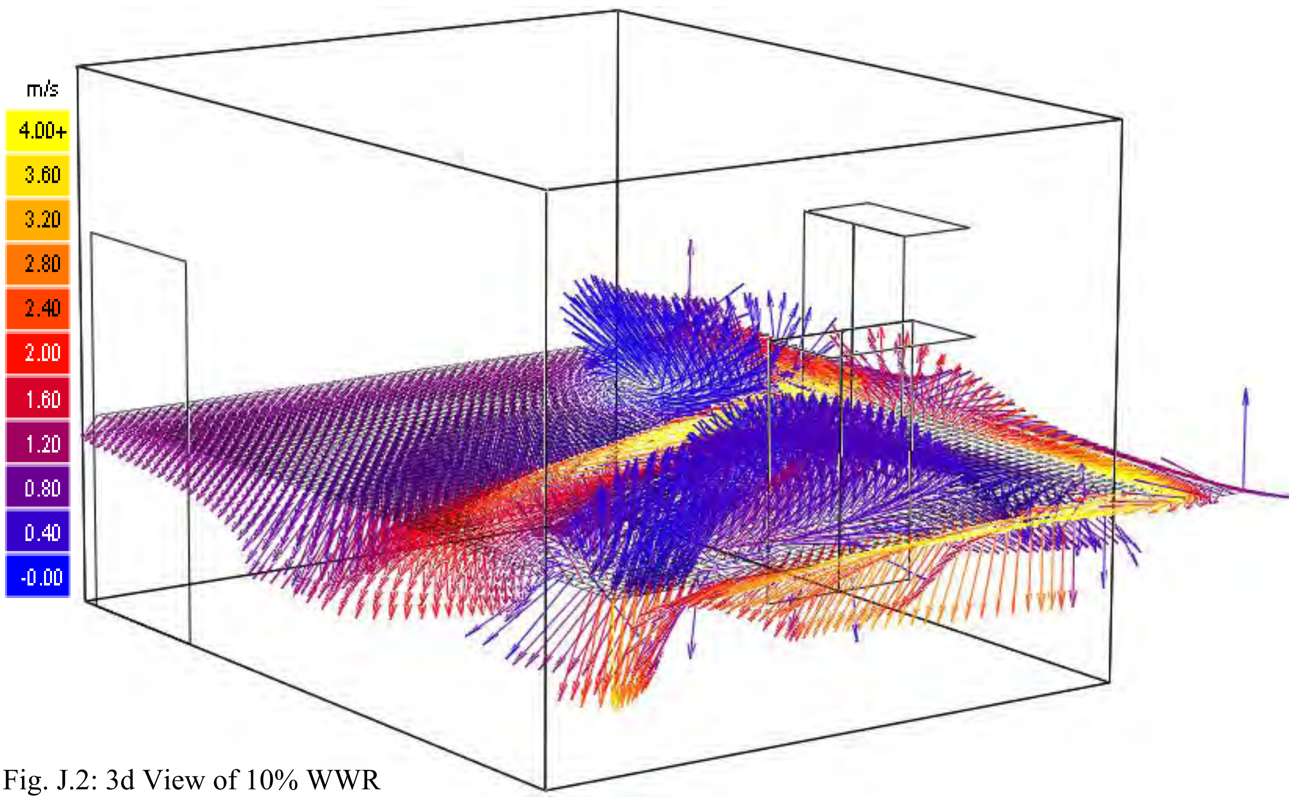


Fig. J.2: 3d View of 10% WWR

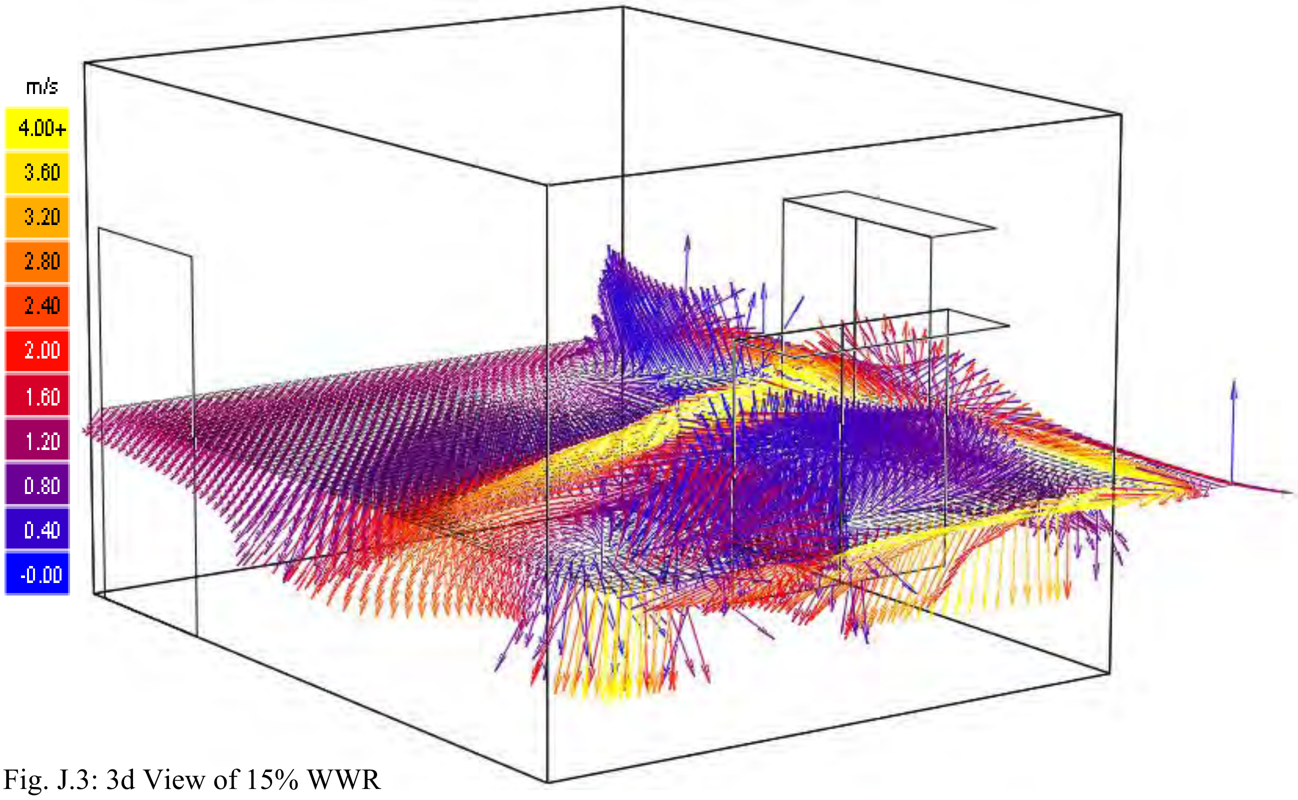


Fig. J.3: 3d View of 15% WWR

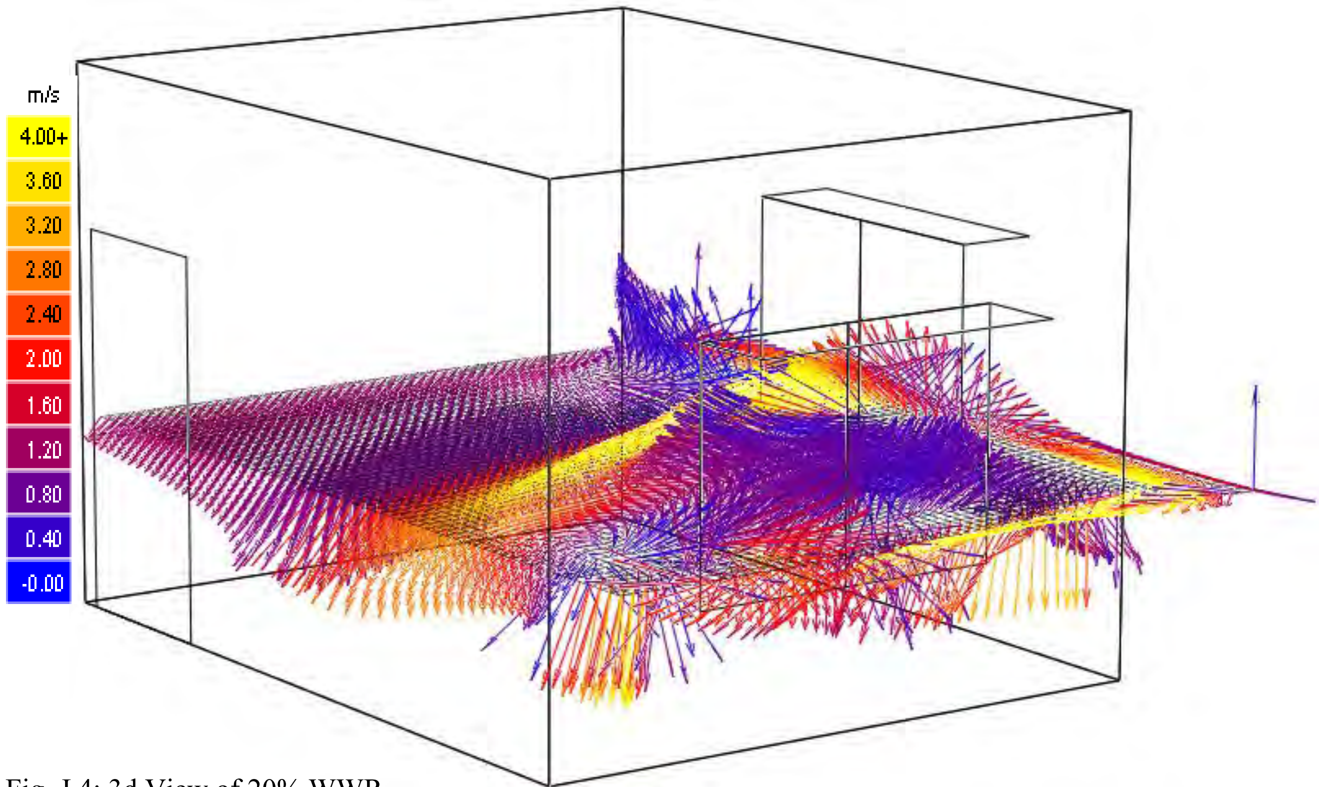


Fig. J.4: 3d View of 20% WWR

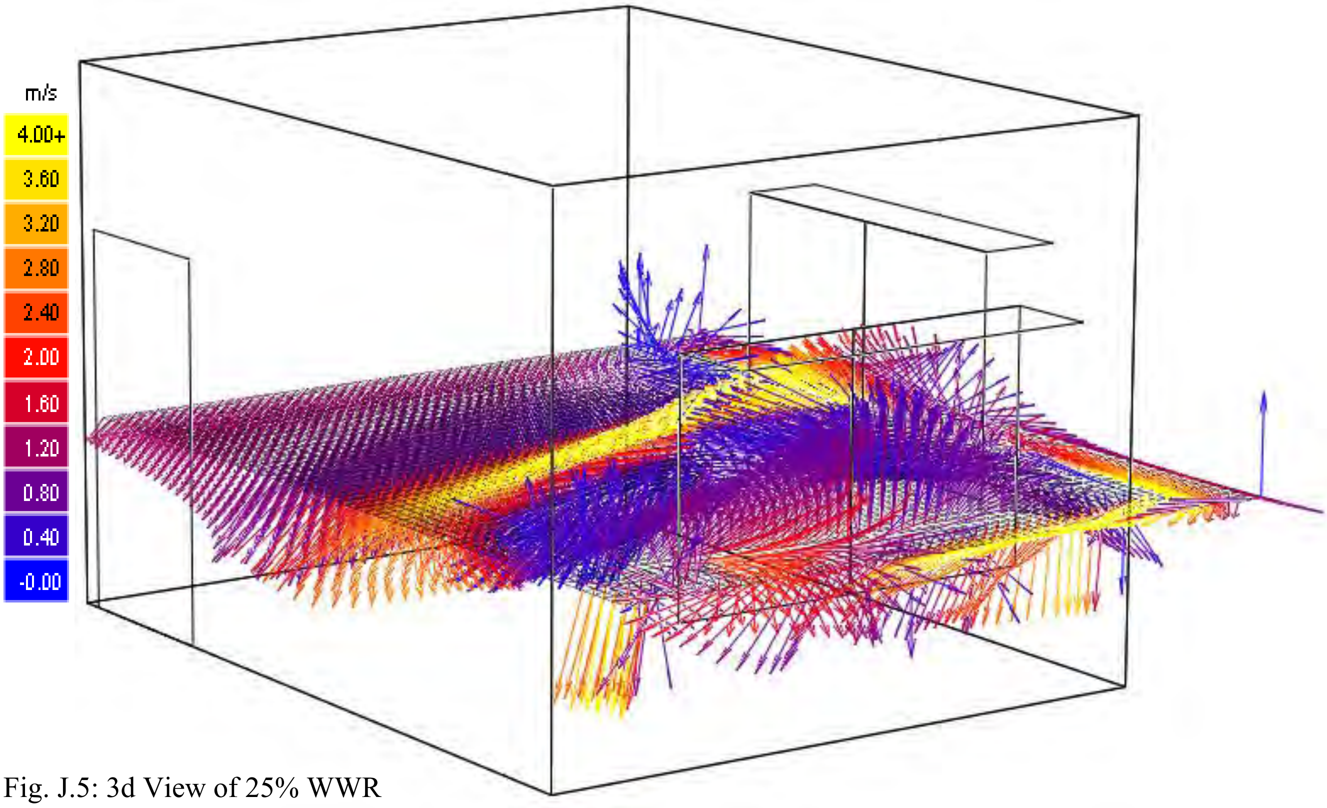


Fig. J.5: 3d View of 25% WWR

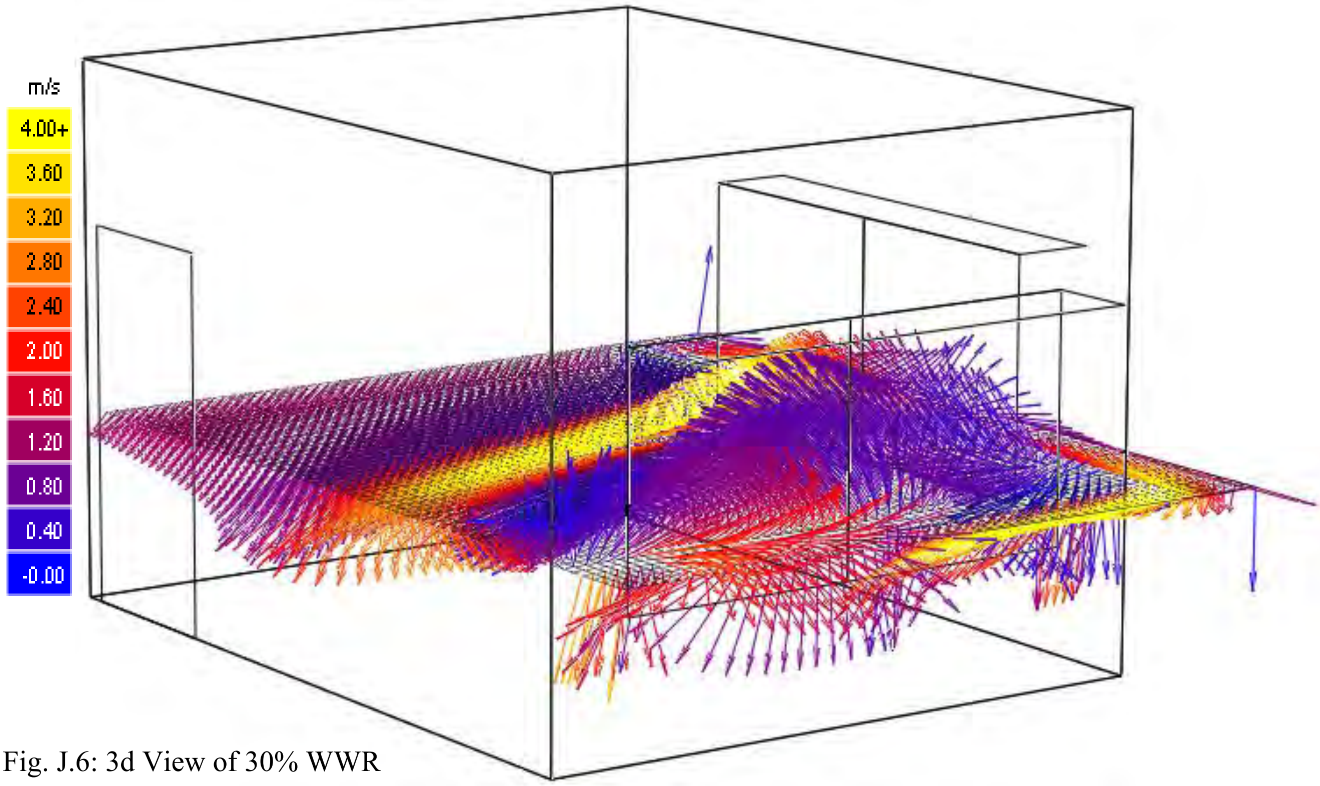


Fig. J.6: 3d View of 30% WWR

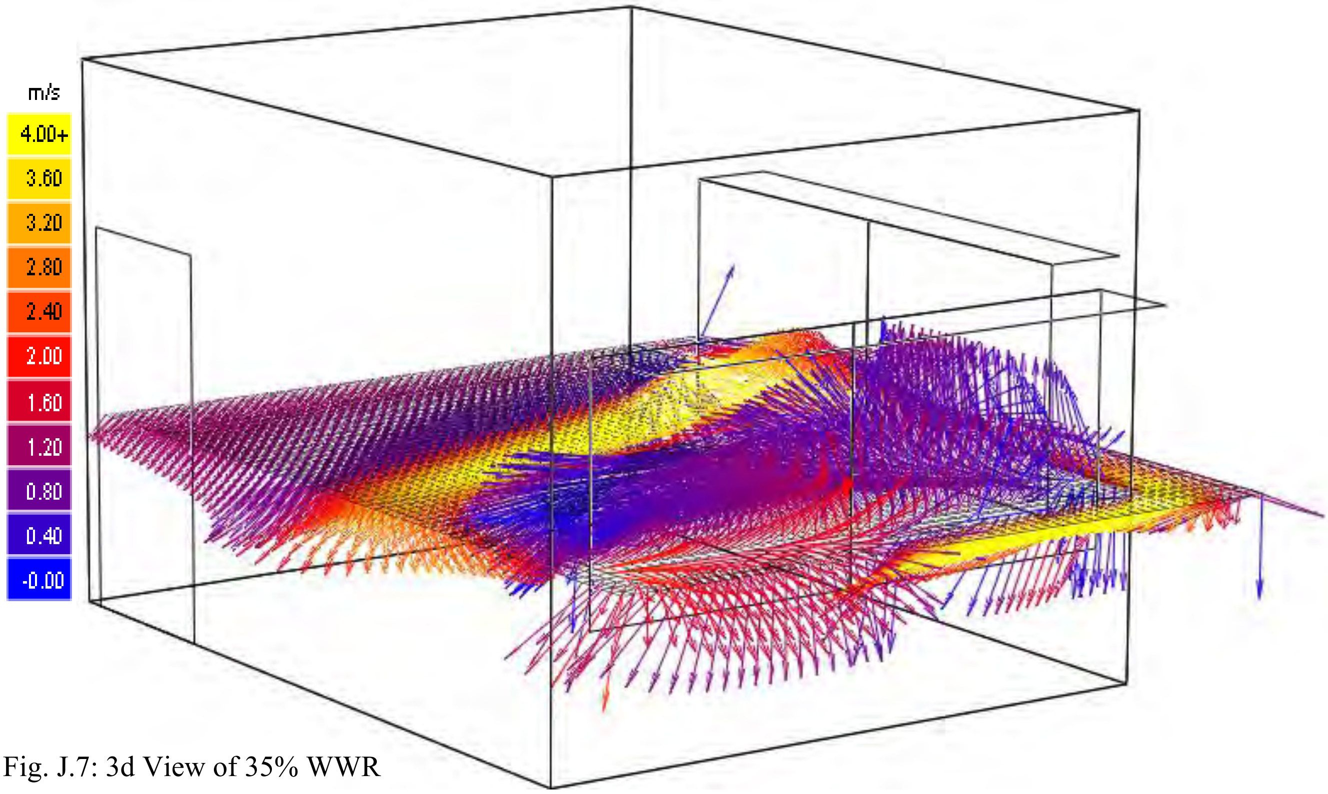


Fig. J.7: 3d View of 35% WWR

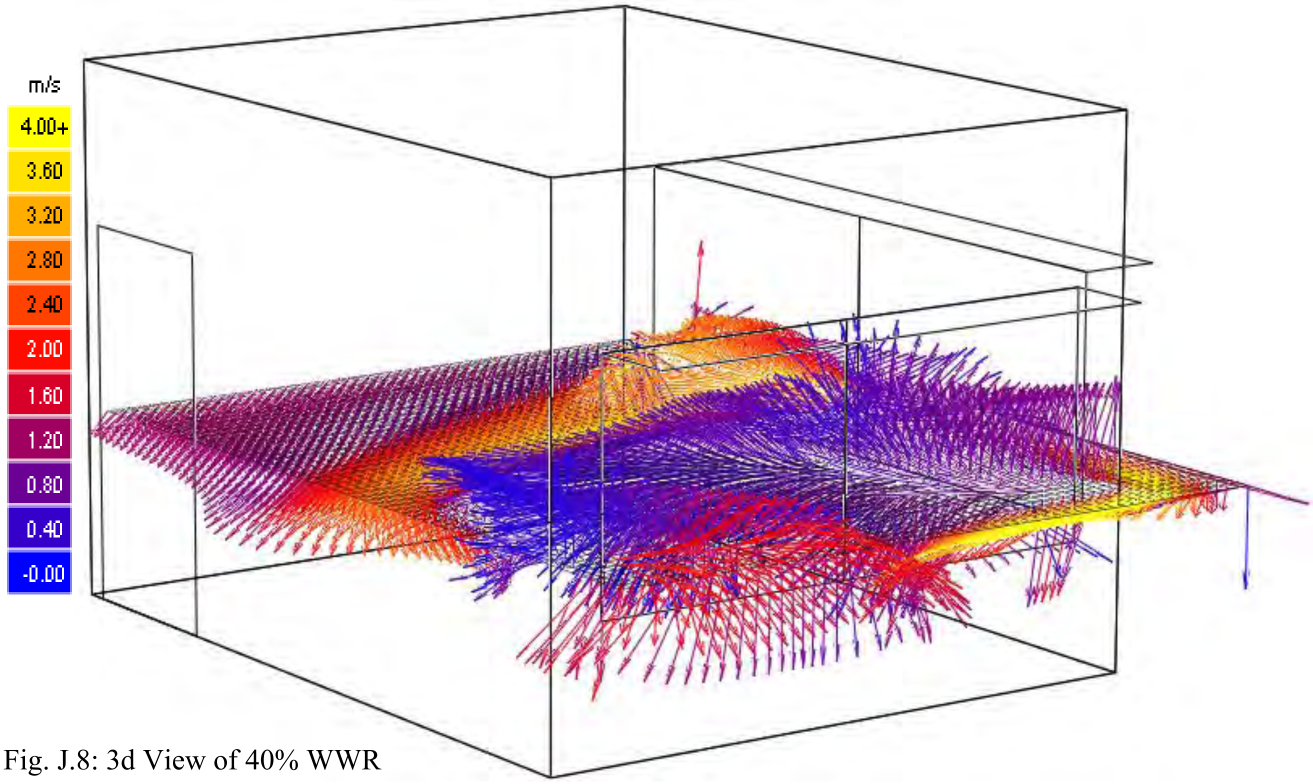


Fig. J.8: 3d View of 40% WWR