A STUDY ON ZONING REGULATIONS' IMPACT ON THERMAL COMFORT CONDITIONS IN NON-CONDITIONED APARTMENT BUILDINGS IN DHAKA CITY

A Dissertation

by

SAIFUL ISLAM

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2011

Major Subject: Architecture

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Approved by:

Chair of Committee,	Phillip J. Tabb
Committee Members,	Charles Culp
	Liliana Beltran
	Shannon Smith Van Zandt
Head of Department,	Ward Wells

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ABSTRACT

A Study on Zoning Regulations' Impact on Thermal Comfort Conditions in Non-conditioned Apartment Buildings in Dhaka City. (December 2011)
Saiful Islam, B.Arch., Ahsanullah University of Science and Technology, Dhaka, Bangladesh;
M.Arch., The University of Texas at San Antonio
Chair of Advisory Committee: Dr. Phillip J. Tabb

Unfavorable thermal comfort conditions are common in the non-conditioned apartment buildings typical of Dhaka (Ali, 2007; Hafiz, 2004). Causes behind such unfavorable thermal comfort conditions include (but are not limited to) Dhaka's climate, microclimate in Dhaka's typical residential neighborhood, its socio-economic context, housing type, and its inadequate planning regulations. Dhaka's climate is hot humid but it can be tackled with well designed buildings as well as well as designed neighborhoods, both of which demands ample open space. However, due to land scarcity and high population density, building developments lack open spaces and that results in unfavorable thermal comfort conditions in apartment buildings. Dhaka's previous zoning regulations were unable to control this dense development, and therefore, a new set of zoning regulations were enacted (2008). However, no post-evaluation study was conducted to research the effect of this new set of regulations.

The intention of this research is to first evaluate the existing regulations, and second, to suggest appropriate zoning regulation schemes for Dhaka's non-conditioned apartment buildings (for a lot size of1/3rd acre), which would provide favorable thermal comfort conditions without changing its existing density. To accomplish the first goal, this research analyzed two existing zoning schemes (one based on regulations of 1996, and the other based on the regulations of 2008). To accomplish the second goal, this

research analyzed two hypothetical zoning schemes. The hypothetical ones were studied because this research finds 1996 and 2008 regulations to be two extremes (in terms of allowing open space and building height), and therefore examination of in-between alternative zoning schemes seemed essential for this study.

To analyze the four zoning regulation schemes' impact on thermal comfort in apartment buildings, four sets of built environment were created in EnergyPlus (Energy Simulation software) as well as in Fluent (Computational Fluid Dynamics software). Each set of built environment is a cluster of nine buildings; and each set is different from each other in terms of their building footprints and building heights.

The building on the center was modeled implicitly, and remaining buildings were modeled as solid blocks (to act as neighboring buildings) for blocking sun and wind. The ES and CFD software simulated possible solar, daylight, and wind availability inside the central building, and consequently produce data on thermal comfort conditions, namely indoor temperature and air velocity. The simulation results were compared to see which zoning schemes provided the most favorable thermal comfort conditions. This research found one of the in-between schemes (60% allowable footprint, 9-story height limit) to be more appropriate in terms of thermal comfort conditions than the other three schemes; because it provides better solar protection and better natural ventilation and consequently it reduces indoor temperature and increases indoor air velocity.

DEDICATION

To my father

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor, Dr. Phillip Tabb, and my committee member, Dr. Charles Culp, for their excellent guidance, invaluable wisdom, and constant support, encouragement and patience throughout the course of this research. The completion of this dissertation would not have been possible without their support. I express my deepest and sincere thanks to Dr. Liliana Beltran, and Dr. Shannon Smith Van Zandt for accepting to serve on my advisory committee. This dissertation has been improved by their comments and fruitful discussions.

I would like to extend my sincere appreciation to Pratanu Roy for his time, support, and suggestion regarding CFD use in this research. I also like to thank T. Van Hoof for his suggestions regarding mesh generation techniques for my CFD studies. I like to thank Marinus Pennings at TAMU Supercomputing center, for his technical support regarding my use of supercomputing facility. I like to thank Brandie Massengale at University Writing Centre (TAMU) for her support. I would also like to acknowledge the Texas A&M Supercomputing Facility's role for allocating enough computing hours to perform large number of simulations on both HYDRA and EOS.

I am greatly indebted to my parents, Mr. Shafiqul Islam and Mrs. Parveen Akhter, for their loving care and support throughout my life and especially throughout my academic pursuit. I also like to appreciate my wife and my only son who sacrificed many happy moments for my PhD endeavor. I also want to thank my three brothers – Arif, Ashik, and Chamila for believing in me and for supporting me all along this journey.

Last but not least, I would like to thank everyone at Texas A&M University who played their roles in making this work successful.

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1. INTRODUCTION

1.1 BACKGROUND

Unfavorable thermal comfort conditions are common in the non-conditioned apartment buildings typical of Dhaka (Ali, 2007; Hafiz, 2004). Figure-1.1 depicts one such example where indoor temperature exceeded 36°C during summer afternoon hours. Ali (2007) recorded indoor and outdoor temperatures in one of the typical non-conditioned apartment buildings, and her results are shown in Figure-1.1. Causes behind such unfavorable thermal comfort conditions include, but are not limited to Dhaka's climate, microclimate in Dhaka's typical residential neighborhood, its socio-economic context, housing type, and its inadequate planning regulations. Brief discussion on these elements will make it easier to realize why zoning regulations need to be studied for the improvement of thermal comfort conditions in Dhaka's apartment buildings.

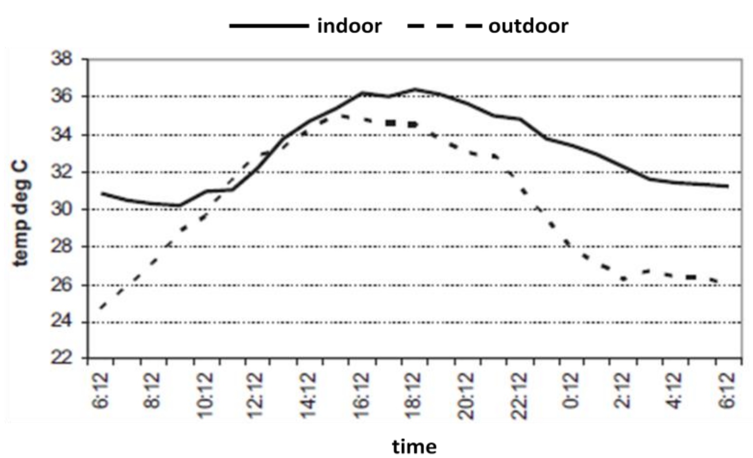


Figure-1.1: Temperature measured in a non-conditioned apartment building on April 10th. (source: Ali, 2007)

This dissertation follows the style and format of the *Journal of Architectural and Planning Research.*

1.1.1 Dhaka's climate

Dhaka's geographic location is defined by 23.77° North Latitude and 90.38° East Longitude which is under a hot humid tropical climate zone. Dhaka's climate can be characterized by high temperature (during most of the year) and high humidity (July to August) (Fuad H, 1996). Unfortunately, both of these characteristics are causes for thermal discomfort.

Figure-1.2 shows the range of Dhaka's dry bulb temperature, created in Climate Consultant 5.1. The round dots show the Recorded High and Low Temperature; the top and bottom of green bars show the Design High and Low Temperatures; the top and bottom of yellow bars show the Average High and Low Temperatures; and the open slots show the Mean or Average Temperature (Microsystems, 2008). As seen in Figure-1.2, during two third of the year, the average high temperature exceeds 30°C. Moreover, in certain months, design high temperature exceeds 35°C. So, outdoor temperatures are above 35°C for a number of hours per day. Figure-1.3 shows that Dhaka's relative humidity is above 80% during half of the year. Therefore, Dhaka's climate has a significant role in the unfavorable thermal comfort conditions in its non-conditioned apartment buildings.

Dhaka's sun-path diagram, a psychometric chart (using adaptive comfort model of ASHRAE-55-2004) for Dhaka's climatic condition, and a set of weather data for the month of April is included in the appendix section.

1.1.2 Microclimate in Dhaka's typical residential neighborhood

Despite Dhaka's unfavorable climate, favorable thermal comfort has been observed in residential buildings where the surrounding microclimate is cooler. One example is the microclimate around residential buildings in Buet Campus (Figure-1.4) (Hafiz, 2004). The microclimate in this neighborhood is cooler for two possible reasons: i) space-gaps between neighboring buildings are adequate to have balcony as well as trees, both of which provide shading, and ii) the wide space-gaps between buildings allow adequate ventilation which flushes out the additional heat away (Corbella & Magalhães, 2008).

This sort of open space and consequent cooler microclimates are rare in Dhaka's typical residential neighborhoods (Figure-1.5); rather the microclimates are warmer than the one observed in Dhaka's weather station (Ahmed, 2003).

Dhaka receives a significant amount of solar radiation throughout the summer months (Figure-1.6 shows that the 'average high' Global Horizontal Solar Radiation in April, the hottest month of the year, is almost 900 Wh/m^2 per hour). The indoor spaces are partly protected from this high solar radiation by densely spaced buildings.

Although this dense development reduces some solar protection, it does not modify wind path in a convenient way for effective ventilation (Z. N. Ahmed, 2010). Figure-1.7 shows speed and direction of prevailing wind on April 5, the hottest day of the month of April (according to the weather file used in this research). However, this wind is no use for effective ventilation due to the dense nature of the building development. As a result, the internal heat as well as the heat gained from solar exposure are trapped inside and make the indoor warmer than the outdoor.

Alike the trapped heated indoor spaces, lack of ventilation also causes presence of corridors of trapped heated outdoors in these neighborhoods, and the microclimates in these neighborhoods show a 5^oC higher temperatures than the one observed in Buet Campus (Hafiz, 2004). These warmer microclimates around the typical apartment buildings are also responsible for the unfavorable thermal comfort conditions.

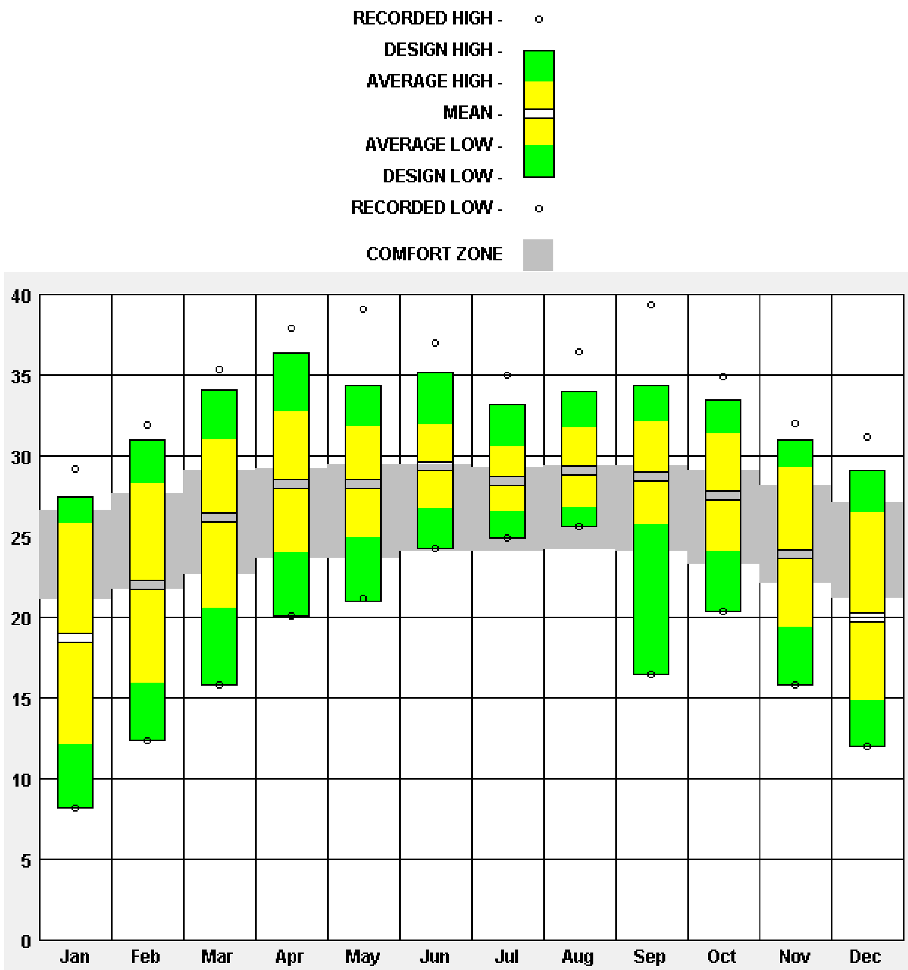


Figure-1.2: Temperature range for Dhaka city, created by Climate Consultant 5.1.

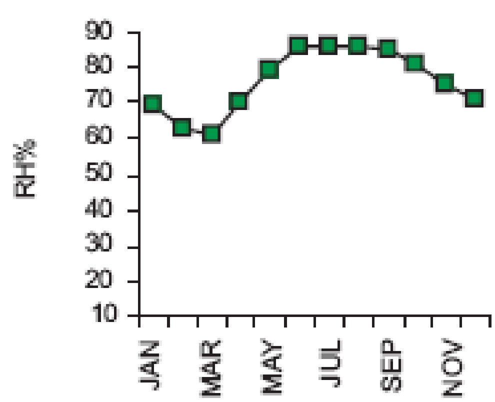


Figure-1.3: Relative humidity in Dhaka city. (source: Ali, 2007)

Figure-1.4: Housing at Buet Campus. (source: Hafiz, 2004)

Figure-1.5: Dhaka's typical residential neighborhood. (source: Ali, 2007)

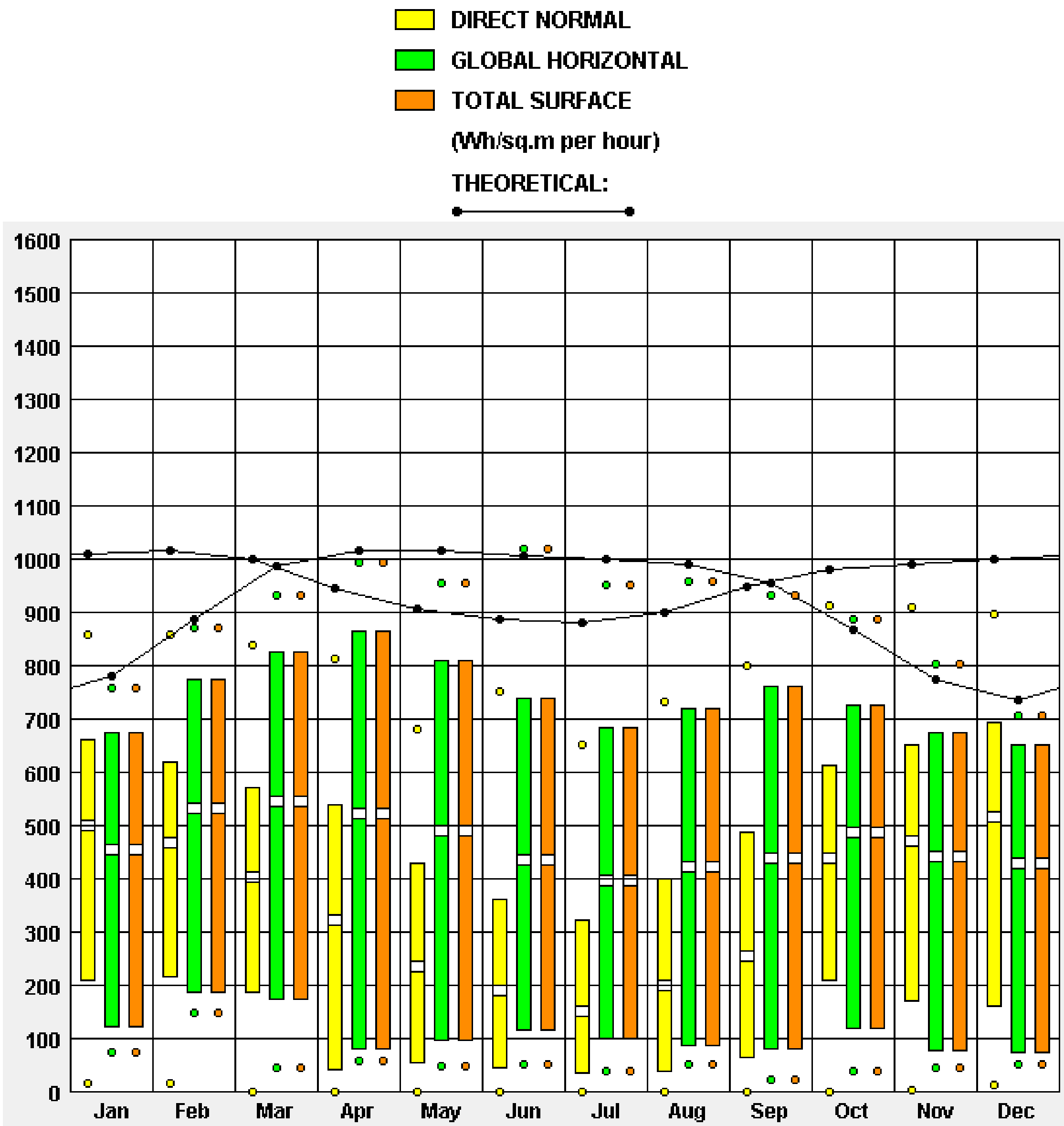


Figure-1.6: Hourly averages of solar radiation data for Dhaka city, created by Climate Consultant 5.1.

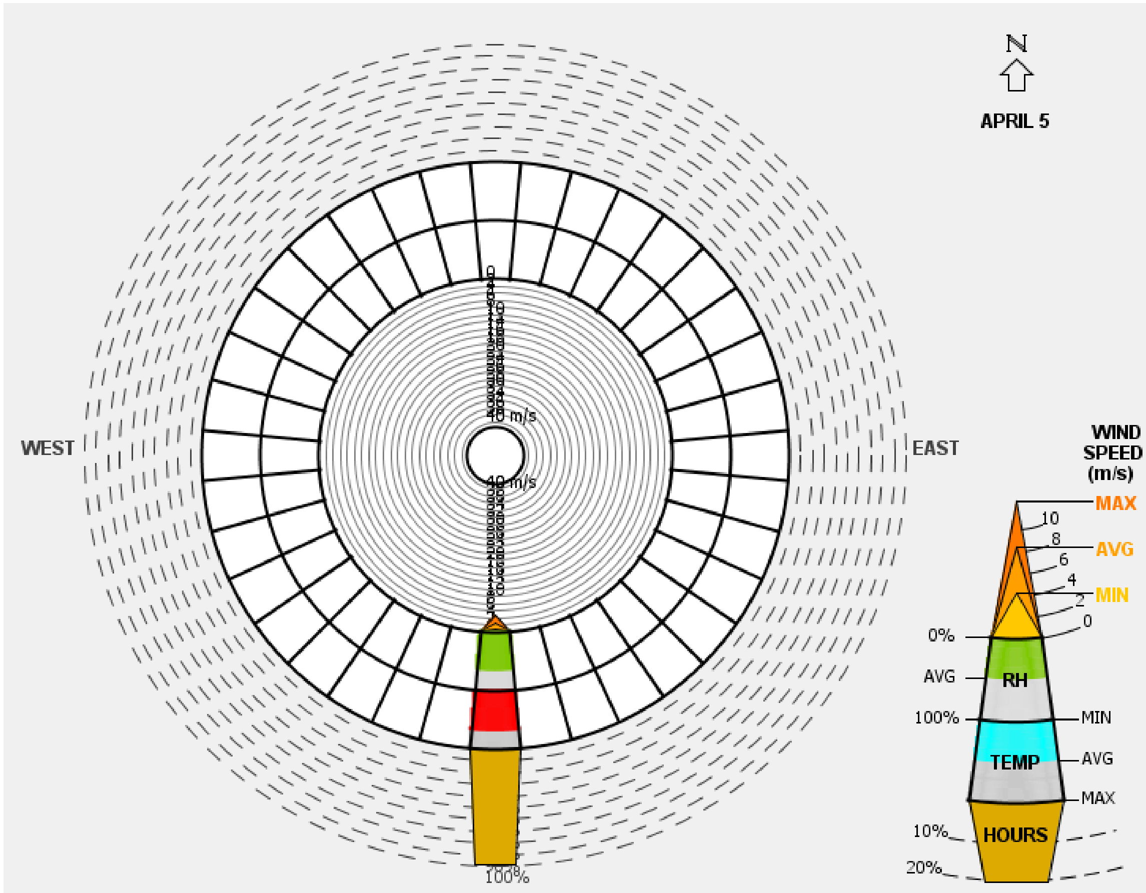


Figure-1.7: Wind speed and direction in Dhaka city, on April 5, created by Climate Consultant 5.1.

1.1.3 Socio-economic context

Dhaka's dense residential neighborhoods are correlated with its socio-economic context. Dhaka is one of the fastest growing metropolises in the world with a population growth rate of 3.34 per year (Seraj, 2009). According to Seraj, 100,000 new household units are required to house the added population every year. Unfortunately, this requirement is difficult to meet by developing additional residential areas in the city outskirt. According to Mahtab-Uz-Zaman and Lau (2000), two major reasons are – i) new infrastructures on the periphery of the city are costly hence not fully developed, and ii) lack of faster and reliable public transportation discourages people to live in the city outskirts. As a result, inner Dhaka is getting more compact and dense, and its land prices are sky rocketing. The price of typical residential land increased 40 times between 1975 and 2006 (Kamruzzaman & Ogura, 2007). Under these circumstances, thermally comfortable less-dense residential neighborhoods like Buet Campus are not economically feasible.

1.1.4 Dhaka's apartment building-form

Within the dense residential neighborhoods, thermally comfortable traditional building-forms of Dhaka's early houses Figure-1.8 became extinct. The building-forms of early houses were typically non-compact where rooms were built around courtyards to get day-light and cross-ventilation, and where continuous covered balconies shaded the rooms from direct sun (Islam, 2003). These climatic considerations do not motivate the contemporary developers; rather the developers prefer a compact building-form for maximum built-to-ground exploitation for greater profit (M, 1998). Dhaka's immediate past zoning regulations, described in following sub-sections, also permitted the developers to build dense and compact buildings and neighborhoods. Ironically, a compact building-form suits the physical form of 'multistory apartment buildings' which is Dhaka's contemporary trend of living (Kamruzzaman & Ogura, 2007).

In these apartment buildings, the traditional concept of space-planning, 'rooms around courtyard,' has been replaced by 'rooms around living/dining area'; people have adopted such change with the influence of Modernism and International Style (N. Ahmed & Khan, 2004). This new concept of 'rooms around living/dining area' would work well in a detached housing unit with adequate exposure to light and ventilation. However, in the contemporary compact apartment building-form, individual dwelling units are not detached; rather they are grouped around a central core (elevator/stair). This allows fewer units to face a street front to enjoy ample daylight and breeze while other units only have exposure to dark and poorly ventilated narrow alleys, created between neighboring buildings. Lack of day-light, in these units, causes additional heat-gain from the use of artificial light. Moreover, in such arrangement, some units largely have west orientation, and consequently face difficulties to avoid direct solar radiation due to the sun's lower angle at afternoon hours. Since external walls in most of these units face poorly ventilated alleys, all the heat generated internally (from humen and equipments) and externally (from direct solar gain) cannot be flushed out and therefore is trapped inside.

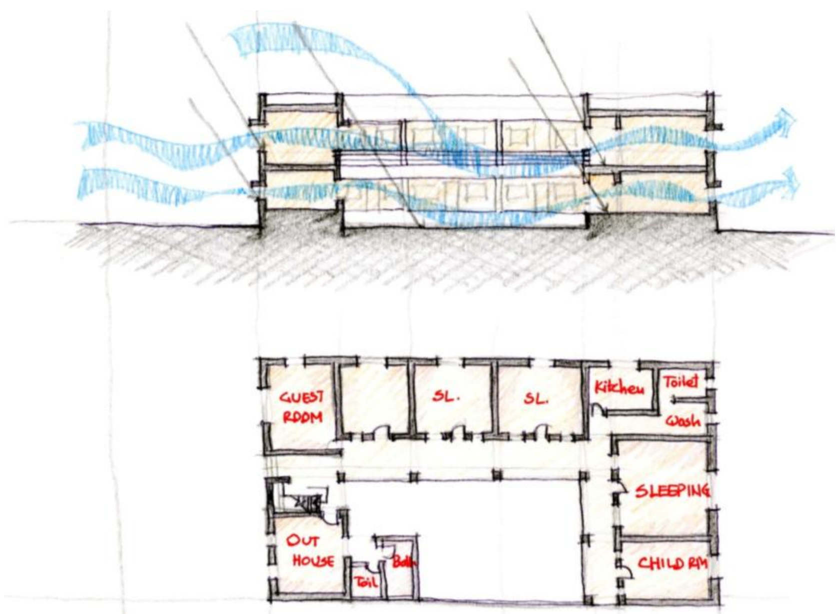


Figure-1.8: Plan and section of an early 20th century Dhaka house. (source: Islam, 2003)

As a result, though this compact building-forms suit the contemporary lifestyle, these do not provide favorable thermal comfort conditions for its occupants. Ali (2007) compared thermal comfort conditions in 'apartment buildings with courtyard' and 'apartment buildings without courtyard'. The former seems to be inspired by Dhaka's traditional building-forms and the later may have been inspired by International Style. Ali's findings show that the former have more favorable thermal comfort conditions than the later ones. However, apartment buildings with courtyards are rare because no owner or developer wants to sacrifice rentable floor areas for open spaces. Zoning regulations are supposed to regulate built environment, to protect the community's health, safety, and welfare (James L. Dougherty & McDonald., 1999). However, none of Dhaka's earlier zoning regulations (except Dhaka Metropolitan Building Construction Act, 2008) were adequate enough to control this dense development (Z. N. Ahmed, 2010; Mahtab-uz-Zaman & Lau, 2000).

1.1.5 Dhaka's zoning regulations

Dhaka's haphazard and dense built environment is the result of its inadequate zoning regulations enacted prior to 2008. To support this statement, the brief history of its zoning regulations (until 2008) shown below has been borrowed from Zaman and Lau's work (2000). The history presented here only talks about subject related to residential development.

1. The Building Construction Act of 1952 – this act first clearly stated that construction of buildings require approval.
2. The Town Improvement Act of 1953 – this act gave the Dhaka Improvement Trust (DIT, now RAJUK) a mandate to undertake development schemes; to provide infrastructure; to acquire, lease, sell or exchange land.
3. The Dhaka Master Plan of 1959 – this plan was the tool for judging planning applications but it was not the tool to control development density.
4. The Building Construction Rules 1996 – these rules replaced earlier versions and were the first to control development density by imposing setback.

So until 1996, zoning regulations had no control over the physical form of building development. From1996, zoning regulations forced a typical residential plot (area of more than 1440 ft^2) to have the following minimum open area – five feet in front, four feet on both sides, and six feet on the rear of the plot (Chakrabarti, 2008). A six-story height-limit was also mentioned in 1996 regulations, for most of the residential neighborhoods (Z. N. Ahmed, 2010). Due to the socio-economic context described earlier, developers built up to these limits for maximum profit, and architects were urged to design for such spatial requirements. This trend of dense development continued until 2008. As a result, Dhaka's typical residential neighborhoods are mostly crammed with six-story high compact buildings with eight feet wide dark alleys between neighboring buildings.

To overcome this situation, The Dhaka Metropolitan Building Construction Act-2008 was enacted. It controls building density by restricting 'allowable building footprint' and 'Floor Area Ratio' (FAR). With the specified 'allowable building footprint', a mandatory open area is preserved in the lot; while with the specified 'FAR', builders and owners of the lot can build higher stories to retrieve their rentable floor spaces. Specific values are assigned for these two aspects based on different site conditions. As an example, for a one third acre lot, the 'allowable building footprint' is 50% and the FAR is 5. Table-1.1 shows the difference between the regulations of 1996 and 2008, in terms of their restrictions for a one third acre lot. With this new set of regulations of 2008, courtyard type building-forms (mentioned earlier for its comfortable indoor spaces) along with other thermally comfortable building-forms are possible without losing rentable floor spaces. The reason is that floor spaces sacrificed in each floor for the courtyard can be retrieved by adding extra floor on top. With this new set of regulations, more open area (up to 50% of the lot) is assured to allow daylight and natural ventilation. Thus it is asserted that the 2008 regulations will improve the built environment (Z. N. Ahmed, 2010).

Table-1.1: Comparison between 1996 and 2008 regulations for a one third acre lot.

Zoning regulations	Allowable building footprint	Height limitation	Floor Area Ratio (FAR)
1996	None However, **80%** is achievable under setback rules.	**6**-stories For some neighborhoods.	None However, **5.1** is achievable.
2008	**50%**	None However, height is determined by FAR	**5**

1.2 RESEARCH QUESTIONS

Although the new set of regulations is assumed to bring improvement, there was no scientific study to see whether the change will improve thermal comfort conditions in apartment buildings. Moreover, there was no scientific study to prove that the mentioned 'allowable building footprint' is the optimum one in terms of thermal comfort. Therefore, this research intends to answer the following questions:

1. How much improvement or change in thermal comfort conditions (in Dhaka's non-conditioned apartment buildings) has been achieved through the change in its zoning regulations?
2. If there is any change or improvement in thermal comfort conditions, what is the level of its significance?
3. What are the other possible modifications in zoning regulations that would improve thermal comfort?
4. What is the optimum allowable building footprint for favorable thermal comfort conditions in Dhaka city?

5. What are the approaches in zoning regulation modifications that preserve existing density and improve thermal comfort conditions in non-conditioned apartment buildings under hot humid climate zone?

1.3 OBJECTIVES

The central objective of this research is to seek zoning regulations' potential to improve thermal comfort conditions in Dhaka's non-conditioned apartment buildings, without sacrificing its existing density. More detail objectives are:

1. To analyze thermal comfort conditions in Dhaka's apartment buildings developed under existing zoning regulations (regulations of 2008).
2. To analyze thermal comfort conditions in Dhaka's apartment buildings developed under previous zoning regulations (regulations of 1996).
3. To compare thermal comfort conditions in various apartment buildings those were developed under different set of zoning regulations
4. To analyze other possible set of zoning regulations that would be more favorable for thermal comfort.
5. Finally, to identify a set of zoning regulations that is the most favorable for thermal comfort in Dhaka's non-conditioned apartment buildings.

1.4 RESEARCH HYPOTHESIS

The central hypothesis of this study is that a set of zoning regulations that allows less congested high-rise development will provide better thermal comfort conditions than a set of zoning regulations that allows congested mid-rise developments.

1.5 SIGNIFICANCE OF THIS RESEARCH

Following are the significance of this research:

1. The research will show zoning regulations' potential to improve thermal comfort conditions in non-conditioned apartment buildings.
2. The results of this research will show whether Dhaka's zoning regulations need further modification in terms of its impact on thermal comfort conditions.
3. The research, through the comparative analysis between congested mid-rise development and less-congested high-rise development, will show strengths and weakness of different development density that will be useful insight for planners of Dhaka city.
4. Since Dhaka's climate is not significantly different from rest of the country, the results of this research will be useful to formulate appropriate zoning regulations for other cities of Bangladesh.
5. In the same way, the central hypothesis, if proved to be right, can be useful in planning of other hot humid cities in developing countries.

1.6 LIMITATIONS OF THIS RESEARCH

Following are the limitations of this research:

1. Zoning regulations vary for different lot size, and this research only considers zoning regulations for a $1/3^{rd}$ acre lot.
2. Different variations in building-forms are possible, and this research only considers building-forms variations that exist in the selected neighborhood.
3. This research only considers existing density and other possible densities are beyond the scope of this research.
4. This research only simulates the zoning schemes' performance for April 5, the hottest day of the year, described by the weather file.
5. The results are based on simulations and depend on the limitations inherent in Computational Fluid Dynamics (CFD) software Fluent and Energy Simulation (ES) software EnergyPlus.

2. LITERATURE REVIEW

This section covers relevant literatures on thermal comfort in hot humid climate zones, passive cooling strategies for hot humid climate zones, and urban housing and zoning regulations for hot humid climate zones. It also discusses literature that deals with building-form and zoning regulations, and their impact on the effectiveness of passive cooling. Following is the section outline:

1. Thermal comfort in non-conditioned spaces in hot humid climates.
2. Passive cooling as a means to achieve thermal comfort.
3. Existing as well as possible passive cooling strategies for dense cities of developing countries.
4. Impact of zoning regulations on available passive cooling strategies.
5. Impact of building-form and multiple buildings on passive cooling strategies.
6. Summary of the reviewed literature.

2.1 THERMAL COMFORT IN NON-CONDITIONED SPACES IN HOT HUMID CLIMATE

2.1.1 Thermal comfort

Since the major aim of this research is to improve thermal comfort conditions, it is essential to recognize parameters regarding thermal comfort and their values, specified by previous researchers. According to Givoni (1998), thermal comfort can be defined as the range of climatic conditions considered comfortable and acceptable to humans (Sreshthaputra, 2003). Beside contextual and cultural factors' influence on peoples' thermal comfort, a person's thermal comfort sense is the result of the body's heat exchange with the environment (Olesen & Brager, 2004). Air temperature, radiant temperature, humidity, and wind speed are the four environmental parameters those influence this heat exchange. There are two personal parameters – clothing level and activity level, those also have influence on this heat exchange (Owen & Kennedy, 2009).

2.1.2 International thermal comfort standards

These above mentioned parameters are specified in different standards around the world. Most frequently cited standards are ASHRAE 55-2004, CEN standard En15251 (CEN 2007), ISO 1984 (Tuohy et. Al., 2009; Sreshthaputra, 2003). The ASHRAE standard is created and published by the American Society of Heating, Refrigerating and Air-conditioning Engineers. The CEN is European Committee for Standardization. ISO is the International Standard Organization. These standards are helpful guide for designers and planners to set their design and planning goals in terms of thermal comfort. The objectives and the concepts in these standards are similar and this literature review includes ASHRAE standards due to the author's familiarity with it.

ASHRAE Standard 55-2004 specifies conditions of indoor thermal environment that will make users comfortable. It incorporates earlier advances that were made in Standard 55-92 and 55-95a. In earlier standards, air temperature and humidity were specified for air-conditioned spaces and therefore the standard was not meaningful for non-conditioned space (Givoni, 1992). For that reason, the 2004 version introduced the concept of adaptation with a separate method for naturally conditioned buildings (Olesen & Brager, 2004). The adaptation method does not predict comfort responses rather it states a range of thermal conditions under which people will feel comfortable (Owen & Kennedy, 2009). Figure-2.1 shows the range of acceptable operative temperature (T_{oc}) in this adaptation method where T_{oc} is a function of outdoor temperature. This method was based on a model which was based on 21,000 measurements taken from four continents (Olesen & Brager, 2004). This method also does not specify any humidity level or air speed limits. However, this standard is less effective for this research since it was developed in the context of conditioned buildings in developed countries (Lomas, 2007).

Beside ASHRAE and the other mentioned standards, there are several other comfort indexes for diagnosing comfort conditions for a given place. These comfort indexes, in the form of graphical chart, have been developed by researchers over last couple of decades. Olgyay was the first to develop such graphical index, named 'Bio-climatic-chart' (Givoni, 1992). The chart is shown in Figure-2.2 where horizontal axis represents relative humidity and vertical axis represents temperature. Comfort ranges for summer and winter are plotted on the chart. For any given location, this chart provides diagnosis of under-heated, comfortable, or overheated conditions through average diurnal loops of temperature and humidity conditions (Givoni, 1992). However, Olgyay's bio-climatic-chart was strictly applicable only to outdoor spaces. Olgay commented that his chart can be used for light-mass and all-day-ventilated building since outdoor and indoor temperature is same in such buildings. However, in high-mass and night-time-ventilated buildings, this chart will not be applicable. Since this research include high-mass and night-time-ventilation strategies, Olgyay's chart will be also less effective.

Givoni (1992) developed Building Bio-climatic Chart (BBCC) to overcome the mentioned drawback of Olgyay's bio-climatic chart. The BBCC uses indoor temperature to construct the comfort index instead of outdoor temperature. The indoor temperature is an estimated one that would change with different passive design strategies like day-time ventilation, thermal mass, evaporative cooling (Sreshthaputra, 2003). According to Givoni's BBCC, 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. BBCC is useful for this research because it has been adjusted for non-conditioned buildings of developing hot humid countries (Sreshthaputra 2003).

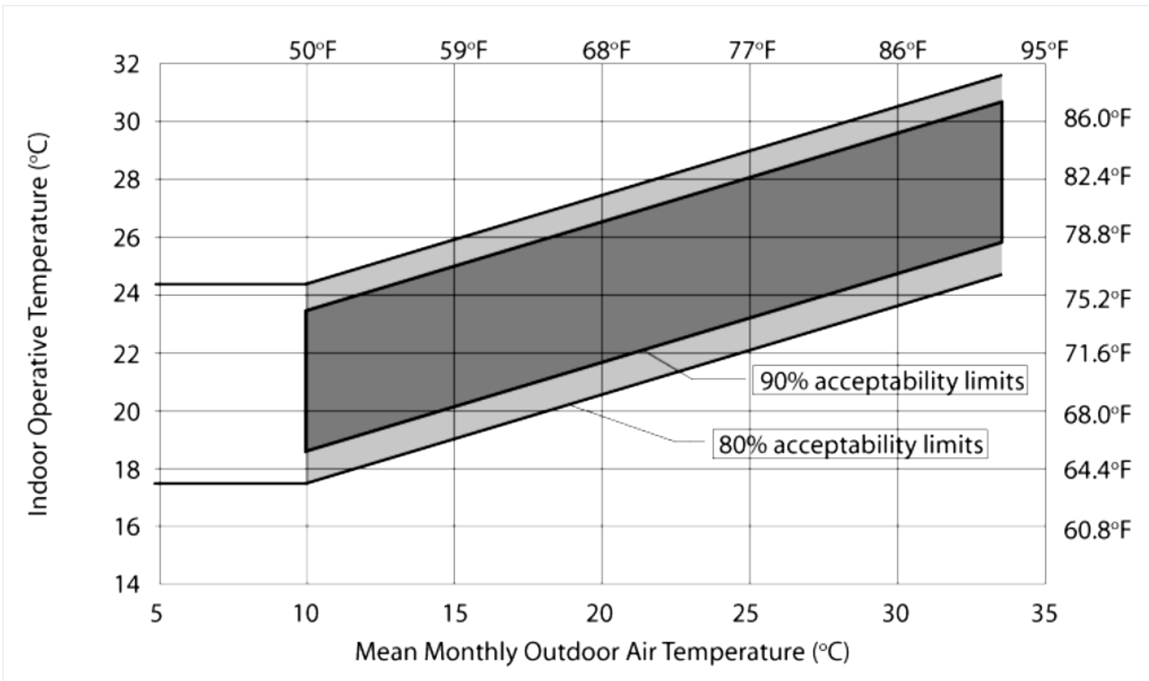


Figure-2.1: Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces. (Source: Lynch and O'Rourke 2009)

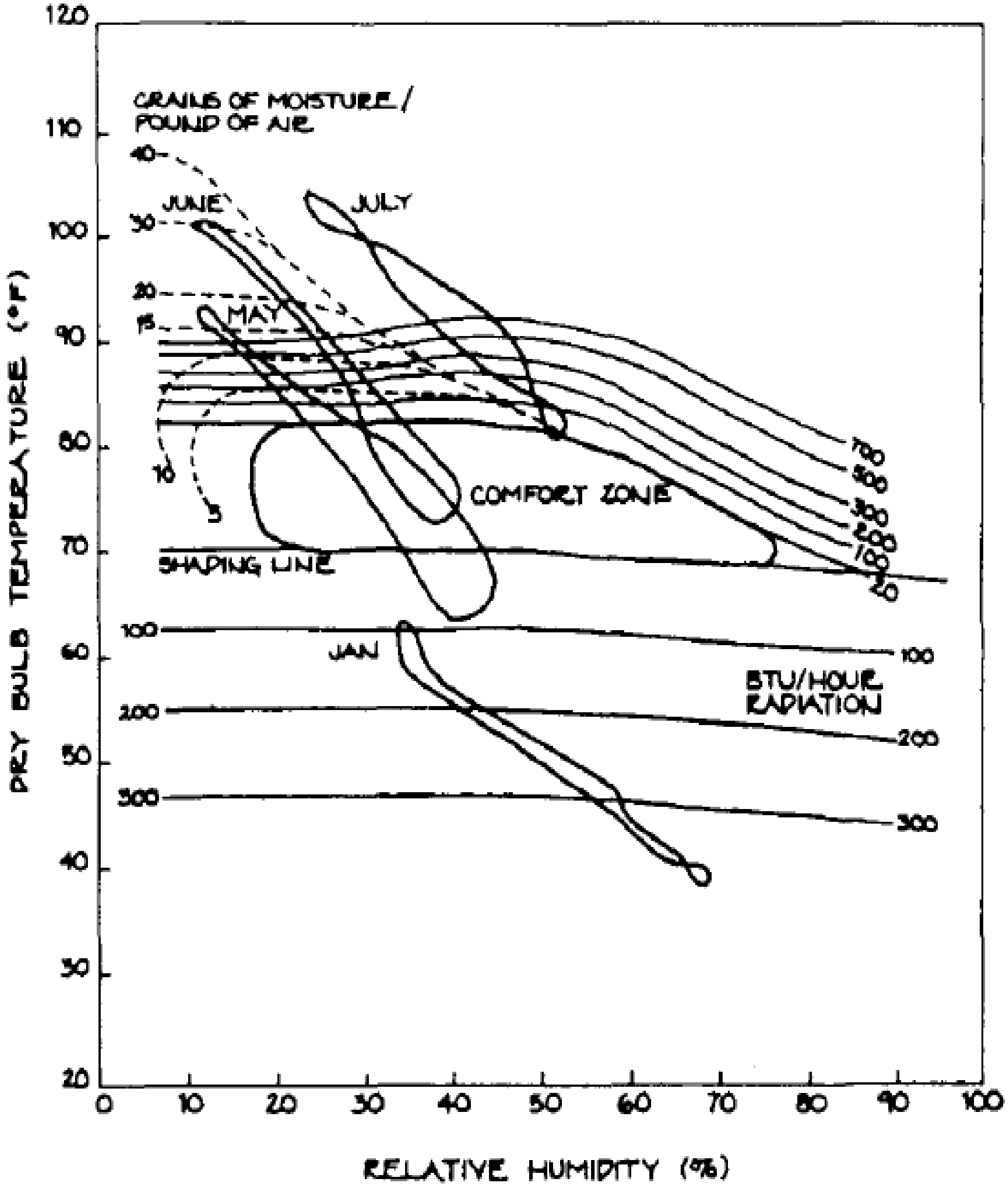


Figure-2.2: Olgyay's Bio-Climatic Chart. (Source: Sreshthaputra, 2003)

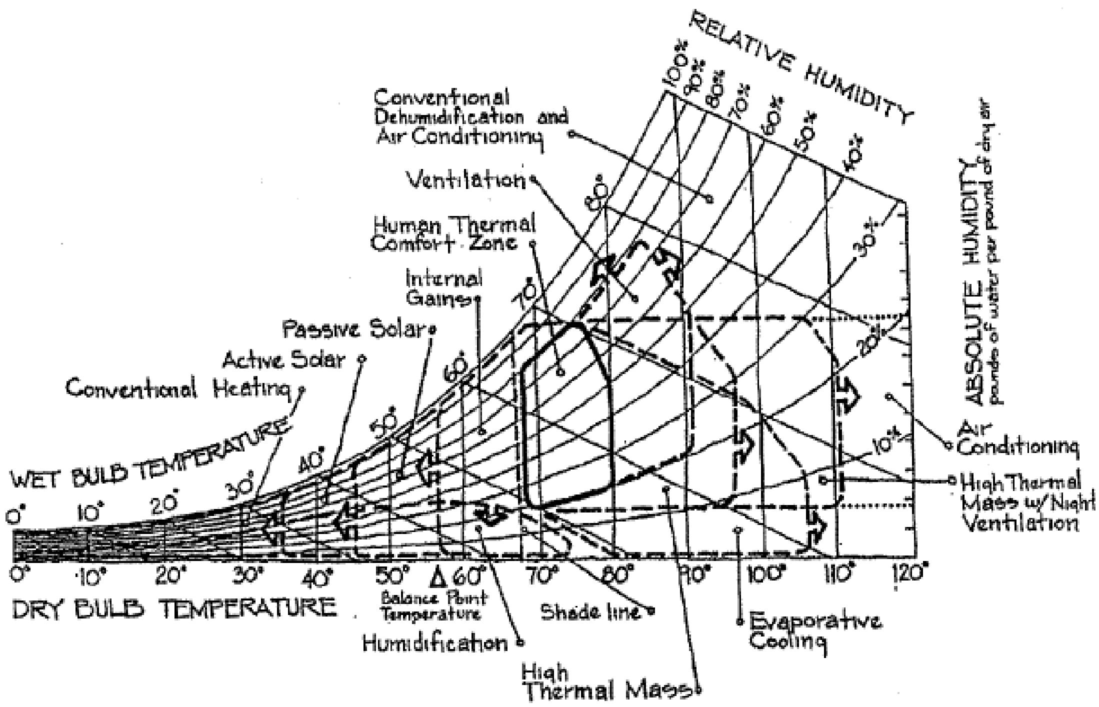


Figure-2.3: Givoni's Building Bio-Climatic Chart. (Source: Sreshthaputra, 2003)

2.1.3 Thermal comfort for Dhaka city

People modify their behavior and manage their building in response to change in climate (Brager & de Dear, 1998; Krüger & Givoni, 2008). Several studies (Humphrey, 1970; Nicol & Humphreys, 2010)Tanabe, 1988; Nicol, 1974) showed that people tolerate higher temperature if the place has higher annual average temperature. Givoni's BBCC (Figure-2.3) works in accordance with this fact. According to Givoni (1992), people in developing hot countries, living mostly in non-conditioned buildings, are acclimatized to and tolerate higher temperature and humidity. Tanabe's work (1988) also shows that an increase in air speed also increase tolerance to higher temperature (Sreshthaputra, 2003). These are all supported by Mallick's work (1996) on acceptable thermal comfort conditions in Dhaka's urban housing.

According to Mallick's work, thermal comfort zone for Dhaka's housing has following characteristics (Figure 2-4):

Without or little air movement –

- Air-temperature range – 24°C to 32°C.
- Humidity – 50% to 90%.

Other important aspects of the thermal comfort are:

- Tolerance to high temperature increase (2.2°C) with an air speed of more than 0.3m/s.
- People are acclimatized and can tolerate high humidity, even 95%. Only critical thing is that temperature tolerance decreases with high humidity.

Conclusion: Since ASHRAE-55-2004, Olgyay's Bio-climatic chart, Givoni's Building Bio-Climatic Chart, and Mallicks work are all based on the adaptation method, and Mallick's work directly represent the context of Dhaka's non-conditioned apartment buildings, Mallick's work will be used in this research.

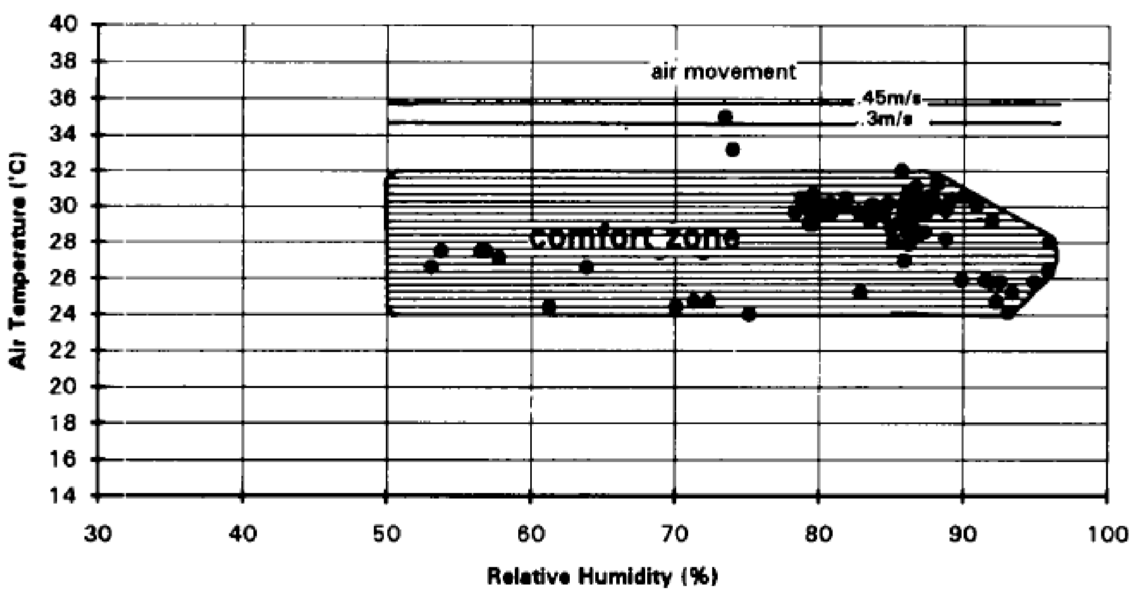


Figure-2.4: Summer comfort zone for Bangladesh.

2.2 PASSIVE COOLING AS A MEANS TO ACHIEVE THERMAL COMFORT

To achieve thermal comfort in traditional houses of Bnagladesh, passive cooling has been widely used (Hassan, Ullah, & Gomes, 2000). Mechanical means of cooling is available for apartment buildings of Dhaka city but they are not economically feasible due to socio-economic reasons (Ali, 2007). According to Cook (1989) and Abrams (1986), there are five passive cooling strategies: a) heat avoidance, b) ventilative cooling, c) radiative cooling, d) evaporative cooling, and e) earth coupling (Sreshthaputra, 2003). In the following paragraphs, these strategies are described and discussed in terms of their relevance to this research.

2.2.1 Heat avoidance

Heat avoidance is a passive cooling strategy that provides protection against heat gain through direct solar radiation. Solar radiation protection is the primary passive cooling strategy in hot humid climate (Ossen, Ahmad, & Madros, 2005). To achieve adequate shading, vernacular houses in hot humid climates typically employ a surrounding veranda, roof overhangs, etc. This provides shading of windows, doors and exterior walls (B, 1994). Apartment building typologies cannot afford surrounding balconies due to constraints of dwelling unit attachment and cost (Mohamed, Prasad, & Tahir, 2008).

Horizontal opaque surfaces, like roofs, are vulnerable to heat gain through conduction due to the sun's altitude and resulting incident angle (Muhaisen & Gadi, 2006). Consequently, shading the entire roof is not economically feasible. In this regard, a vertical tower-type apartment building-form, due to its smaller roof area, is more preferable than horizontal building-form (Al-Sallal, 2001). However, a typical tower-type apartment building-form has other disadvantages: in a tower-type apartment building, individual dwelling units are arranged around central core where some units have east-west orientation and others have north-south orientation. The east-west oriented units are more vulnerable to direct solar heat gain because west and east facing windows are difficult to shade at morning and late afternoon because of the low sun angles and solar radiation penetration into the dwelling units (Kristensen, Tang, Reimann, & smail, 2007).

2.2.2 Ventilative cooling

Wind induced ventilation is the most common passive cooling strategy, and tends to work well in hot humid climate zones. It works when outside ambient temperature is pleasant, that is below 32^{o}C (Cook, 1998). This cooler outside air replaces warmer indoor air through wind flow. During summer in hot humid climate zones, ambient temperature is sometimes (several hours around noon) higher than 32^{o}C (Ali, 2007), and then wind induced ventilation becomes ineffective. An effective way to ameliorate this problem is to keep the windows closed to avoid convective heat gain through warmer outdoor air during those hours (Ubbelohde & Loisos). Another way for addressing this problem is to create "cool islands" around apartment buildings so that surrounding air temperature remains below 32^{o}C (Emmanuel, Rosenlund, & Johansson, 2007). Cool Islands are the result of adequate shading from buildings and trees in urban areas, which create an envelope of cooler ambient air surrounding the building. It is also the result of heat exchange between the hot air, trees and moisture in the ground. However, effort to create the "Cool Island" effect through proper planning and urban design is lacking in of most hot humid cities (Corbella & Magalhães, 2008).

Night ventilation, although traditionally used in hot arid climate, can be another effective passive cooling strategy for hot humid climate (Carrilho da Graça, Chen, Glicksman, & Norford, 2002). When outdoor ambient temperature rises beyond tolerable limit during day time, windows are kept closed and heat is absorbed in thermal mass of the building, including the interior air (B, 1994). With night time ventilation, this stored heat is released to lower the indoor temperature as heat naturally flows from warmer indoor spaces to cooler outdoor at night (Artmann, Manz, & Heiselberg, 2008). Some researchers argue that night ventilation is not appropriate for hot humid climate due to lower diurnal temperature difference and some researchers argue that night ventilation is possible in hot humid climate (Kubota, Chyee, & Ahmad, 2009; Shaviv, Yezioro, & Capeluto, 2001). While controversial, night ventilation will be explored in this research to see whether nighttime ventilation is beneficial to Dhaka's apartments.

Subrato Chandra, in *Passive Cooling* (1998), has described the above two strategies as 'building cooling' strategies (Cook, 1998). He included 'people cooling' as another passive cooling strategy for hot humid climate. In 'people cooling', certain levels of wind speed, higher than the one for wind induced ventilation, is needed. Wind flow passing over the human body extracts heat if the air temperature is lower than skin temperature (Tablada, De Troyer, Blocken, Carmeliet, & Verschure, 2009). This convective heat transfer works well in humid air due to perspiration (Tsutsumi, Katayama, Ishii, He, & Hayashi, 1996). Therefore, people cooling with adequate wind speed is a desirable passive cooling strategy in hot humid climate. However, during the presence of excessive wind speed, windows and doors need to be closed.

2.2.3 Radiative cooling

In radiative cooling, heat is transferred from heat source to heat sink through radiation. This process is used in cooling of indoor spaces (through flat-plate radiators mounted on rooftops) as well as cooling of building-mass (Erell and Etzion, 2000). The flat-plate radiators are connected to indoor spaces through a series of water circulating tubes. At night, water in these tubes collect heat from warm indoor air and transport and release it to the cooler night sky through radiation. These flat-plate radiators can be placed in any unobstructed part of a flat roof. The various building-forms that will be studied in this research are all with flat roof. Therefore, there variation in building-forms will not affect the effectiveness of radiators. Moreover, this type of radiative cooling use pumps for its working fluid. For this reason, flat-plate radiator will not be included in the study. Radiative cooling of building-mass is the process where building-mass absorbs solar heat during day and radiates it back to cooler outdoor ambient air and clear night sky

(Cook 1998). In hot arid climate, night-time outdoor temperature is cooler and night sky is also clear hence radiative cooling works effectively. However, most hot humid cities have mostly overcast sky during summer months. In addition to this, humidity is also high during the summer which minimizes radiative cooling (Jaffer, 2006). These factors reduce the rate of night-time radiative heat transfer and cause trapping of heat in buildings interior (Sreshthaputra 2003). This is why radiative cooling is less effective in hot humid climate (Martin 1989 (Ratti, Raydan, & Steemers, 2003). However, if a little effect of radiative cooling can be achieved along with wind-induced ventilation, radiative cooling can be utilized in night-time ventilation for hot humid climate.

2.2.4 Evaporative cooling

Evaporative cooling is inappropriate for this study because high humidity make evaporative cooling ineffective in hot humid climate (Naz, 2008). Evaporative cooling works better when water vapor deficit is high in ambient air, compared to ambient air with low water vapor deficit (Cohen, Stanhill, & Fuchs, 1983). Despite the inefficiency of evaporative cooling in hot humid climate, Yong and Chong studied evaporative cooling behavior of misting fan in hot humid climate of Singapore (Wong & Chong, 2010). According to their work, mist allows ambient air to cool from its dry-bulb temperature to its wet bulb temperature if the droplets are fully vaporized. However, their findings comply with W Solomon’s work (1979) which states that mist provide favorable environment for yeast and bacteria (Wong & Chong, 2010). Therefore, evaporative cooling is ignored in this study.

2.2.5 Earth coupling

Earth coupling is suitable for low-rise buildings and sloping topography where underground walls and floors are used to dissipate heat towards the surrounding earth (Andolsun, Culp, Haberl, & Witte, 2011). This research deals with a specific type of apartment building, typically found in Dhaka, where the first floor is designed for parking and the rest of the upper floors are for dwelling units (Kamruzzaman & Ogura, 2007). Therefore, earth coupling is not a solution for passive cooling strategy for this particular building type. Beside, earth coupling requires ground temperature to be in a range of 68o F to 78o F (Cook, 1998) and Dhaka's average ground temperature is 79o F hence does not provide a powerful heat sink for cooling (Naz, 2008).

2.3 PASSIVE COOLING IN DENSE CITIES

Due to rapid urbanization and land scarcity, cities like Dhaka or any other south Asian city are denser and their buildings are compact than those in Western countries (Cheng, Steemers, Montavon, & Compagnon, 2006). This is not environmentally sustainable for hot humid climates because compact building forms are not conductive to energy efficient natural cooling techniques (Wende, Huelsmann, Marty, Penn-Bressel, & Bobylev, 2010). The compact building forms inhibit wind flow (Tablada et al. 2009). Therefore, the effectiveness of passive cooling techniques within this context is limited by the density of built form and inadequate exposure to natural forces (Su 2001).

Densification alters the shape, compactness, and proportion of traditional building features and these three were meant to support passive cooling (Rashid, no date). As an example, the aspect ratio of courtyard in low rise houses' has been altered: the modified multistory structures have courtyard with similar horizontal cross section but the height of the courtyard is several times larger. Therefore, courtyards are now transformed into narrow light and ventilation wells for high rise apartment buildings (Tablada, et al., 2009). These narrow wells neither bring ample daylight nor do they allow internal heat to be released outside. Lack of daylight brings the need for artificial lighting adding heat to the interior (Perez & Capeluto, 2009). Another example is the change in building width where traditional houses of Bangladesh were a single room wide that allowed for excellent cross ventilation. For newer apartments, building widths have multiple rooms, which reduces the opportunity and effectiveness of cross ventilation (Fuad H, 1996). Therefore, natural ventilation in apartment buildings is difficult to achieve.

Compact form, due to densification (and diminished plot to building rations) impacts the energy performance in several ways. One is with reduced daylight. Two is with reduced dwelling surface area for more adequate natural ventilation. And three minimizes vegetated surfaces of the lot. Lack of vegetated surface and open space is correlated with higher ambient temperature (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006). The reason is that abundance of vegetation and moisture in ground transform most of the incoming solar radiation into latent heat rather than sensible heat (Oke, 1987). With this logic, it is said that vegetated open space create 'cool island' in hot humid urban areas (Emmanuel, et al., 2007) and can potentially improve comfort conditions in surrounding apartments (Khandaker Shabbir, 2003). Being too dense and compact, apartments in cities of developing countries are unable to get benefit from "cool islands".

Summary: based on the above discussion on passive cooling strategies, as well as dense city context, this research is using the following two passive cooling strategies: i) heat avoidance, and ii) ventilative cooling.

2.4 IMPACT OF BUILDING-FORM ON AVAILABLE PASSIVE COOLING STRATEGIES

2.4.1 Impact of building-form on solar protection

Building-form affect solar access and thus it plays important role in passive cooling through solar protection (Cadima 2000). The relationship between solar protection and building form has been studied by several researchers [Ratti, Raydan and Steemers (2003); Muhaisen and Gadi (2006); Cheung, Fuller and Luther (2005); Mallick (1994); Shaviv and Capeluto (1992); Al-Sallal (1996); Giridharan, Ganesan and Lau (2004); ASHRAE Special Project-102 (1999); Mclain, MacDonald, and Goldenburg (no date);

Kristensen, Tang, Reimann, and Ismail (no date); Hafiz (2000); Cadima (2000)]. Following are several works which are related to this study:

1) Ratti, Raydan and Steemers (2003) studied environmental impact of two types of building-form –pavilion type and courtyard type. They studied urban arrays of both types in three variations (Figure-2.5) with a constant built volume and compared these forms' solar protection performance. They analyzed surface to volume ratio and shadow density along with few other environmental variables. Higher surface to volume ratio of courtyard form, along with high thermal mass, act as heat sink during day time; at night, due to much lower temperature, courtyard form act as heat source for the cooler night. Moreover, courtyard form's shadow density is higher than pavilion.

Finding in this study, relevant to this research, is discussed below:

Courtyard form performs better than pavilion in terms of solar protection.

Limitation observed in this study, relevant to this research, is discussed below:

According to the study, courtyard form will not perform well in hot humid climate due to lower diurnal temperature difference. However, they did not mention whether pavilion or some other form would perform well in hot humid climate.

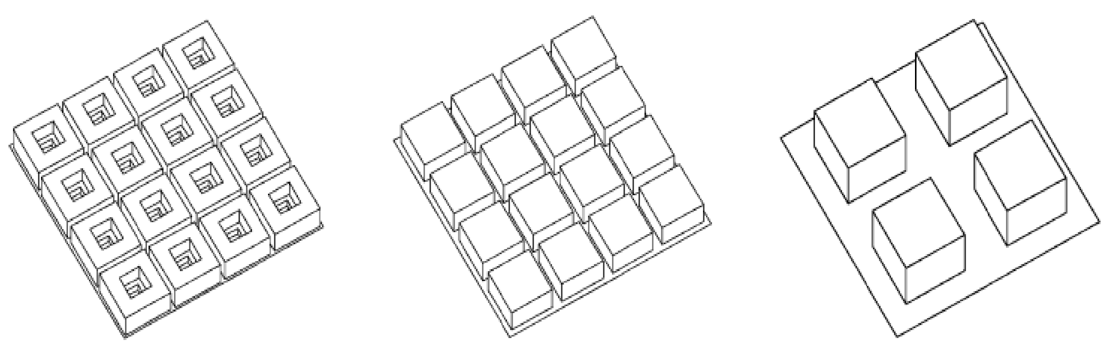


Figure-2.5: Three types of building-forms studied by Ratti, Raydan and Steemers (2003).

2) Al-Sallal (1996) studied solar access in traditional housing cluster in Sana, Yemen. He studied tower building form in terms of its behavior to sun. Sana's

traditional houses are tower forms, mostly four to five floors and some up to nine floors. The high sun altitude makes the vertical walls less vulnerable to direct sun and does the opposite for the roof. Sana's tower form compliments such solar behavior because tower form has least roof area and higher wall area. Therefore, in summer the tower form perform well in terms of solar protection.

Finding in this study, relevant to this research, is discussed below:

For a constant built volume, taller building-form is better than shorter (but thicker) building-form.

Limitation observed in this study, relevant to this research, is discussed below:

Sana's tower form house compliments its traditional lifestyle by zoning each side of the house for different domestic tasks like – south for living areas, north for service areas, lower floors for storage areas. However, tower form of contemporary apartment building cannot have this luxury. Since each side of the building-form is occupied by an individual dwelling unit, symmetry has to be maintained. Therefore, some unit will have more environmental benefit than the other.

3) Cadima (2000) studied O-shape, L-shape, and U-shape building-form in terms of their behavior to solar access (Figure-2.6). They analyzed the impact of change in seasonal variation, orientation, height to width ratio, and height.

Finding in this study, relevant to this research, is discussed below:

Increase in height decreases solar radiation and increase in length does the opposite. O-shape form reacts to this fact more than L-shape form. Orientation has least effects on O-shape and it has more effect on L-shape than U-shape.

Limitation observed in this study, relevant to this research, is discussed below:

Cadima's study was done for 32^o North latitude. This research considers 23^o North latitude. Solar angle for the studied building-forms would be lower for both summer and winter. This would require a revised analysis for 23^o North latitude.

4) Muhaisen and Gadi (2006) studied courtyard's proportion and its impact on solar access (Figure-2.7). They concluded that physical parameters of the courtyard form are crucial to solar access and hence influence the need for heating and cooling. They

examined different proportions of courtyard based on two varying ratios – R1 (perimeter/height) and R2 (width/length).

Finding in this study, relevant to this research, is discussed below:

When the courtyard form is shallower, solar protection is difficult. First reason is that it has more roof area. Second reason is that it allows more radiation in the courtyard and therefore less self-shading is achieved.

Limitation observed in this study, relevant to this research, is discussed below:

The study was done for 42^{o} North latitude. Sun's altitude is lower than that for 23^{o} North latitude and thus self-shading in courtyard would be different and needs to be revised.

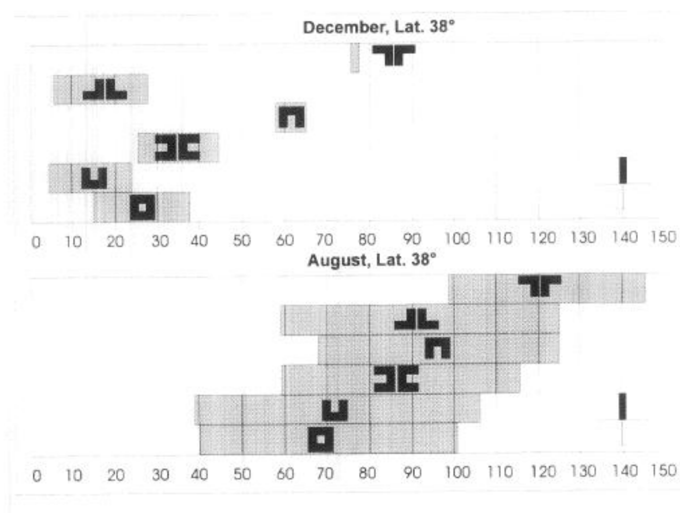


Figure-2.6: Solar access analysis in O-shape, L-shape, and U-shape building-form. (Source: Cadima, 2007)

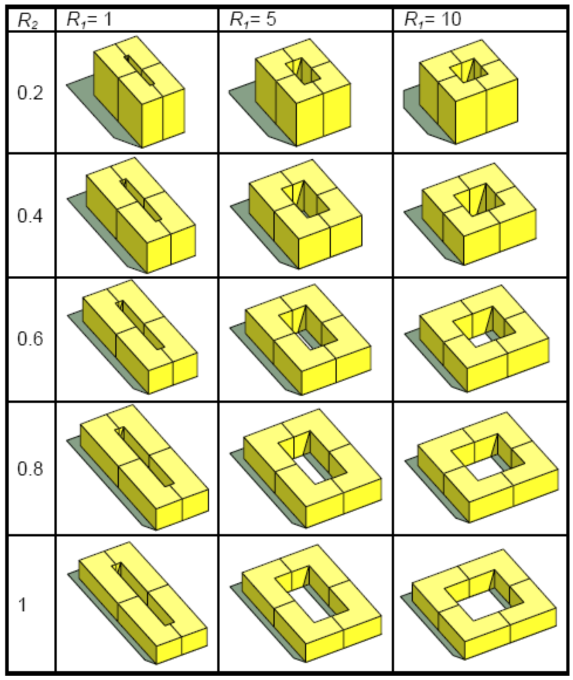


Figure-2.7: Study of solar access under different courtyard proportions. (Muhaisen and Gadi, 2006)

5) Shaviv and Capeluto (1992) studied the relationship between a building's energy performance and its several geometrical parameters. Their findings regarding building's proportion and solar access are relevant to this research because it was done for hot humid climate.

Finding in this study, relevant to this research, is discussed below:

For hot humid climate, defining a precise building proportion is not necessary as it was mentioned by Olgyay (1963). Olgyay mentioned 1:1.7 (elongated on the east-west axis) to be the optimum proportion. Shaviv and Capeluto concluded that such proportion is not complimentary to their study but too much elongation of the form on north-south axis should be avoided.

Limitation observed in this study, relevant to this research, is discussed below:

The statement that proportion has less significance on solar heat gain is valid when the windows are all shaded. Windows on east and west façade cannot be shaded entirely in early morning or late afternoon. During those hours, window shutter are required to shade eastern and western windows which cause daylight reduction. Since apartment building may have dwelling units on all four sides, some units will be less privileged than the others.

2.4.2 Impact of building-form on wind induced ventilation

Following are five studies those analyzed building-form's effect on natural ventilation.

1) Givoni (1994) laid out design guidelines to utilize wind induced ventilation in multi-story apartment buildings for hot humid climate. For getting better wind flow inside houses, Givoni suggested to orient rooms in an angle between 30^{o} to 120^{o} to the prevailing wind direction. In such manner, rooms will have windows in both windward walls and leeward walls where cross ventilation will happen due to positive and negative pressure zones.

Finding in this study, relevant to this research, is discussed below:

Building's orientation needs to be oblique to the prevailing wind.

Limitation observed in this study, relevant to this research, is discussed below:

Unfortunately, these guidelines do not work for apartment buildings in dense urban areas of developing countries because of surrounding physical conditions. Moreover, detailed study on the effect of surrounding buildings on natural ventilation is scarce (Hoof and Blocken 2010).

2) Abbelohde and Loisos (date unknown) studied thermal behavior of Ahemadabadi Pol house, a traditional courtyard house in dense urban area of Ahmedabad. Ahmedabad is on 23.5^{o} North latitude that is similar to Dhaka. According to the authors, south shading in summer is easy in this latitude. However, in summer months, the sun's altitude is high and horizontal opening causes highest solar heat gain. The tall and narrow courtyard of the Pol House (Figure-2.8) is appropriate to successfully reduce this direct solar gain through self-shading. Moreover, the Pol Houses share long party walls and expose only narrow end walls. These narrow end walls also

face narrow and deep street canyon which assure further shading. This is a successful shading strategy. However, this strategy do not allow adequate exterior opening to provide ventilation. This causes stagnant and damp interior spaces.

Finding in this study, relevant to this research, is discussed below:

The combined goal of shading and ventilation is challenging. Larger surface to volume ratio, with adequate shading is needed.

Limitation observed in this study, relevant to this research, is discussed below:

The Ahmedabadi Pol House has to operate in a seasonal cycle of hot-dry, hot-humid, and temperate-dry climate. Therefore, its design features will not be the same for a dominant hot humid climate.

3) Tablada et al. (2009) studied thermal comfort in old courtyard houses of Havana where climate is hot humid and built environment is dense. Their study shows a combine effect of outdoor and indoor design features on indoor thermal comfort. First, through literature survey, they established that wider streets provide better street ventilation than narrower ones. Second, they established that courtyard could enhance ventilation of the house if it is permeable to those well ventilated streets, both from ground floor and from the top (Figure-2.9). According to their study, such courtyards allow higher ventilation than the ones those are only open at the top.

Finding in this study, relevant to this research, is discussed below:

This particular research is relevant for this study because the apartments in Dhaka city are all open at ground floor for parking purpose. Moreover, most of them have ‘light & ventilation well’ which may have potential to act like the deep courtyards of old Havana houses.

Limitation observed in this study, relevant to this research, is discussed below:

The studied houses are all low rise structure and therefore the mentioned ventilation effect has to be tested for high-rise buildings.

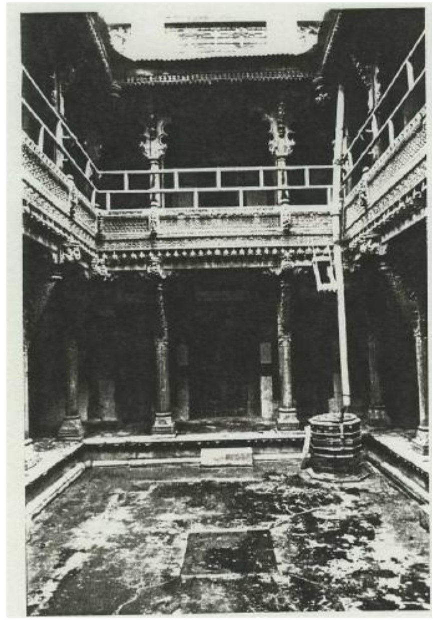


Figure-2.8: The courtyard in Ahmedabadi Pol House. (Source: Abbelohde and Loisos, n. d.)

Figure-2.9: The courtyard having connection with the street front. (Source: Tabelada, 2009)

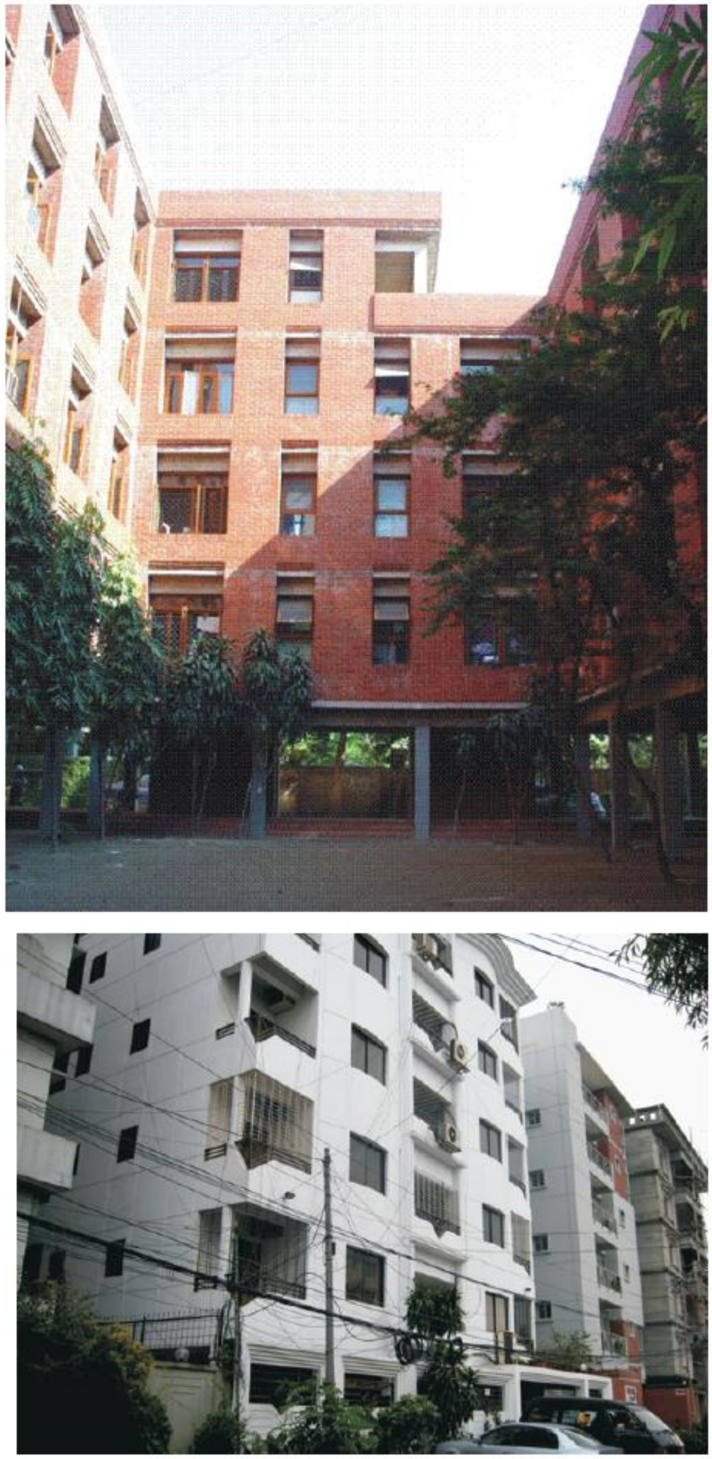


Figure-2.10: Courtyard type (top) and non-courtyard type (bottom) apartment buildings in Dhaka city. (Source: Ali, 2007)

4) The above mentioned courtyards' ventilation potential can be related with Ali's work on Dhaka apartments (2007). Ali compared thermal comfort in apartments with courtyard and apartments without courtyard (Figure-2.10). All of the apartments' first floors are open. Therefore, the courtyards have similar characteristic as old Havana houses that is they are exposed to exterior environment, both from ground floor and from the top. Ali's findings show that apartments with courtyard provide better thermal environment than apartments without courtyard.

Finding in this study, relevant to this research, is discussed below:

This particular research is relevant for this study because the apartments in Dhaka city are all open at ground floor for parking purpose. Moreover, most of them have 'light & ventilation well' which may have potential to act like the deep courtyards of old Havana houses.

Limitation observed in this study, relevant to this research, is discussed below:

Both of the apartment types are different in building volume or usable floor area but similar in height. Therefore, they do not preserve a constant density which is one of the primary objectives of this research.

5) Murakami's research (2004) is in individual building scale, in terms of shading and ventilation enhancement for high density houses in hot humid climate. Based on Dr Kojima's 'space block' design method, he proposed a porous-type residential building model to enhance shading and cross ventilation (Figure-2.11). Space block method simultaneously considers substantial portions and voids of a building as cubes. Therefore, effective placement of voids create self-shading as well as allow cross ventilation. His results shows an 11% decrease in cooling load through cross ventilation.

Finding in this study, relevant to this research, is discussed below:

Effective introduction of void spaces both in horizontal cross section and vertical cross section of a building can promote passive cooling through self-shading and cross ventilation.

Limitation observed in this study, relevant to this research, is discussed below:

Specification regarding the optimum percentage of such void spaces as well as their position could be beneficial.

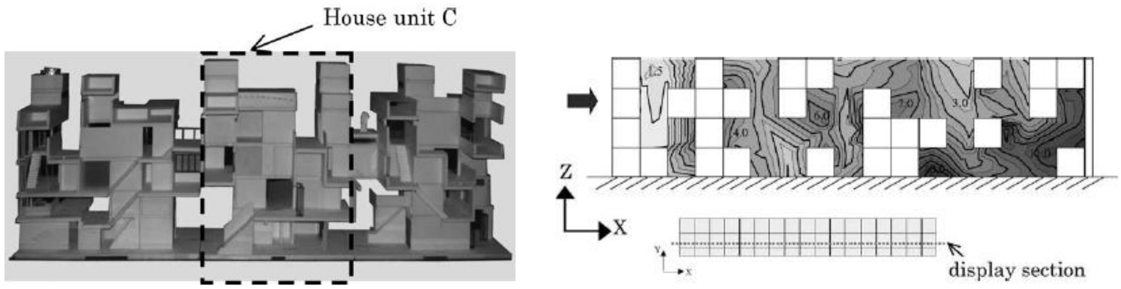


Figure-2.11: Scale model (left) and distribution of age of air (right) in the Hanoi experimental house. (Source: Murakami, 2004)

2.4.3 Impact of building-form on night-time ventilation

Night only ventilation is appropriate if day time outdoor dry bulb temperature exceeds comfort range. In a number of summer days, Dhaka city experience higher temperature (higher than comfort range) during daytime. It is pointless to allow daytime ventilation in such condition because it will replace the cooler indoor air (cooled down through night) with warmer outdoor air. Following are some research works those studied several aspects of night ventilation.

1) Givoni (1994) suggested spread-out building layout for better night ventilation due to its higher surface-to-volume ratio. Ratti et al. (2003) studied environmental performance of different building-forms in hot arid climate. Their findings also suggest that optimum building-form has higher surface to volume ratio to utilize night ventilation. Higher surface to volume ratio receives more solar radiation but with appropriate building mass, it can flush out the heat to the cooler outdoor at night. Krüger, E. and B. Givoni (2008) studied night ventilation in a passive solar house in

Sede-Boqer of Israel. Their result shows that night ventilation causes significant drop in indoor temperature in summer months.

Finding in this study, relevant to this research, is discussed below:

Higher surface to volume ratio is good for night time ventilation.

Limitation observed in this study, relevant to this research, is discussed below:

Both of these studies were conducted under hot arid climate where diurnal temperature difference is high. Night ventilation studies in hot humid climate have to be reviewed.

2) Beside higher surface-to-volume ratio, high thermal mass is another crucial factor for night time ventilation. According to Krausse et al. (2007), night time ventilation was proven as a successful passive cooling strategy in a UK library. According to the authors – "Night-time venting is used to cool the exposed thermal mass of the building so that it can absorb heat during warm periods of the following day." This along with few other passive cooling strategies, kept the indoor temperature of the library 5-8^{o} C below ambient temperature.

Finding in this study, relevant to this research, is discussed below:

High thermal mass is good for night time ventilation.

Limitation observed in this study, relevant to this research, is discussed below:

The diurnal temperature difference at the study location was over 15^{o} C. This is a reasonable night-time cooling potential. This may not the case for hot humid climate.

3) Majority of the research on night ventilation were done in hot arid or moderate climate and most of them suggest higher diurnal temperature difference as the key requirement for successful night ventilation. Carrilho Da Graca et al. (2002) simulated night ventilation in a six-story apartment building for the context of Beijing and Shanghai. Both the cities have hot humid summer but the case for Beijing was successful where as Shanghai was not. The authors argued that smaller diurnal temperature difference, high air temperature and humidity act as obstacles for night ventilation. This can be implied as source of uncertainty for the use of night ventilation in hot humid

climate. Further studies on night ventilation for hot humid climate are therefore needed to be reviewed.

Finding in this study, relevant to this research, is discussed below:

Higher diurnal temperature difference as the key requirement for successful night ventilation.

Limitation observed in this study, relevant to this research, is discussed below:

For effective night-time ventilation, there is no stated range for diurnal temperature difference.

4) According to literature, for night ventilation in hot humid climate, diurnal temperature difference is the primary consideration. Scholars have different opinion regarding the optimum value of diurnal temperature difference (Kubota 2009). Givoni (1994) mentioned the most conservative one and that is 10^{o}C. In a study done by Liping and Hien (2007), it is evident that night ventilation can be successful if the difference is 7-8^{o}C. According to Shaviv et al. (2001) (ref. Kubota 2009), 3^{o}C reduction in peak day time temperature is possible if the diurnal temperature difference is more than 6^{o}C.

2.5 IMPACT OF ZONING REGULATION ON AVAILABLE PASSIVE COOLING STRATEGIES

2.5.1 Impact of zoning regulation on solar protection

Like building-form, urban form also influences solar access of an individual building (Ratti et al. 2000). Components of zoning regulation like – buildable area of individual lot, setbacks, and building height influence the urban form. The literature search for this research has not found any study that discusses the relationship between solar protection and the stated components of zoning regulation. However, several researchers worked on the relationship between urban planning guidelines and solar access. Some researchers studied urban form and solar access and their results could be synthesized to prepare appropriate zoning regulation for optimum solar access. This research finds these literatures to be useful to be included in this literature review. Following are some relevant works:

1) The most relevant research work regarding solar control and zoning regulation is done by Ralph Knowles. Ralph Knowles first conceived and tested 'Solar envelop' as a zoning concept (Knowles, 2003). Solar envelop was meant to assure solar access in urban areas (Knowles, Berry & Solar Energy Information Data Bank, 1980). According to Knowles, the solar envelope avoids unacceptable shadows above designated boundaries called "shadow fences" or in simple words – livable space. This same concept can be explored in the study of 'protection from direct solar radiation through zoning regulation'.

Finding in this study, relevant to this research, is discussed below:

'Solar envelop' may sound anti-urban and anti-property rights (Knowles and Marguerite, 1980). However, Knowles's 2003 study on solar envelop shows that a variety of possibilities are there for solar envelop to house a maximum of 128 Du/acre within a height range of three to seven storied buildings.

Limitation observed in this study, relevant to this research, is discussed below:

'Solar envelop' were tested mostly for passive heating. Similar concept should be tested against solar protection in hot humid climate.

2) From Sarkar's study (2009), it is evident that formulation of low energy zoning regulation is crucial. He admitted that neither urban planning guidelines nor building regulations can effectively provide low energy urban block. The former concentrate on land use, transportation, and finance and the later concentrate on individual building's energy efficiency. Sarkar advocated solar envelope to be a means to achieve low energy urban block and discussed different process of constructing solar envelope.

Finding in this study, relevant to this research, is discussed below:

There is a significant demand for urban block level zoning regulations. These regulations have to be context specific.

Limitation observed in this study, relevant to this research, is discussed below:

Sarkar's work concentrated on passive heating, day-lighting and the use of photovoltaic, for colder climate. Therefore, solar access was prioritized than solar control.

3) Regarding building-form, solar access, and planning regulation; another relevant study is in Germany, done by Wende et *al*. (2010). The authors admitted that in urban development of Germany, local development planning regulation should facilitate low-shade positioning of structures during winter and active-constructive shading during summer. However, their study focused on heating of the structures. Through Figure-2.12, they illustrated the effect of urban density on surface-to-volume ratio and associated heating demand.

Finding in this study, relevant to this research, is discussed below:

The authors suggested following points to be added as by-law in local development planning regulations. These points can be tested against the context of this research too.

- Specify height of structural facilities.
- Specify land area to be built on/ not to be built on.
- Specify size, depth and width of plots of land for building.
- Specify provision and location of planting.

Limitation observed in this study, relevant to this research, is discussed below:

The authors did not mention any use of simulation tools or other methods to verify the credibility of their ideas. Therefore, these ideas are subject to be tested, especially in the context of this research.

4) Gupta (unknown date) studied cluster of building forms in terms of solar access. He emphasized cluster over individual form because according to him – thermal behavior of common building forms is well known but this behavior is altered when buildings are laid out in clusters. Moreover, Gupta admitted that study on the relationship between solar access and consequent discomfort in non-conditioned building is not well known. Gupta considered a large building volume and analyzed a number of possible clusters for solar exposure (Figure-2.13). Although he did not

analyze these clusters in terms of zoning regulation, his findings can be interpreted in terms of urban block level zoning regulation like – street layout, size and shape of individual lot, allowable footprint in a lot, etc.

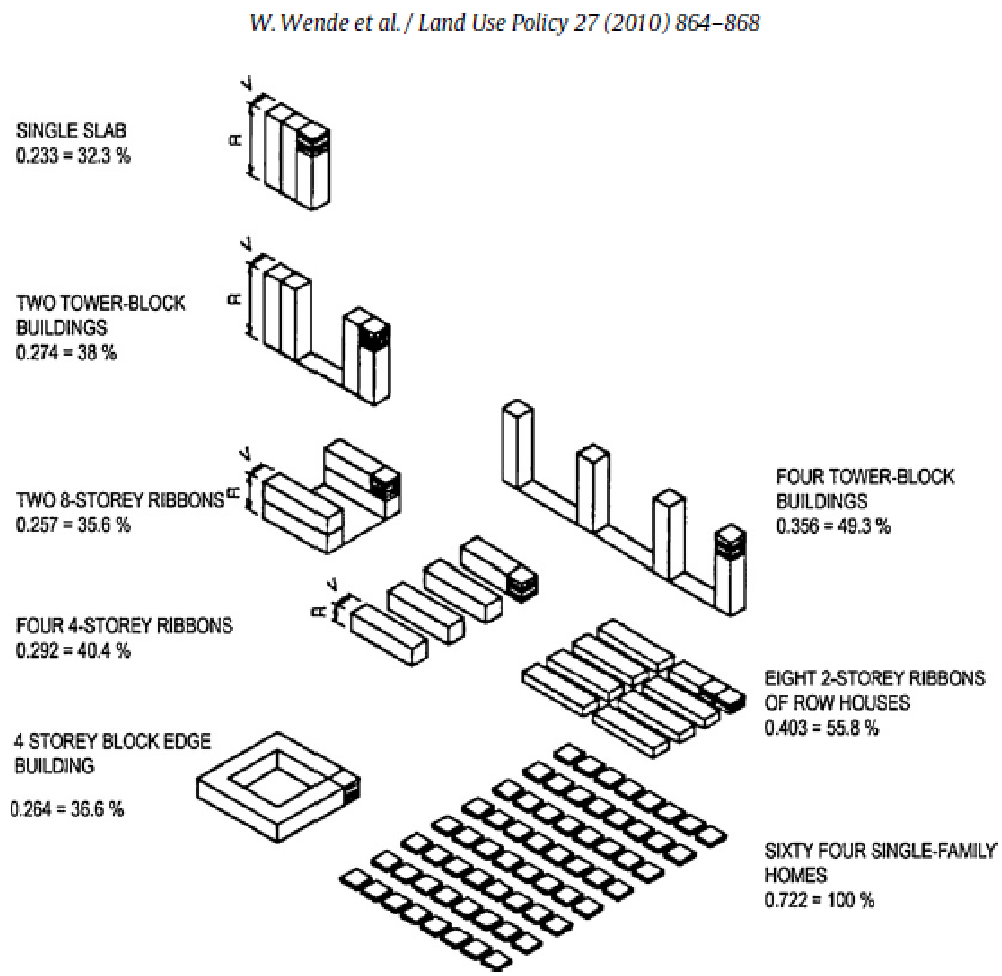


Figure-2.12: Different building shapes with equal building mass, offering different surface-to-volume ratio, and therefore creating different heating demand. (Source: Wende et. Al., 2010)

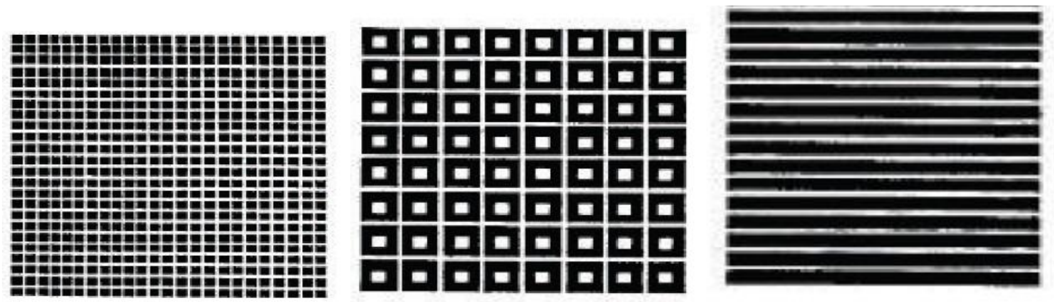


Figure-2.13: Three possible configurations of a given building volume of 800,000m3: (A) Pavilion, (B) Court, (C) Street. The first two are possible housing layouts while the third represents institutional or commercial building. (Source: Gupta, n.d.)

Finding in this study, relevant to this research, is discussed below:

Gupta concluded that for hot climate, solar exposure alone is not a good index for building-form's thermal efficiency. Other building features can alter its effect on building's thermal behavior. However, he added that if all other building features were same, solar exposure should be considered for form selection.

Limitation observed in this study, relevant to this research, is discussed below:

Solar heat transfer between external walls and internal walls/slabs only considered convection and radiation but not conduction. Moreover, temperatures in surrounding street or courtyard were assumed to be uniform which is far from reality. Therefore, a detailed heat transfer analysis is required.

5) Cheng et al. (2006) studied solar exposure in different urban forms with varying density. They admitted that recent planning guidelines are promoting higher density through compact urban form without examining thermal effect of compactness. They analyzed solar behavior in eighteen generic model of urban development; each comprises different combinations of building-form and density. These eighteen models are generated based on the following:

- Four built form categories based on horizontal and vertical randomness (Figure-2.14).

- Three classes of plot ratios (total floor area to site area) – 1.4 for low density, 3.6 for medium density, and 7.2 for high density.
- Two classes of site coverage – 9% for low coverage development, and 36% for high coverage development.

The analysis of solar behavior was done under three design criteria – openness at ground level, daylight on building façade, and PV potential on building envelope.

Finding in this study, relevant to this research, is discussed below:

Density affects solar potential differently if the manifestation of density is different. In this case, impact of plot ratio was different than the impact of site coverage. It is possible to increase usable floor area and plot ratio without undermining solar resources.

Limitation observed in this study, relevant to this research, is discussed below:

The climate context was different than that of this research and therefore findings could vary if the focus is solar control instead of solar access.

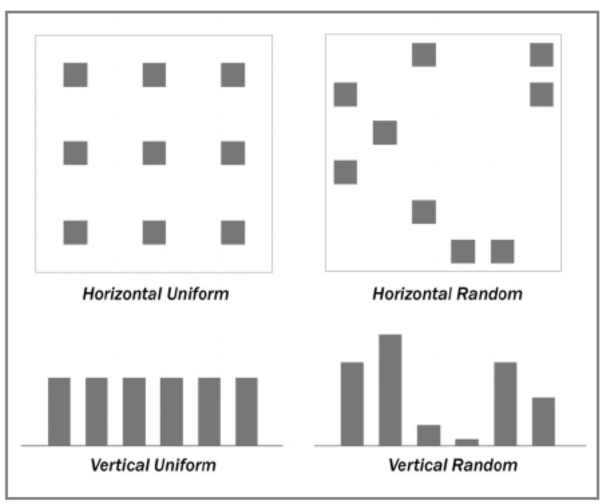


Figure-2.14: Horizontal and vertical urban layouts showing different building-forms with different density.

6) Emmanuel (1995) developed a set of energy efficient urban design guideline for hot humid climate of Colombo. These guidelines were developed after reviewing energy efficient urban design guidelines of cities of temperate climate. Emmanuel analyzed following parameters in those guidelines: Foor Area Ratio (FAR), plot size, building height, open space, waterfront development, and landscaping. One of his guideline, relevant to this research, is that building blocks should be North or South facing instead of East or West facing. This was based on but opposite of urban guidelines for Sacremento, Bolder etc. while Emmanuel's suggestion compliment solar shading, the source guidelines were for solar exposure. The other relevant guideline is for ventilation and it will be discussed in later part of this section.

2.5.2 Impact of zoning regulations on wind induced ventilation

Ventilation in an apartment building does not only depend on its building-form but also depends on the microclimate around it (Hoof and Blocken 2010). This microclimate is influenced by geometrical configuration of surrounding buildings and street canyons, or in simple words – on urban form (Yannas 1998, ref. Jabereen 1998). Urban block level zoning regulation can play important role in creating ventilation supportive urban form (Sarkar 2009). Following are few researches that dealt similar issues about ventilation:

1) Fahme and Sharples (2008) studied three patterns (Figure-2.15) of urban form and compared their impact on availability of shading and ventilation. The first urban pattern is for high density multifamily low income apartment housing. There exists narrow gaps among each building and buildings are five-story. The second pattern is for medium density mixed clustered-dot single and multifamily apartments. The gaps are little wider and buildings are four-story. The third one is dot single and multifamily which allows wider gap between buildings.

The first pattern performed best for first half of the day due to self-shading through compact urban form. However, due to compactness, lack of wind flow did not allow the stored heat to be dissipated in the afternoon. Second pattern did not perform well until mid day since wider gap between buildings could not provide self-shading. However, it allowed wind induced ventilation which eventually cools down the canyon at afternoon hours. The third pattern, until mid afternoon, performed better than the second one due to higher wind flow. From mid afternoon, too much wide gap among buildings allowed direct solar radiation on south and west canyon walls and consequently deteriorate the comfort conditions.

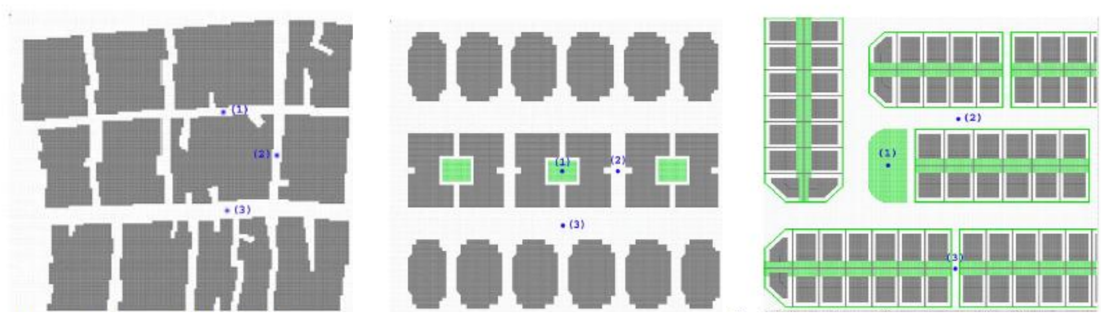


Figure-2.15: Impact of three patterns of urban forms on outdoor shading and ventilation. (Source: Fahme and Sharples, 2008)

Finding in this study, relevant to this research, is discussed below:

Medium density can provide balance shading and ventilation through medium aspect ratio and medium sky view factor of canyon geometry. The clustered form proportion did not allow wind access through its courtyards and resulted discomfort among the courtyards.

Limitation observed in this study, relevant to this research, is discussed below:

The climate of the studied urban patterns is hot arid. Therefore, the results have to be verified for hot humid climate zone.

2) Mohamed, Prasad and Tahir (date unknown) studied ventilation enhancement potential of balcony and found balcony to be beneficial for ventilation in hot humid climate. Balcony works as wind scoop for better ventilation. By referring Chand et al.

(1998), the authors stated that balcony creates turbulence and generates wind pressure to provide air flow in interior spaces.

Finding in this study, relevant to this research, is discussed below:

Although it seems unrelated to zoning laws, this literature review finds it relevant for dense urban areas. In dense urban area, developer utilizes entire ‘buildable area’ of a lot for indoor spaces for maximum revenue. Zoning regulation could mention whether a lot’s allowable built area include or exclude mandatory provision of balcony. Moreover, zoning regulations could allow balcony beyond ‘buildable area’ if the open area of the lot is enough.

Limitation observed in this study, relevant to this research, is discussed below:

More specification regarding physical structure of balcony is needed. Moreover, like optimum window-to-floor area ratio, an optimum balcony area-to-floor area ratio as well as position of balcony needs to be identified. This could be more helpful to formulate passive cooling friendly zoning regulations.

3) In medium density housing in an Australian hot humid city, Su (2001) studied outdoor ventilation for two different building configurations. The total building volume is same. One is single story and the other is double story but its footprint is half of the former. Natural ventilation for both configurations was studied using polystyrene bead visual test method and tracer gas test method in wind tunnel. The later configuration showed 18-20% improvement in outdoor ventilation.

Finding in this study, relevant to this research, is discussed below:

Lowering site coverage with an increased building height improves outdoor ventilation.

Limitation observed in this study, relevant to this research, is discussed below:

Similar concept needs to be studied for high density multifamily housing.

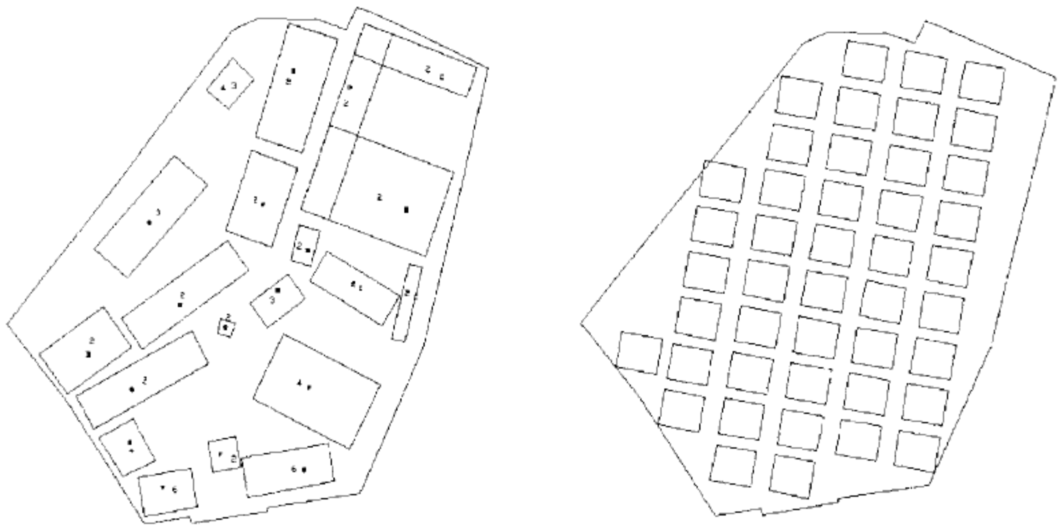


Figure-2.16: A study on aerodynamic characters of building-forms: comparing wind behavior of an array of true urban forms with its simpler representation (extrapolated from the actual one). (Source: Grosso and Banchio, 2000)

4) Grosso and Banchio (2000) studied the impact of plan area density, a possible zoning component, on wind driven cross ventilation. Their study considered five European locations with varying plan area density. One of their objectives was to explore whether urban drag coefficient (C_d) varies with plan area density and how it modify the nature of ventilative cooling. In authors' word, "C_d represents the relative wind pressure force acting upon the vertical surfaces of a considered urban area along the wind flow". Their study shows that a decrease in plan area density increase C_d and increased C_d increases ventilative cooling.

Finding in this study, relevant to this research, is discussed below:

One of the assumption of this study was – existed differences in aerodynamic character of all buildings, in a neighborhood, can be leveled out if drag of the whole area is considered". Under this assumption, they performed thermal simulations on arrays of cube-shape buildings which are extrapolation of actual urban scenario (Figure-2.16).

This simplification reduces time and computing resources and this can be a useful concept for this research.

Limitation observed in this study, relevant to this research, is discussed below:

The results were compared with CFD results and it shows under estimation of wind drag. Therefore, a CFD analysis is required.

5) Mentioning Emmanuel's work (1995) again is significant in terms of zoning regulation and ventilation. In his recommendations, some stated earlier in this literature review, he mentioned "stepped massing" around water bodies to ensure see breeze for maximum inhabitants.

Finding in this study, relevant to this research, is discussed below:

Although Dhaka city is not in a marine context, the stepped massing can be encouraged along street facing building blocks to get benefit from street ventilation.

Limitation observed in this study, relevant to this research, is discussed below:

Emmanuel's suggested steeper light plane (narrow courtyard and spaces between buildings) to discourage unwanted light from bright tropical sky. This suggestion however seems contradictory in terms of allowing wind movement around buildings.

2.5.3 Impact of zoning regulation on night-time ventilation

From the above discussion, it is clear that night temperature at outdoor spaces has to be significantly lower than day time temperature for successful night-time ventilation. However, the diurnal temperature difference shown in weather file should not be a determinant factor to select night-time ventilation. The reason is that nocturnal Urban Heat Island (UHI) increases night temperature at urban outdoor spaces (Smith and Livermore 2008). Geros et al (2005) showed that contributors to UHI also contribute to reduced night ventilation. Certain geometrical parameters of urban building-form, like 'height-to-floor area ratio', 'sky view factor', and 'street canyon geometry' contribute to nocturnal UHI (Giridharan et al. 2005). These variables can be guided by zoning regulation. Therefore, these variables need to be studied as a zoning component to allow effective night-time ventilation through mitigating nocturnal UHI. In the following paragraphs, we will explore literatures on UHI and see how they can assist this study, and at the same time, will identify the gaps which can be filled by this study.

1) Among the fewer studies on UHI for hot humid climate, Giridharan et al. (2005) studied UHI for hot humid climate of Hong Kong. Their case studies show nocturnal UHI in the order of 1.3^{o}C. According to them, tall concrete residential buildings with sharp edges and low aspect ratio trap both short wave and long wave radiation and cause nocturnal UHI. Another study on UHI for hot humid climate was done by Kruger et al. (2011) where relationship between urban morphology and UHI has been explored. The authors' findings supported the works of Giridharan et al.

Finding in this study, relevant to this research, is discussed below:

Heat stored in combined mass of densely placed building cannot be released through night-time ventilation. Building density and height is crucial for effective night-time ventilation.

Limitation observed in this study, relevant to this research, is discussed below:

However, the study focused on pedestrian level comfort and did not relate it with indoor temperature in the surrounding buildings.

2) Similar type of study was done by Wong et al. (2011). The authors evaluated surrounding urban morphology's influence on urban temperature. They considered surrounding building height, surrounding building density and presence of vegetation for the study. It seems higher surrounding buildings lower daytime temperature but increase nocturnal UHI. Maximum density also has similar effect. In the same direction, combined effect of maximum height and maximum density offers higher nocturnal UHI. Although more open area (lower density) increases daytime UHI, it can reduce the ambient temperature if it is properly vegetated. The reason is that vegetation absorbs 50% of the incident solar radiation (Corbella et al. 2011).

Finding in this study, relevant to this research, is discussed below:

Higher density, with higher Floor Area Ratio (FAR), can provide more open spaces for vegetation and higher wind circulation. In this regard, higher density can be supportive for both daytime UHI mitigation as well as nocturnal UHI mitigation.

Limitation observed in this study, relevant to this research, is discussed below:

However, the above paragraph is only an assumption. It needs to be verified.

3) For hot humid climate, nocturnal UHI mitigation through urban morphology is not flawless. Such endeavor increases daytime UHI because optimum street canyon geometry, aspect ratio or sky view factor (SVF) for night-time ventilation also increases solar exposure (Wong et al. 2011). In such dilemma, according to Corbella (2008), building use should be considered. He suggested day time UHI mitigation for office buildings and nocturnal UHI mitigation for dormitories.

Finding in this study, relevant to this research, is discussed below:

Both daytime UHI mitigation and nocturnal UHI mitigation strategies contradict each other and therefore building use (time wise) has to be considered for over all passive cooling goals.

Limitation observed in this study, relevant to this research, is discussed below:

Apartment buildings are not entirely similar to dormitories since children, senior citizens or some other members are supposed to be using the facility at day time. Therefore, selecting nocturnal UHI mitigation over day time UHI mitigation has to be carefully considered.

2.6 SUMMARY OF THE LITERATURE REVIEW

This literature review discussed relevant (to this research) studies on thermal comfort, and also discussed studies that deal with passive cooling strategies. This literature review also included studies those analyzed zoning regulation and building-forms' impact on thermal comfort as well as different passive cooling strategies. Each of these studies has either relevance to this research or has potential to be used in this research.

Among the relevant thermal comfort criteria discussed in this research, Mallick's range of thermal comfort was chosen, because his work was done based on the thermal comfort perception of Dhaka's apartment dwellers.

The passive cooling strategies those were found (in the literature review) to be crucial for hot humid climates, will be used as performance measures for zoning regulations' impact on thermal comfort. The selected strategies are following:

1) Solar protection.
2) Daylight maximization.
3) Ventilation maximization.
4) Night-time ventilation.
5) Air velocity enhancement.

The significant (in terms of thermal comfort or passive cooling) behavior and characteristics of building-forms and zoning regulations, discussed in this literature review, will be addressed and used for making assumption and deduction during this research. Several such behaviors are mentioned below:

1) Zoning regulations that allows higher density increases shading but it reduces air flow.
2) Lower density does the opposite.
3) The zoning regulations that causes higher ratio in canyon geometry, allows more shading but less air flow.
4) Tower type building-forms are better for low latitude location because its vertical surface area is larger than its horizontal surface area.
5) For shading purpose, courtyard type building-form is better than pavilion type building-forms.
6) A street type (Figure-2.13) building-form works best for cross ventilation, and if oriented to the south, can cut solar radiation through the use of moderate size shading device.
7) Use of veranda provides shade as well as it increases wind pressure on buildings, which consequently cause good air flow.

3. METHODOLOGY

The literature review summarized that the appropriateness of zoning regulations needs to be studied in order to improve the thermal comfort conditions in non-conditioned apartment buildings; and the reasons are: i) zoning regulations regulate an individual building's building-form in dense urban environment, ii) zoning regulations regulate the form of the built-environment around the individual building, and iii) by regulating the form of the individual building as well as its surrounding built-environment, zoning regulations control the access of sun and wind into the individual dwelling units and consequently control its thermal comfort conditions.

Zoning regulations are comprised of different components, which vary for different site conditions. Studying all the components of zoning regulations, for all site conditions, is beyond the scope of a single research endeavor. Therefore, the studied zoning regulation components as well as the studied lot size are limited in this research. The rationale behind this research project and its methodology are explained through the following points and their elaboration in the subsequent paragraphs:

1. Selection of zoning regulation components as independent variables for this study.
2. Selection of varied zoning schemes for this study.
3. Selection of neighborhood to study the selected zoning schemes.
4. Selection of building-forms to match the selected zoning schemes.
5. Selection of simulation tools.
6. Methods to use the selected simulation tools.
7. Summary of the research methodology.

3.1 SELECTION OF ZONING REGULATION COMPONENTS AS THE INDEPENDENT VARIABLES FOR THIS STUDY

The literature review (Section-2) summarized how zoning regulations affect buildings' access to sun and wind, by regulating following components: i) the maximum buildable area in a lot, ii) the maximum size and height of buildings, iii) density (either mentioned by Dwelling Unit/acre or Floor Area Ratio), iv) setbacks, v) orientation, etc. (Selmi & Kushner., 2004). Buildings' access to sun and wind is crucial to its energy use as well as its occupants' thermal comfort. In several literatures, these components were addressed as independent variables to study buildings' energy use. However, these were never addressed as independent variables to study occupants' thermal comfort.

This research will address these components as its independent variables, because 'energy reduction' through controlling solar and wind access is conceptually similar to 'thermal comfort enhancement' through controlling solar and wind access. A pilot study was conducted to examine these components' validity as independent variables for thermal comfort conditions. Indoor temperature and indoor wind velocity were chosen as dependent variables in the pilot study. These two were chosen because the literature review on Dhaka's thermal comfort found these variables most crucial for its citizens' thermal comfort.

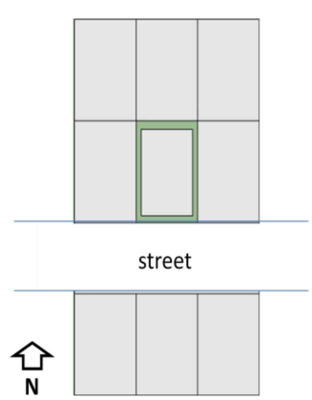


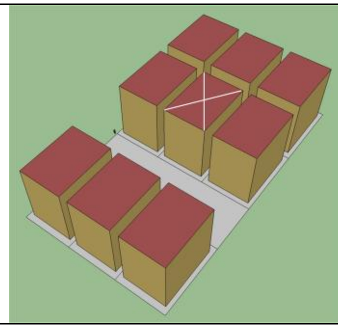
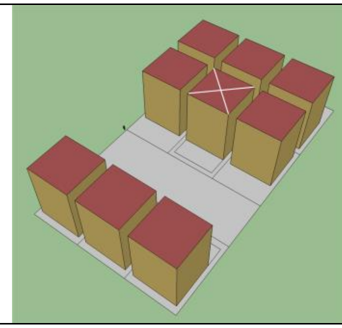
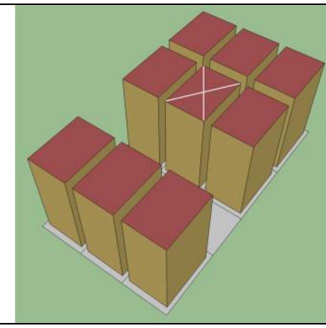
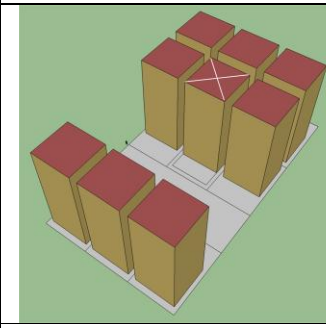
Figure-3.1 Site contexts for the pilot study.

A cluster of nine individual lots (Figure-3.1) was the context to run computer simulations for the pilot study. Each lot is 1/12th acre (3600 square feet or 5 'Kathas' in local terms) which represents the typical lot size in Dhaka's housing scenario (Rashid, no date). Four different built environments (shown in Table-3.1) were simulated where each was modeled based on different values of 'buildable area,' 'building height limit,' and 'density.' 'Orientation' was excluded because four variations in 'orientation' need sixteen (4 orientation X 4 different built environments) sets of simulations. This is a large number in terms of available computing time and resources. 'Setback' was also excluded for the same reason because its possible variations are limitless. The building on the center lot was the main subject and the rest acted as neighboring buildings.

Table-3.1 shows the details of the pilot study. To run the pilot study, first, a 'Base Case' was established based on the stereotype residential development in Dhaka city which reflects The Building Construction Rules 1996 (Chakrabarti, 2008; Kamruzzaman & Ogura, 2007). In the Base Case, 'buildable area' was seventy percent and 'building height limit' was six-stories. Here, FAR was 3.5 and density was 120 DU/Acre. The first floor was for parking and the rest of the floors have two dwelling units each (popular practice for this lot size is two units per floor).

To analyze the impact of 'buildable area,' the Base Case was compared with a second case named Case-II. Case-II was a hypothetical one, where 'buildable area' was fifty percent but 'building height limit' was the same as the Base Case. Here, FAR was 2.5 and density was 60 DU/Acre (one larger unit per floor). To analyze the impact of height, the Base Case was compared with Case-III where 'buildable area' was as same as the Base Case but 'building height limit' was increased to ten-stories. Here, FAR was 6.3 and density was 216 DU/Acre (zwelling unit size and its number per floor is similar to the base case).

Table-3.1: Independent variables in the pilot study.

Name of Independent variable	Base Case	Case-II	Case-III	Case-IV
				
Change in 'buildable area' and 'building height'	The base case.	Reduced 'buildable area' but same 'building height	Same 'buildable area' but increased 'building height	Reduced 'buildable area' and increased 'building height
'Buildable area'	70%	50%	70%	50%
'Building height limit'	6-story.	6-story.	10-story.	10-story.
Density (FAR)	3.5	2.5	6.3	5
Density (DU/Acre)	120	60	216	120

To analyze the impact of density, either in terms of FAR or DU/Acre, Base Case (120 Du/Acre, FAR of 3.5), Case-II (60 DU/Acre, FAR of 2.5), and Case-III (210 DU/Acre, FAR of 6.3) were compared. In addition, a case named Case-IV (with a similar density, in terms of DU/Acre, as the Base case but with more open space) was simulated and compared with the Base Case. The similar density, in Case-IV, was derived through reducing footprint and increasing building height.

The details about the process of temperature analysis and wind velocity analysis will be discussed in the later sub-sections of this section. The results of the pilot study are shown in Table-3.2. From Table-3.2, it is evident that all of the independent variables have impact, either positive or negative, on the dependent variables. Therefore, these three components of zoning regulations are worthwhile to consider as independent variables for the context of this research.

3.2 SELECTION OF VARIED ZONING SCHEMES FOR THIS STUDY

One of the research objectives, mentioned earlier in Section-1, is to identify a zoning regulation scheme or a set of zoning regulations that is most favorable for thermal comfort in Dhaka's non-conditioned apartment buildings. In order to address this objective, existing and possible zoning schemes (composed of the selected independent variables) will be identified and compared. For this, first, the values of independent variables mentioned in The Building Construction Rules-1996 and in The Dhaka Metropolitan Building Construction Act-2008 need to be analyzed.

The values of independent variables, regulated by each zoning scheme, vary based on lot sizes. In Dhaka's housing context, common lot sizes are 3 Katha, 5 Katha, 7.5 Katha, 10 Katha, and 20 Katha, where1 Katha is equal to 720 ft^2 (Rashid, n.d.). Table-3.3 shows the values of 'allowable building footprint', 'building height limit', 'FAR' and 'setbacks' for these lot sizes, allowed under regulations of 1996 and 2008. 1996 regulations did not specifically mentioned 'allowable building footprint' but 'allowable building footprint' has been calculated using 'setbacks', because building construction was only restricted on the setback areas. 1996 regulations also did not mention FAR but it has been calculated from 'setbacks' and 'building height limit'. 2008 regulations do not specifically mention 'building height limit' but possible 'building height' for maximum use of 'allowable building footprint' has been calculated from FAR.

Table-3.2: Impact of independent variables on dependent variables.

Change in independent variable			**Change in dependent variables**	
Name of dependent variable		**Change in value** (from Base Case)	**Change in indoor temperature**	**Change in indoor wind velocity**
Allowable building footprint		From 70% to 50%	-1°C	-0.13 m/s
Building height limit		From 6-stories to 10-stories	+1°C	-0.43 m/s
Density	FAR	From 3.5 to 2.5	-1°C	-0.13 m/s
		From 3.5 to 6.3	+1°C	-0.43 m/s
	DU/Acre	From 120 to 60	-1°C	-0.13 m/s
		From 120 to 210	+1°C	-0.43 m/s
		No change (Case-IV)	+2°C	-0.6 m/s

Table-3.3: Values of selected independent variables under zoning regulations of 1996 and 2008.

Zoning regulations		Buildable area	Building height	Density	
year	Lot size			FAR	DU/Acre
1996	3 Katha or 1/18th acre	70%	6-story	4.2	
	5 Katha or 1/12th acre	71%	6-story	4.26	
	7.5 Katha or 1/8th acre	76%	6-story	4.56	
	10 Katha or 1/6th acre	78%	6-story	4.68	
	20 Katha or 1/3rd acre	80%	6-story	5.1	
2008	3 Katha or 1/18th acre	65%	5-story	3.25	
	5 Katha or 1/12th acre	60%	5-story	3.5	
	7.5 Katha or 1/8th acre	60%	6-story	3.75	
	10 Katha or 1/6th acre	60%	7-story	4	
	20 Katha or 1/3rd acre	50%	10-story	5	

Note: some of the variables were not specified in the selected regulations but they were calculated for the purpose of comparison. See previous paragraph for details on calculations of these variables.

Since the values of independent variables vary for different lot sizes, it is beyond the scope of this research to compare both these regulations for all lot sizes. For the convenience of this research, one lot size needs to be selected. Table-3.3 shows that density for 20-Katha lot is similar in both 1996 and 2008 regulations. Since one of the objectives of this research is to examine whether thermal comfort conditions can be improved without sacrificing the existing density, a lot size of 20-Katha was chosen for this study. This allows thermal comfort to be compared between two zoning schemes where 'allowable building footprint' and 'building height' are different but density is the same. So two possible zoning schemes, assumed to be the preliminary zoning schemes, for this research will look like Table-3.4.

Table-3.4: Preliminary Zoning Schemes for 1/3rd Acre Lot.

Possible zoning regulation schemes	Basis for the schemes	Allowable building footprint	Building height limit	Density (FAR)
Scheme #1	Regulations of 1996	80%	6-story	5.1
Scheme #2	Regulations of 2008	50%	10-story	5

Table-3.3 also shows that density in terms of DU/Acre was never mentioned in any of the two sets of zoning regulations. Density in terms of DU/Acre is crucial for this research because thermal comfort conditions will be compared between individual buildings as well as individual dwelling units. Therefore, if all zoning schemes have a similar number of uniform size dwelling units, the comparison will be stable.

Since density was not mentioned in DU/Acre, possible density in DU/Acre needs to be calculated for the purpose of comparing two zoning schemes. Under 1996 regulations, the typical number of dwelling units in a 1/3rd acre lot was thirty. With the 'six-story height limit' of 1996 regulations, a typical apartment building allowed its first floor to have parking, and allowed each of the other five floors to have six units. So, under scheme #1, density in terms of DU/Acre should be 120.

To maintain similar density, in terms of DU/Acre, scheme #2 needs little adjustment in 'building height limit'. With 50% allowable building footprint, apartment buildings under scheme #2 can contain three similar (similar as found in scheme #1) size dwelling units per floor. Since the first floor is for parking, a building needs eleven floors to provide thirty dwelling units. So the variation in the revised zoning schemes will look like Table-3.5.

Table-3.5: Revised Zoning Schemes for 1/3rd Acre Lot.

Possible zoning regulation schemes	Basis for the schemes	Allowable building footprint	Building height limit	Density (DU/Acre)	Dwelling Units/floor
Scheme #1	Regulations of 1996	80%	6-story (first floor-parking)	120	6
Scheme #2	Regulations of 2008	50%	11-story (first floor-parking)	120	3

So, Table-3.5 shows two revised zoning schemes those are based on zoning regulations of 1996 and 2008. The difference in 'allowable building footprint' in 1996 and 2008 regulations only covers two extreme variations - one is 80% and the other is 50%. This research seeks to investigate more variations in between these two 'allowable building footprints'. Therefore, two more variations – one having 70% 'allowable building footprint' and the other having 60% 'allowable building footprint' have been included in this research. This 10% difference also compliments the gradual change in the number of dwelling units/floor. Since 10% of the lot is almost close to the size of a single dwelling unit, 70% 'allowable building footprint' can have 5 Units/floor and 60% 'allowable building footprint' can have 4 Units/floor. So, finally, the variations in the four zoning schemes will look like Table-3.6.

Table-3.6: Final Zoning Schemes for 1/3rd Acre Lot.

Possible zoning regulation schemes	Basis for the schemes	Allowable building footprint	Building height limit	Density (DU/Acre)	Dwelling Units/floor
Scheme #1	Regulations of 1996	80%	6-story (first floor-parking)	120	6
Scheme #2	Hypothetical	70%	7-story (first floor-parking)	120	5
Scheme #3	Hypothetical	60%	9-story (first floor-parking)	120	4
Scheme #4	Regulations of 2008	50%	11-story (first floor-parking)	120	3

3.3 SELECTION OF NEIGHBORHOOD FOR THIS STUDY

Dhanmondi Residential Area has been selected to analyze the four zoning schemes because it is the only planned residential neighborhood where the majority of the lots are $1/3^{rd}$ acre. Dhanmondi's average lot size is $1296m^2$ which is close to $1/3^{rd}$ acre (Mahtab-uz-Zaman & Lau, 2000). In other planned residential neighborhoods, like Uttara Model Town, majority of the lot sizes are $1/18^{th}$ acre (3-Katha) or $1/12^{th}$ acre (5-Katha)(Rashid, no date).

Figure-3.2: Satellite images of residential buildings at Dhanmondi and Uttara. (Source: Google map, accessed on September-13, 2011).

Figure-3.2 shows satellite images of both Dhanmondi Residential Area and Uttara Model Town. The scale is constant in both images. The lots at Dhanmondi are $1/3^{rd}$ acre, and the lots at Uttara are $1/12^{th}$ acre. The comparable sizes of buildings, resulted from lot sizes, are apparent in both these images.

The other reason to select Dhanmondi is that it is the best example of a residential neighborhood where most single-family houses transitioned to multi-family apartment buildings (Kamruzzaman & Ogura, 2007). Owners and developers in Dhanmodi have tried different variations of apartment building-forms to meet their spatial and other residential needs. Therefore, Dhanmondi presents a number of variations in apartment building-forms. These variations in existing building-forms will be a resourceful pool to select an appropriate building-form for each of the four zoning schemes.

3.4 SELECTION OF BUILDING-FORMS TO MATCH THE RESTRICTIONS OF SELECTED ZONING SCHEMES

To study the selected zoning schemes' impact on indoor thermal comfort conditions, particular building-form needs to be selected for each zoning scheme. A building-form that needs 80% of the lot for its footprint (regulated by zoning scheme-1) will not fit zoning scheme-4, which only allows 50% of the lot to be built upon. Moreover, there is more than one possible building-form for each zoning scheme. Examining all possible building-forms for each zoning scheme is beyond the scope of this research. Therefore, this research will identify one appropriate building-form for each zoning scheme.

Since Dhanmondi Residential Area offers a number of variations in apartment building-forms, a visual survey has been conducted to identify Dhanmondi's building-form typology. A total of 117 apartment buildings were visually surveyed to identify and graphically record these apartment buildings' building-forms. These 117 apartment buildings were selected based on the following two criteria:

- The lot has to be $1/3^{rd}$ acre.
- The building has to be transformed from earlier single family house to six-story multi-family apartment building, constructed under Dhaka Building Code of 1996.

The recorded building-forms and their typology were cross-checked by a CAD drawing that documented building roof-prints observed in Dhanmondi's satellite image. The building-form typology as well as number and percentage of each building-form type are shown in Table-3.7.

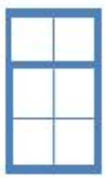
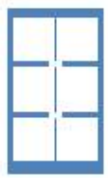
Zoning Scheme-1: Table-3.7 shows that type-1 is the most common building-form. Fifty two percent of the observed buildings used type-1 building-form that occupies 80% lot area. Each of type-2 to type-5 also occupies 80% lot area but they are not as common as type-1. Since type-1 has been used in maximum number of apartment buildings, it has been chosen for zoning scheme-1.

Zoning Scheme-2: Type-6 occupies 70% lot area and represents only one apartment building out of the 117 surveyed. Since no other building-form was observed that occupies 70% lot area, type-6 has been chosen for zoning scheme-2.

Zoning Scheme-3: Both of type-7 and type-8 occupy 60% lot area. Since type-7 has been observed in five buildings and type-8 has been observed in one building, type-7 has been chosen for zoning scheme-3.

Zoning Scheme-4: There is not a single multistory apartment building that occupies 50% lot area. Therefore, a hypothetical apartment building was designed that fulfills the regulations of zoning scheme-4. Using the author's professional experience in Dhaka's apartment design industry, a building-form that occupies 50% lot area and is 11-stories high was generated. Figure-3.3 shows its footprint and building-form. Table-3.8 shows all four zoning schemes with their building-forms along with their footprints.

Table-3.7: Building-form typology observed in Dhanmondi Residential Area.

ID number	1	2	3	4	5	6	7	8
Satellite image of the Building-form								
Footprint of the Building-form								
Number of each type	60	21	14	9	5	2	5	1
Percentage of each type	52%	18%	11%	08%	04%	02%	04%	0.8%
Lot area occupied by building footprint	80%	80%	80%	80%	80%	70%	60%	60%

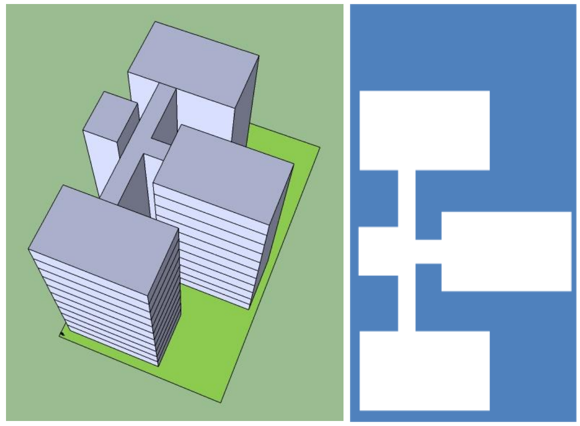
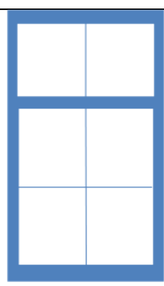
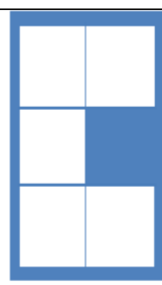
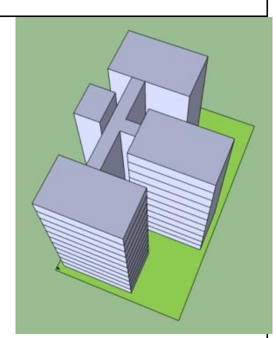


Figure-3.3: Hypothetical footprint and building-form for zoning scheme-4.

Table-3.8: Building-forms and footprints selected for four zoning schemes.

Zoning scheme-1	Zoning scheme-2	Zoning scheme-3	Zoning scheme-4
			
			

3.5 SELECTION OF SIMULATION TOOLS

The literature review summarized that zoning regulations affect thermal comfort conditions by controlling the amount of solar radiation, wind, and day-light entering a dwelling unit. There are a number of simulation tools to calculate the amount of these three elements. The following paragraphs discuss available tools and the one that is used in this research.

3.5.1 Tools to calculate the amount of solar radiation

Solar radiation causes rise in indoor temperature as well as indoor mean radiant temperature, two environmental parameters of thermal comfort (Atmaca, Kaynakli, & Yigit, 2007; Krüger & Givoni, 2008). So monitoring the changes in these temperatures, due to the change in zoning regulations, will show whether a zoning scheme is effectively controlling solar radiation to improve thermal comfort or not. However, these two indoor temperatures also depend on other factors like indoor wind velocity, air change per hour, thermal mass, etc. (Eftekhari, Marjanovic, & Pinnock, 2003). Therefore, monitoring the rise and fall of these two temperatures will not accurately show whether a zoning scheme is adequate enough to control unwanted solar radiation. Rather, it is also important to monitor each zoning scheme's ability to provide shading.

Architects and designers use sun diagrams, manual protractor, etc. to graphically analyze the effects of building geometry on shading (Kensek, Noble, Schiler, & Setiadarma, 1996; Oh & Haberl, 1997). These manual tools are tedious to use, and they are not error free either; because an architect needs to calculate several angles and then mentally translate Cartesian coordinates of those angles into a special coordinate system, to see if intended shading is achieved or not (Oh & Haberl, 1997).

Tabb used photography to analyze shading in his studied settlements (Tabb, 1990). By photographing shadow patterns on building facades, Tabb recorded images of shaded areas and non-shaded areas during different hours of the day. Translating these images into architectural drawings allowed him to quantify and compare total shaded and non-shaded areas among different settlements. Thus, photography played a crucial part in Tabb's shading analysis. Alike Tabb, Lam (2000) also used photography to study shading effects caused by nearby buildings in the context of Hong Kong (Joseph C, 2000). However, this photography strategy is not possible for this research because it is not meant for hypothetical buildings. Moreover, photography strategy is time consuming if it is compared to the latest computer tools. In this manner, sun diagrams and sun protractors too are time consuming.

Computer tools, on the other hand, are less time consuming and more error free. Following are some other advantages of computer tools (Capeluto, 2003):

- Easy and fast to evaluate several design alternatives for building geometry.
- Date, time, and location are easily changeable.

Computer tools also can provide data regarding 'solar beam radiation' falling on surfaces, considering the effects of shadowing (EnergyPlus, 2010). This is expressed in Watts/m^2 which also shows the intensity of received solar radiation. Thus, using such data is more tangible to compare zoning schemes' impact on shading than using visual tool like sun diagram or photography. Moreover, computer tools allow the researcher to carry out parametric study and to get hourly values (Ossen, et al., 2005). Therefore, this research uses computer tools.

Among the available computer tools, the U.S. Department of Energy's (DOE) DOE-2 has been widely used, and its validation has been widely accepted (Sulivan, 1998). However, in 1995, DOE started working on a new generation computer simulation tool, and the result was EnergyPlus (Crawley, Pedersen, Lawrie, & Winkelmann, 2000). EnergyPlus is based on the strengths of DOE-2, but it is simpler and more graphically interactive. Moreover, EnergyPlus has the following features which DOE-2 does not have, and these features of EnergyPlus make it more robust than DOE-2 (Crawley, et al., 2001):

- Integrated, simultaneous solutions.
- Iterative solutions.

- Multiple time step approach (Variable time-step for interactions between zone air mass (≥1 min)).
- Heat balance calculation- simultaneous calculation of radiation and convection at each time step.
- Interior surface convection is dependent on temperature and air flow, as well as thermal mass.

Due to these features, EnergyPlus can provide more accurate 'indoor temperature' and 'indoor mean radiant temperature' along with 'solar beam radiation' data. Therefore, this research will use EnergyPlus to analyze each zoning schemes' impact on shading as well as their impact on indoor temperature and indoor mean radiant temperature.

3.5.2 Tools to calculate the amount of day-light

This research is interested in zoning schemes' impact on day-lighting because when there is a lack of daylight, people use 'heat generating artificial light' which causes a rise in indoor temperature (Lechner., 2009). Therefore, the goal for using a day-light simulation tool is three-fold – i) to calculate internal illuminance in individual rooms, ii) to calculate the amount of artificial light that would be needed if internal illuminance is inadequate in those individual rooms, and iii) to calculate the rise of indoor temperature due to the use of these artificial lights.

To calculate internal illuminance in individual rooms, there are two types of computer tools – i) tools purely for day-light simulations, and ii) tools that can do thermal analysis as well as day-light analysis (Kota & Haberl, 2009). The first group includes tools like Radiance, Daysim, etc., and the second group includes eQuest, EnergyPlus, etc. The first group is more robust than the second group, in terms of day-light analysis, but they cannot do thermal analysis. Since they cannot do thermal analysis, they cannot calculate the rise of indoor temperature due to the use of artificial lights. Therefore, for convenience, a tool from the second group is used in this research. Since EnergyPlus has already been selected to do the solar radiation analysis of the zoning schemes, EnergyPlus has been chosen for day-light simulation too.

Despite the convenience mentioned above, the literature on appropriateness of EnergyPlus was further reviewed due to its questionable robustness. Ramos and Ghishi (2010) performed a comparative analysis between EnergyPlus and Daysim/Radiance. They studied three individual rooms with three different proportions – 1:1, 1:2, and 2:1 (Ramos & Ghisi, 2010). Their results show that both EnergyPlus and Daysim/radiance calculated similar day-light availability in the room with a proportion of 1:1. For the deeper room (proportion of 2:1), EnergyPlus shows constant day-lighting availability from the middle to the rear of the room; Daysim/Radiance shows a gradual decrease in daylight from the middle to the rear of the room. This means the daylight calculation in reference points close to the rear wall is questionable. However, this research is considering reference points (one for each room) only at the room centers. Therefore, this mentioned weakness of 'over estimation at rear part of the rooms' is overlooked in this research.

Based on the above discussion, this research finds EnergyPlus to be the most suitable tool for day-light simulations for the selected zoning schemes.

3.5.3 Tools to calculate the amount of wind flow

The literature review summarized that zoning regulations could control building development to provide adequate airflow within the building. Adequate airflow is necessary for thermal comfort because it flushes out unwanted heat from inside and also, with a certain speed, it provides a comfort sensation for the occupants. Two possible ways to analyze adequacy of airflow within a building are – i) to estimate Air Change per Hour (ACH) in a zone or room, and ii) to estimate air velocity within that room (Hamdy & Fikry, 1998; M.N.A, 1997).

The most commonly used techniques to study wind flow in and around buildings are – i) experimental correlation, ii) inverted salt gradients, iii) wind tunnel testing, iv) airflow network model, and v) Computational Fluid Dynamics (Sreshthaputra, 2003). Experimental correlations are simple to use, but they lack flexibility to handle variable room geometries, because the correlations are obtained from a particular type of geometry (Graça, 2003). Both the 'inverted salt gradients' and 'wind tunnel test' posses the following limitations: i) measurement data of wind velocity are limited to a few points, and ii) instrumentation used for the velocity measurement can disturb flow pattern (Jiang, Alexander, Jenkins, Arthur, & Chen, 2003). Therefore, only 'airflow network model' and Computational Fluid Dynamics are used in this research to calculate wind data (CFD).

The airflow network model simulates airflow within a building as well as through the building (Huang, et al., 1999). An electrical circuit is a good analogy for airflow network model, where following representative details exist: i) airflow corresponds to electric current, ii) each room or zone corresponds to an electrical node, iii) room or zone pressure corresponds to voltage at an electrical node, and iv) doors and windows connecting two rooms correspond to an electrical conduit (Owen & Kennedy, 2009). Through different equations, the model represents: i) pressure versus airflow relationship in the doors or windows, ii) mass conservation in the rooms, and iii) hydrostatic pressure variations in the rooms (David M, 2002). Using these equations, the model calculates average pressure in each room and average airflow rate through each door or window, based on the pressure versus airflow relationship defined for each door or window (Gu, 2007).

From the above discussion, it is evident that the network model does not provide details about airflow distribution within a zone; rather it provides an average air flow rate for the entire zone. This is acceptable in terms of a room's ventilation rate (ACH) because ventilation rate is the average measure of airflow in a room. However, to get air velocity in a specific area of a room, the airflow network model will not be useful. In this regard, Computational Fluid Dynamics (CFD) tools will be superior because CFD programs provide detailed information about pressure and air velocity for multiple points in a room (Caciolo, Marchio, & Stabat, 2009).

The principal reason behind robustness in CFD results is the microscopic nature of its numerical solutions (Owen & Kennedy, 2009). While the airflow network model assumes each room as a node and solves a network of (among multiple rooms) mass balance equations, CFD programs divide a room into thousands of cells and solve a set of simultaneous, non-linear, coupled partial differential equations for each of those cells (Mak & Yik, 2002). This is why the network model has been widely validated for providing faster results in terms of average values (like ventilation rate, average air velocity) in a room, and CFD has been widely validated for providing detail flow field information in a room (So & Lu, 2001). However, CFD is more practical for wind analysis in single rooms and steady-state solutions due to its large computing time and resource requirement.

So, to estimate ventilation rate (ACH) in individual rooms in the dwelling units, the airflow network model will be used; to estimate air velocity within those rooms, the CFD program will be used. Energylus uses the airflow network model to calculate natural ventilation. Since it has been already chosen for solar radiation and day-light simulation, it will also be used to calculate ventilation rate for this research. Moreover, according to Lixing Gu (2007) "EnergyPlus' airflow network model was validated against measured data from both the Oak Ridge National Laboratory (ORNL) and the Florida Solar Energy Center (FSEC) (Gu, 2007)." For validation of CFD programs against measured data, numerous studies have been performed and success was shown (Cheung & Liu, 2011; Qingyan, 2009; Su, Riffat, Lin, & Khan, 2008). Most of these studies used a commercial CFD program named Fluent and therefore, this research uses Fluent to calculate indoor air velocity in individual rooms.

3.6 USE OF SELECTED SIMULATION TOOLS TO CALCULATE THE DEPENDENT VARIABLES

EnergyPlus and Fluent are selected to calculate data on solar radiation, daylight, ventilation rate, and air velocity. The first three types of data are gathered using EnergyPlus, and the fourth type is gathered using Fluent. However, a specific output from Fluent is used in EnergyPlus to calculate ventilation rate. This sub-section discusses how these two simulation tools are used in the investigation of the zoning schemes.

EnergyPlus calculates air flow through open or partially open exterior windows. To calculate airflow through open windows, EnergyPlus needs wind pressure coefficient data, measured or calculated on the exterior of these windows. For simple rectangular buildings, EnergyPlus uses ‘surface average calculation’ procedure to get these pressure coefficients. Surface average calculation is based on previously recorded and published data for free-standing rectangular buildings (EnergyPlus, 2010). Although the apartment buildings in this research are simple rectangles, they are not free-standing; rather their surroundings vary based on different zoning schemes. Therefore, ‘surface average calculation’ will not be a rigorous approach in this research (D. Cóstola, Blocken, & Hensen, 2009). To make it rigorous, pressure coefficient data are needed, either measured in experiments or calculated in CFD programs (Daniel Cóstola & Alucci, 2007).

Since Fluent has been chosen to perform CFD task for the indoor wind analysis, it will also be used to perform a CFD task for the outdoor wind analysis, to calculate pressure coefficient on external window surfaces. Interestingly no additional outdoor CFD simulation is needed to get these pressure coefficients. The reasons are: i) this research is using a ‘decoupled CFD simulation’ where both outdoor wind analysis and indoor wind analysis is performed separately; ii) the outdoor wind analysis creates wind pressure data of various forms like total pressure, static pressure, pressure coefficients (ANSYS, 2009); and iii) the data regarding ‘total pressures’ is used as the input for

Fluent's indoor wind analysis, and the data regarding 'pressure coefficients' can be used as the input for EnergyPlus.

This strategy of decoupled CFD simulations has been chosen because: i) simultaneous simulations of the apartment building and the surrounding requires large computer resources, and ii) due to the scale difference between an individual building (meter) and a site (hundred meters), a large number of numerical grids (cells within the flow domain) are needed to get the preferred accuracy level in the computation (Zhai, et al., 2000). In decoupled simulations, the outdoor wind analysis assumes that the buildings are solid blocks; whereas, in simultaneous simulations, the buildings have open windows and doors. This conceptually makes decoupled simulations less accurate than simultaneous simulations. However, decoupled simulations have been validated by the results of simultaneous simulations with the following condition: buildings in decoupled simulations need to have window area of less than $1/6^{th}$ of the total surface area (Chen & Srebric, 2001; Vickery & Karakatsanis, 1987). Since the individual dwelling units in this research have window area of less than $1/6^{th}$ of their total surface area, decoupled CFD simulations have been chosen for this research.

In the following two sub-sections, the procedure and detail about the use of EnergyPlus and Fluent are discussed:

3.6.1 Simulation using EnergyPlus – the selected parameters and the procedure

1. Dhaka Weather file is used in EnergyPlus to get weather data for the simulation period. The weather data is included in the appendix.
2. OpenStudio, a building energy simulation plug-in for Google SketchUp 3D drawing program, is used to make building geometry for each of the zoning schemes.
3. the exterior walls in the model represents typical ten inch brick walls used in Dhaka's apartments. Window glazing represents a single pane six mm glass. No insulation is introduced in the model since it is not common in Dhaka's context.

4. ‘Conduction transfer function’ is used as the heat balance algorithm, which only solves sensible heat and does not consider moisture storage or diffusion in the construction elements.
5. Solar distribution is analyzed by acknowledging ‘full interior and exterior with reflections’.
6. Different schedules are used to represent occupants’ presence, activities, clothing and their use of equipment to acknowledge internal heat gain. These schedules are included in the appendix section.
7. To study each individual dwelling unit, a multi-zone model of the dwelling unit is created. The neighboring units and the neighboring buildings are all treated as single-zone model. An example is shown in Figure-3.10.
8. Each zone in a multi-zone model represents a single room, and they are all linked through an ‘airflow network’. The ‘airflow network’ calculates transfer of heat and air from outside to each individual room as well as one room to another, and thereby provide average temperature and ventilation rate for each room.
9. To calculate the flow from outside to inside, ‘airflow network’ uses wind pressure coefficient data that is gathered from the outdoor wind simulation done in Fluent.
10. With all these information, EnergyPlus produces the following outputs for this research:
    a. Surface Exterior Solar Beam Incident – to quantify the effect of shading.
    b. Daylight Illumination at Reference Points – to quantify the amount of daylight at the center of each room.
    c. Lights Total Heat Gain– to quantify heat gain due to use of artificial light.
    d. AirflowNetwork Zone Infiltration Air Change Rate [ach] – to quantify ventilation rate in each room.
    e. Zone Mean Air Temperature.
    f. Zone Mean Radiant Temperature.

3.6.2 Simulation using Fluent – the selected parameters and the procedure

1. Model geometry: A pre-processor named Gambit is used to create the geometry and grid for the Fluent's CFD simulations. To simulate outdoor wind flow for each zoning scheme, the studied apartment building along with its neighboring buildings are modeled as solid blocks. The neighboring buildings also follow the apartment buildig's geometry. The buildings placed beyond the neighboring sites are ignored but they are represented by applying a 'roughness height of mean city center' on the ground surface of the computation domain (Ghiaus & Allard, 2005). Figure-3.10 shows the floor of the computation domain, with the solid blocks on top of it.
2. Computation domain: size of computation domain was different for different zoning schemes because it depends on the apartment building's height. According to the 'Best practice guideline for CFD simulation of flows in the urban environment,' the distance between the studied building and the side of the domain has to be at least five times the height of the building. The same is true for the front of the domain; for the rear, it has to be at least fifteen times the height of the building (Franke, Hellsten, Schlünzen, & Carissimo, 2007). These guidelines were strictly followed which is visible in Figure-3.11.
3. Computational grid: accuracy of CFD solutions depends on its grid size as well as number and quality of its grids. Uniform structured grids are better in terms of acccuracy (Eli, 1986) but its large computation cost is impractical for most urban wind analysis scenario (Franke, et al., 2007). To overcome this large computation cost, non-structured grids are used in following manner: i) high resolution grids are generated around the close visnity of the subject, and ii) the grids get coarser (with reasonable gradient) as they go further from the subject (Wu, Yang, Tseng, & Liu, 2011). However, such grid generation need special care to achieve desired accuracy. Hooff and Blocken (2010) presented a non-structured grid-generation methodology where the geometry and computation grid were generated

simultaniously, with a sufficient control over local grid resolution, grid stretching, control volume skewness and aspect ratio (van Hooff & Blocken, 2010). The methodology briefly follows following steps (actual steps are included in the appendix):

a. First, body-fitted 2-D grids are generated for horizontal surfaces representing building footprints, streets, alleyes, etc. Desirable local grid resolution are maintained wherever it is needed.
b. Second, a set of vertical lines, representing heights of different buildings, are created and grids are assigned to these lines. Assigning grids on these lines also follows desirable gradient, that is denser grid at the bottom and coarser grid at the top.
c. Third, another set of lines are created that start at the top of the buildings and finish at the top of the computation domain.
d. Fourth, the horizontal surfaces along with their grids are extruded along the first set of vertical lines. This transforms all the surfaces into volumes, and the 2-D grids on the surfaces become 3-D grids within the volumes. Therefore, some of these volumes represent the buildings and others represent open spaces in between buildings.
e. Fifth, all the top surfaces of these newly created volumes are again extruded along the second set of vertical lines. Therefore, these new set of volumes will represent open spaces above the buildings.
f. At this point, all the volumes those represent the buildings are deleted. Therefore, the remaining volumes, all together represent the entire flow volume.

However, this methodology did not work successfully (in terms of reaching reaching desired residual levels) for this research and therefore, adjustment were maid. The methodology that is used in this research is below (the figures are not representative of any of the zoning schemes):

a. The bottom surface of the computation domain is created as a union of several planes (Figure-3.4-a). A group of smaller planes create the center of the domain, and a large plane surrounds it. The center represents the footprints of the buildings along with the alleys and streets. The surrounding plane represent the free flow domain.

b. Instead of body-fitted grids, uniform structured grid are chosen for the building footprints and adjusent streets and alleys. According to the 'best practice guideline,' a minimum of 10 grids are required between two buildings (Franke, et al., 2007). Since the space gap between two buildings is 8 feet or 2.5 meter, grid size in the alley ways need to be of 0.25 meter. It allows 10 grids between two buildings. To maintain the uniform grid, similar size grids are assigned to the rest of the central planes (Figure-3.4-b).

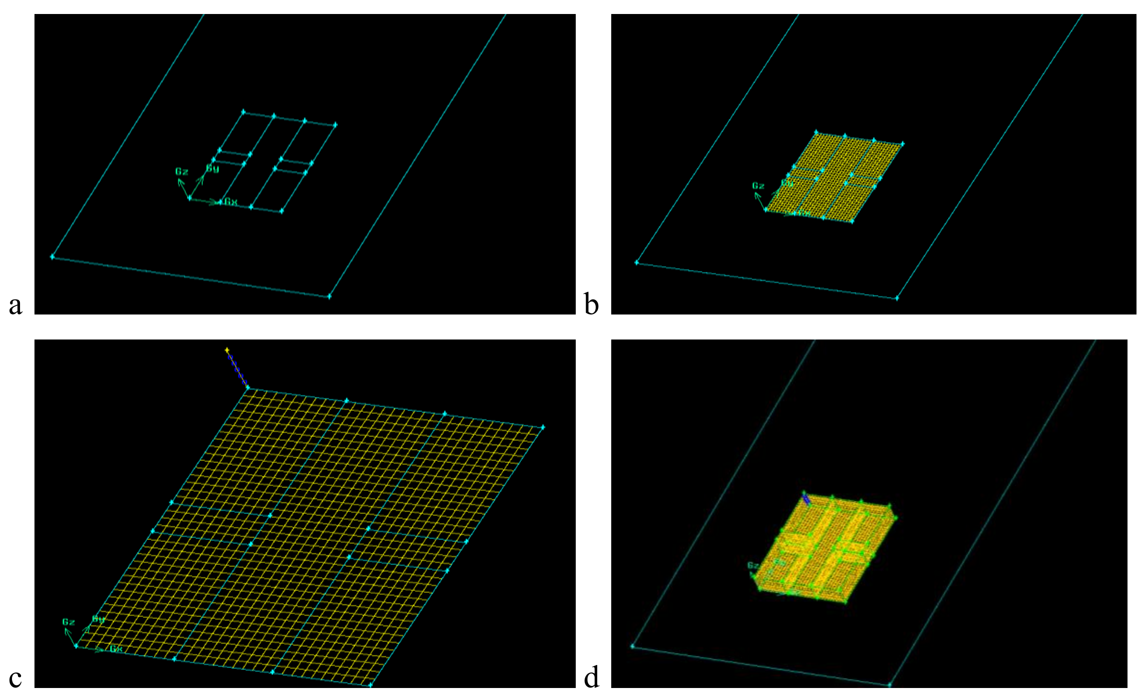


Figure-3.4: Grid generation methodology (Figure 'a' to 'd').

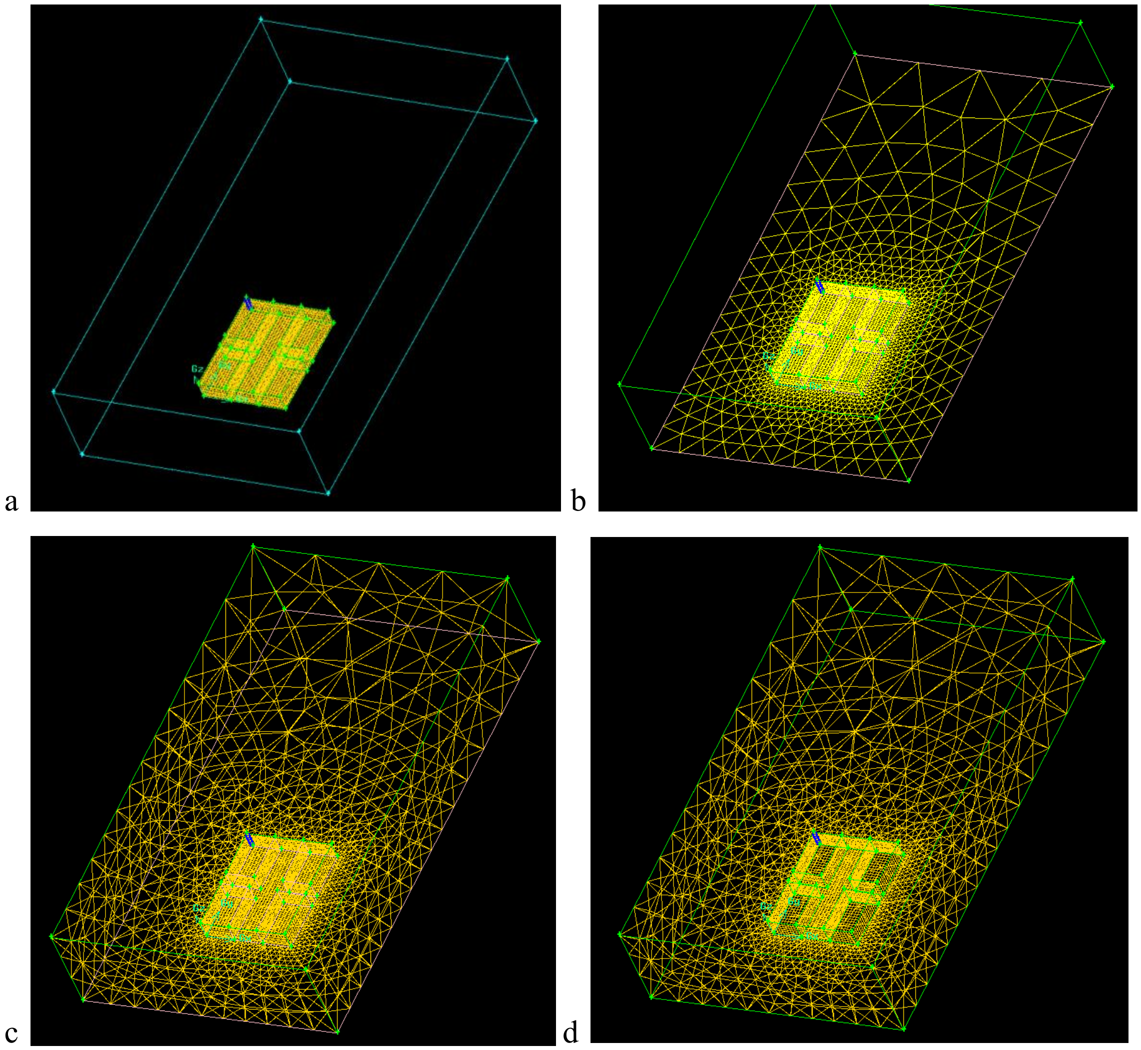


Figure-3.5: Grid generation methodology-continued (Figure 'a' to 'd').

c. One vertical line is created to represent the building height. Similar size uniform grids are assigned to this line (Figure-3.4-c).

d. The group of planes at the center of the domain, along with their grids, are extruded along the vertical line. It creates a set of volumes with uniform structured grids. Volumes on top of building footprints are representing the buildings, and the rest of the volumes are representing the open spaces on top of the alley ways and streets. At this point, the grid development looks like Figure-3.4-d.

e. At this step, four vertical planes and one horizontal pnae are created. The vertical ones represent the sides of the computation domain and the horizontal one represent the top of the domain (Figure-3.5-a).
f. With these five planes, along with the large plane on the bottom, and the outer planes (marked on the Figure-3.5-a) of the central group of volumes, a new volume is created. This volume represents the free flowing outer part of the computation domain where non-uniform unstructured grid can be assigned.
g. To create non-uniform grid for this outer domain, a size function is created. This size function allows gradation in grid sizes so that following grid size variation is achieved: i) grids next to the central group of volumes are similar in size as the uniform structured grid, used in the central group of volumes, and ii) grids those are further away from the central volumes gets larger in sizes, following the assigned growth rate in the size function. This gradation in grid sizes are shown on the bottom of the flow domain (Figure-3.5-b).
h. After creating all the volumes (Figure-3.5-c), the building volumes are deleted (Figure-3.5-d). Therefore, the model is now consist of volumes that represent only flow domain where outer volume is made of non-uniform grid, and the inner volume is made up of uniform grids.

Following this grid generation methodology, zoning scheme-4 uses 5 million grids to achieve desired computation accuracy (mentioned in subsequent paragraph).

4. Boundary conditions: The south face of the domain is chosen as 'velocity inlet' because on april 5th, wind is blowing from south direction for alll day long. No velocity profile is chosen for this inlet condition because the four zoning schemes are only compared with each other, not with any recorded measurements. Instead, a

velocity of 2.775m/s is assigned in this velocity inlet which is the average wind speed recorded for April 5th. No temperature is assigned since the simulations are isothermal and they are only for wind flow calculations. The north face is chosen as 'pressure outlet' and the two sides and the top of the domain are chosen as 'symettry' boundary conditions. The standard wall functions are used with sand-grain base roughness modification that is default to Fluent.

5. The 'realizable k-ε turbulance model is chosen to run the simulations because its good performance has been validated by Franke et al. (2004) (van Hooff & Blocken, 2010).
6. Convergence criteria: according to the 'best practice guideline' convergence of the scaled residuals are set to 10^{-5}. However, residuals for continuity equation reaches close to 10^{-5}, and other reache close to 10^{-7}. The greatest benefit regarding convergence is achieved through the use of uniform grid around the buildings (mentioned earlier). It helps to bring the convergence from 10^{-3} to 10^{-5}.

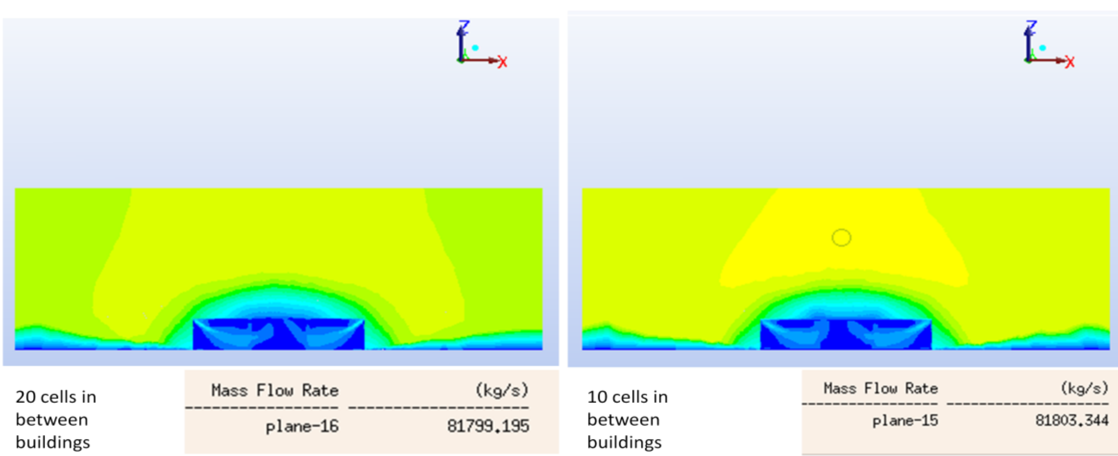


Figure-3.6: Difference between velocity contours and mass flow rate values, showing 'grid indepndenceness' of the grid generation methodology.

7. Grid independence test: a grid independent test was performed before finally using the mentioned grid generation methodology. The main concern regarding this methodology is that whether 10 grids between two buildings is reasonable or not. First a simulation environment was created based on this methodology. Then a second simulation environment was created where 20 grids were assigned between two buildings. In both cases, a virtual plane was chosen crossing the alley way; and mass flow rate was calculated through this plane. The performance difference between these two is 0.004%. Therefore, it was found that 10 cells scheme works reasonably close to the 20 cells scheme. Figure-3.6 shows the comparetive wind velocity contours on the selected planes. Therefore, the simulations performed using this grid generation methodology can be called grid independent.

3.7 SUMMARY OF THE RESEARCH METHODOLOGY

The literature review summarized that in order to improve thermal comfort conditions, zoning regulations need to be optimized to achieve the following four missions: i) minimize solar beam radiation by allowing more shading, ii) minimize the use of heat generating artificial light by allowing more daylight, iii) maximize ventilation (non-mechanical) rate by allowing more airflow to flush out unwanted heat, and iv) provide adequate air velocity to increase occupants' thermal comfort sensation. In sub-section five of this section, it is argued that EnergyPlus is the simulation tool to analyze the performance of the first three missions, and Fluent is the simulation tool to analyze the performance of the fourth mission. Sub-section six shows how the other two software, namely SketchUp and Gambit, are used to create the 3d models for EnergyPlus and Fluent. Figure-3.7 is a flow diagram where the relationship between dependent variables, resultant built environment, simulation tools, independent variables, and resultant effect on thermal comfort conditions is depicted.

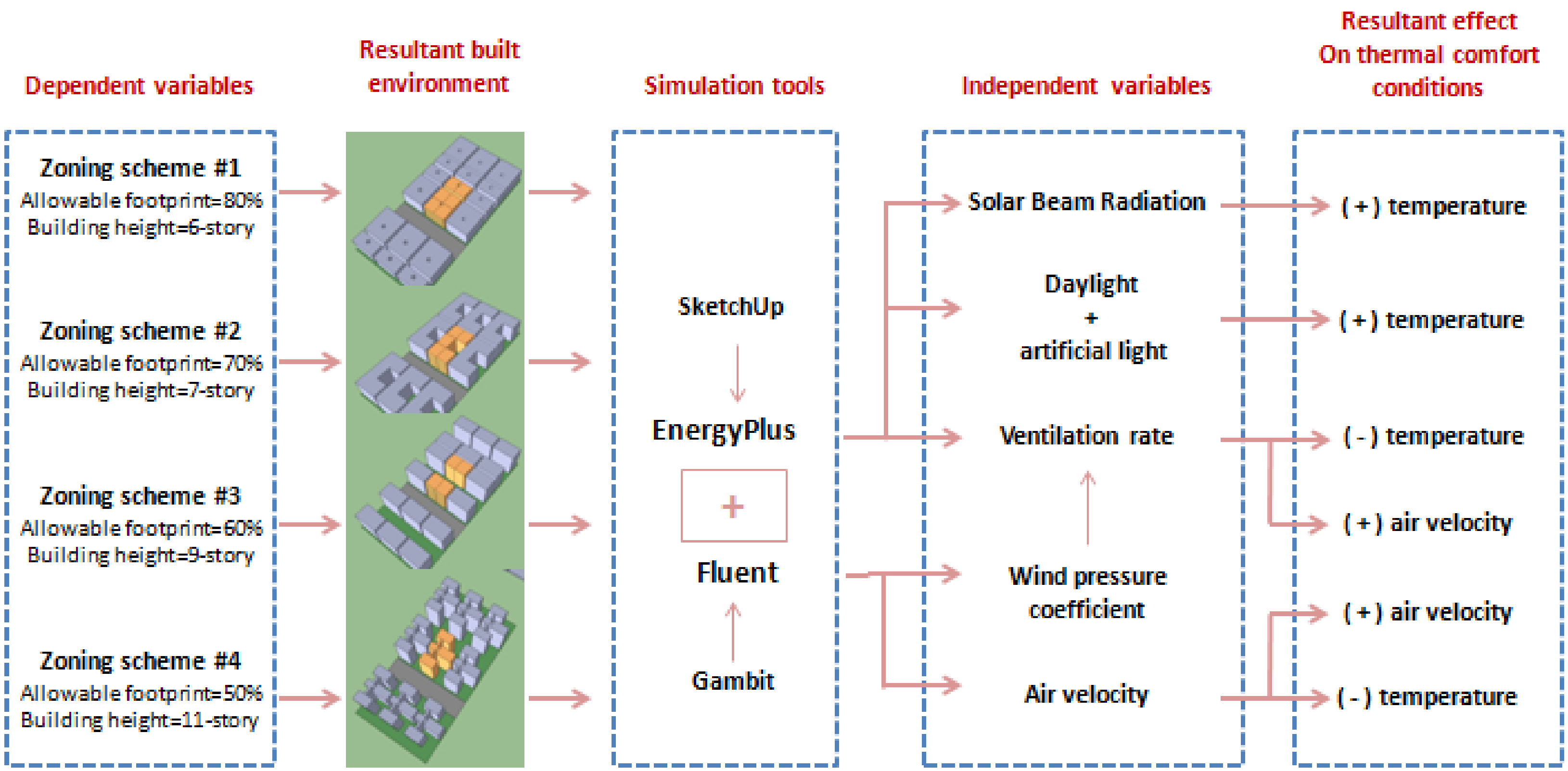


Figure-3.7 Flow diagram showing the relationship between dependent variables, resultant built environment, simulation tools, independent variables, and resultant effect on thermal comfort conditions.

Instead of a year round analysis, this research analyzes the zoning schemes on the hottest day of the year. This allows the evaluation of the zoning schemes' performance for the worst climatic condition, and also it saves computation time and resources. According to Ali (2007), April 10th is one of the most thermally stressful days of the year. This research reviewed weather data of the entire year and found April 5th to be the hottest day. So, all the simulations performed in this research either by EnergyPlus or Fluent represents April 5th.

Since dwelling units at lower floors get least amount of daylight and wind (wind speed reduces as it gets close to ground level), they are more thermally stressful than the units at upper floors. Therefore, instead of analyzing all thirty dwelling units in each zoning scheme, this research only analyzes units on the second floors since the first floors are used for parking. So, for zoning scheme-1, six dwelling units will be analyzed for all independent variables; for zoning scheme-2, five dwelling units will be analyzed; for zoning scheme-3, four dwelling units will be analyzed; and for zoning scheme-1, three dwelling units will be analyzed.

So, the above discussion concludes that this methodology works best to analyze and compare the zoning schemes in terms of accuracy under reasonable computing time and resource limitations. In the following section, the results using this methodology are discussed.

4. RESULTS

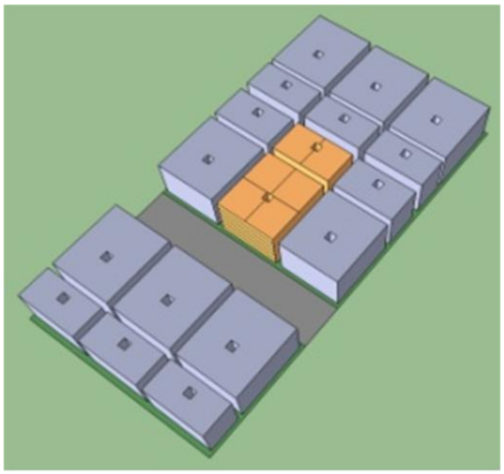
As discussed in the methodology section, the four zoning schemes' impact on thermal comfort is judged by evaluating their following performances: i) minimization of solar beam radiation, by allowing more shading, ii) minimization of the use of heat generating artificial light, by allowing more daylight, iii) maximization of ventilation (non-mechanical) rate, by allowing more airflow to flush out unwanted heat, and iv) maximization of occupants' thermal comfort sensation, by allowing adequate air velocity.

This section discusses these zoning schemes' performances in the following five sub-sections:

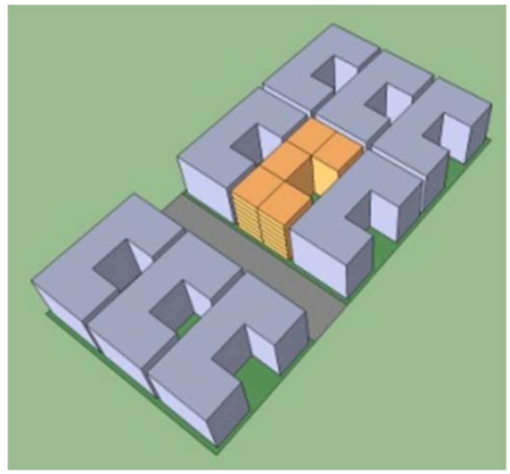
1. Performance of solar radiation reduction.
2. Performance of daylight maximization.
3. Performance of ventilation rate maximization.
4. Performance of air velocity maximization (within limits).
5. Summary of the results.

4.1 PERFORMANCE OF SOLAR RADIATION REDUCTION

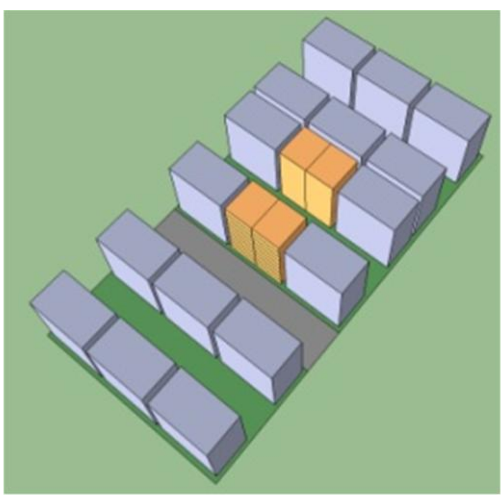
The amount of solar radiation received by an apartment building depends on its building-form as well as the physical form of its surrounding neighborhood. Building-form determines the amount and orientation of building surfaces that are exposed to sun; physical form of the neighborhood determines the amount and position of shadow that would block that solar exposure. Both the building-form and the physical form of the neighborhood vary based on the variation in zoning regulation schemes. Thus, through four different built environments (Figure-4.1-a to Figure-4.1-d), the four zoning schemes perform differently in terms of solar radiation reduction in the studied apartment building. Their performances are evaluated in the following three stages: i) comparing the building-forms in terms of their exposure to solar radiation, ii) comparing the floor plans in terms of their vulnerability to solar radiation, and iii) comparing the solar radiation data gathered from the simulations.



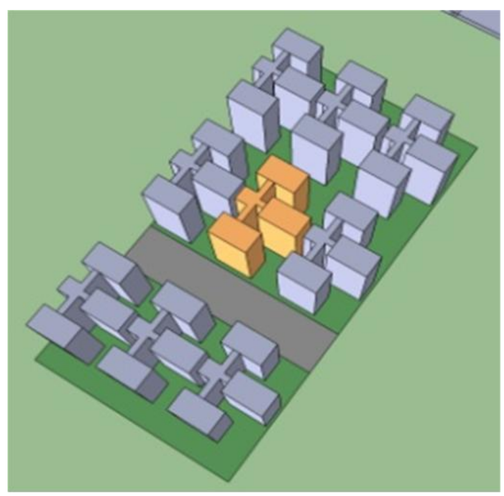
a. Built environment under Zoning scheme #1



b. Built environment under Zoning scheme #2



c. Built environment under Zoning scheme #3



d. Built environment under Zoning scheme #4

Figure-4.1: Four different built environments developed under four zoning schemes.

The building-form is crucial because it determines the amount of exposed surfaces and their orientation, two critical issues in direct solar heat gain. In a lower latitude location like Dhaka, intensity of direct solar heat gain varies based on the surface orientation. In summer months, due to the sun's higher altitude angle, horizontal surfaces like roofs get more intense solar radiation than vertical surfaces. North facades hardly get direct solar radiation due to the site's location in northern latitude. Intensity of solar radiation on south facades is milder than the roofs because of their orientation towards summer sun. Moreover, in Dhaka's latitude, south surfaces can be shaded using a moderate size shading device. East and west facades get intense solar radiation during several hours at early morning and afternoon, due to the sun's perpendicular position to these surfaces, at those hours. Therefore, an appropriate zoning scheme should allow a building-form that has less roof surfaces, more south or north-facing surfaces, and less east or west-facing surfaces.

A visual analysis of Figure-4.1 shows that the studied apartment building under zoning scheme-4 has less roof surface than its other counterparts; it also has more wall surfaces than the others. However, exact calculation is needed to get the amount of all surface types, and this was done based on the hypothetical floor plans and elevations of the studied apartment buildings, under the four zoning schemes. The four variations in the floor plan of the apartment building are shown in Figure-4.3 and Figure-4.4. Figure-4.3 shows floor plans for zoning scheme 1 and 4; Figure-4.4 shows floor plans for zoning scheme 2 and 3. The calculation results of the different surface areas are shown in Table-4.1, and they are elaborated in the subsequent paragraphs.

Roof surfaces: Table-4.1 shows that the apartment building under zoning scheme-1 has the largest amount of roof surfaces at 11,226 square feet. The next largest is the apartment building under zoning scheme-3, with an amount of 9,083 square feet. The third largest or second smallest amount of roof surface is 7,484 square feet under zoning scheme-2. So, the building under zoning scheme-1 has the smallest amount of roof surfaces (4,500 square feet), and seems favorable in terms of the building's resistance to solar radiation.

Table-4.1: The amount of different exposed surfaces in the studied apartment building, under different zoning scheme.

	Zoning scheme-1	Zoning scheme-2	Zoning scheme-3	Zoning scheme-4
Total roof surfaces	11,226 ft^2	9,083 ft^2	7,484 ft^2	4,500 ft^2
Total wall surfaces	37,400 ft^2	46,080 ft^2	48,640 ft^2	48,000 ft^2
Total south surfaces	9250 ft^2	13140 ft^2	14240 ft^2	15000 ft^2
Total north surfaces	9250 ft^2	13140 ft^2	14240 ft^2	15000 ft^2
Total west surfaces	9450 ft^2	9900 ft^2	10080 ft^2	9000 ft^2
Total east surfaces	9450 ft^2	9900 ft^2	10080 ft^2	9000 ft^2

Total wall surfaces: Table-4.1 shows that the apartment building under zoning scheme-1 has the smallest amount of total wall surface at37,400 square feet. The next smallest is the apartment building under zoning scheme-2, with an amount of 46,080 square feet. The third smallest or second highest amount of total wall surface is under zoning scheme-1at 48,000 square feet. So, the building under zoning scheme-3 has the highest amount of roof surfaces (48,640 square feet). However, the building under zoning scheme-4 would have more wall areas if the free-standing elevator core was included. Since it is not directly impacting apartment interior, it was excluded.

Total south/north facing surfaces: the total amount of either north or south facing surfaces is the same in the buildings in all four zoning schemes, and therefore is discussed together. Table-4.1 shows that the apartment building under zoning scheme-1 has the smallest amount of total north/south facing surfaces at 9,250 square feet. The next smallest is the apartment building under zoning scheme-2, with 13,140 square feet. The third smallest or second highest amount of total north/south facing surfaces is under zoning scheme-3 (14,240 square feet). So, the building under zoning scheme-4 has the highest amount of total north/south facing surfaces (15,000 square feet) and therefore, can benefit most from south breeze without the direct solar radiation.

Total east/west facing surfaces: the building under zoning scheme-3 has the highest amount of total east/west facing surface (10,080 square feet). The next highest is in zoning scheme-2 (9,900 square feet). The building under zoning scheme-1 has 9,450 square feet total east/west facing surface. So the building under zoning scheme-4 has the smallest amount of total east/west facing surface, and therefore seems most favorable in terms of building's resistance to solar radiation.

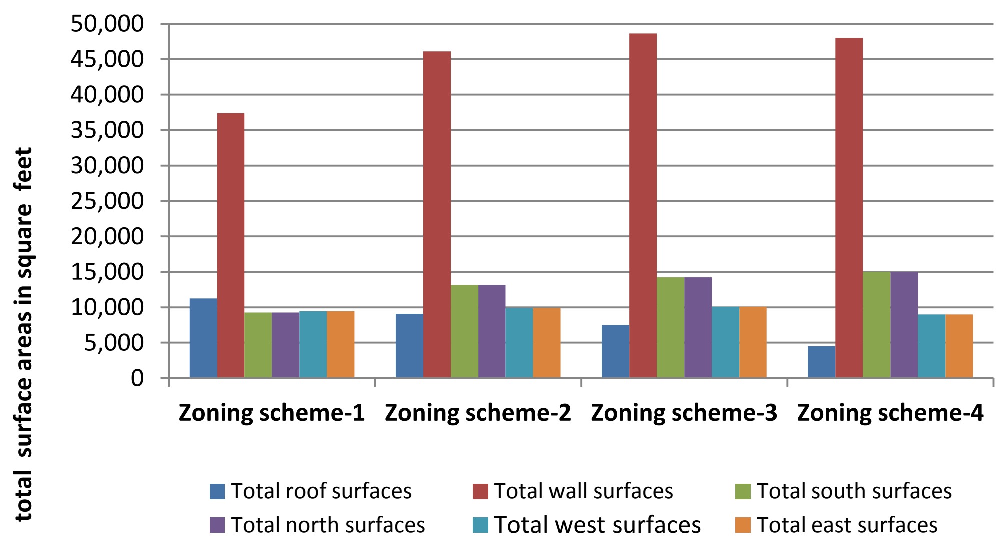


Figure-4.2: Amount of 'total surface areas' in different facades of the studied apartment building, designed under different zoning schemes.

Figure-4.2 shows that the apartment building under zoning scheme-4 has the lowest amount of roof surfaces and the highest amount of wall surfaces. Moreover, it has the highest amount of north/south facing wall surfaces and the lowest amount of east/west facing wall surfaces. Therefore, in terms of solar radiation reduction through building-form, zoning scheme-1 performs the best. In terms of ranking in this performance, zoning scheme-3 is the second best, because the building-form under this zoning scheme has fewer amounts of roof surfaces than the remaining two alternatives; it has more wall surfaces than the remaining two; it has more north/south facing wall surfaces than the remaining two; and it has fewer amount of east/west facing wall surfaces. Figure-4.2 can be referred to say that solar radiation reduction is lowest in zoning scheme-1.Another simple logic to support this discussion is that the building under zoning scheme-4 has only three dwelling units attached to the hot roof surfaces, whereas, the building under zoning scheme-1 has six dwelling units attached to the hot roof surfaces.

4.1.1 Comparing the floor plans in terms of solar radiation reduction

In the following paragraphs, floor plans for each zoning schemes are analyzed in terms of their potential for solar radiation reduction.

Floor plan under zoning scheme-1: Figure-4.3 (left) shows that the building under zoning scheme-1 has the following features that make it difficult to reduce direct solar radiation:

- Four out of six dwelling units have 60% west/east facing exterior wall.
- Two out of six dwelling units have 30% west/east facing exterior wall and therefore, they perform better than the rest of the four units.
- Due to space constrain, none of the exterior walls a have deep shading device like a veranda.

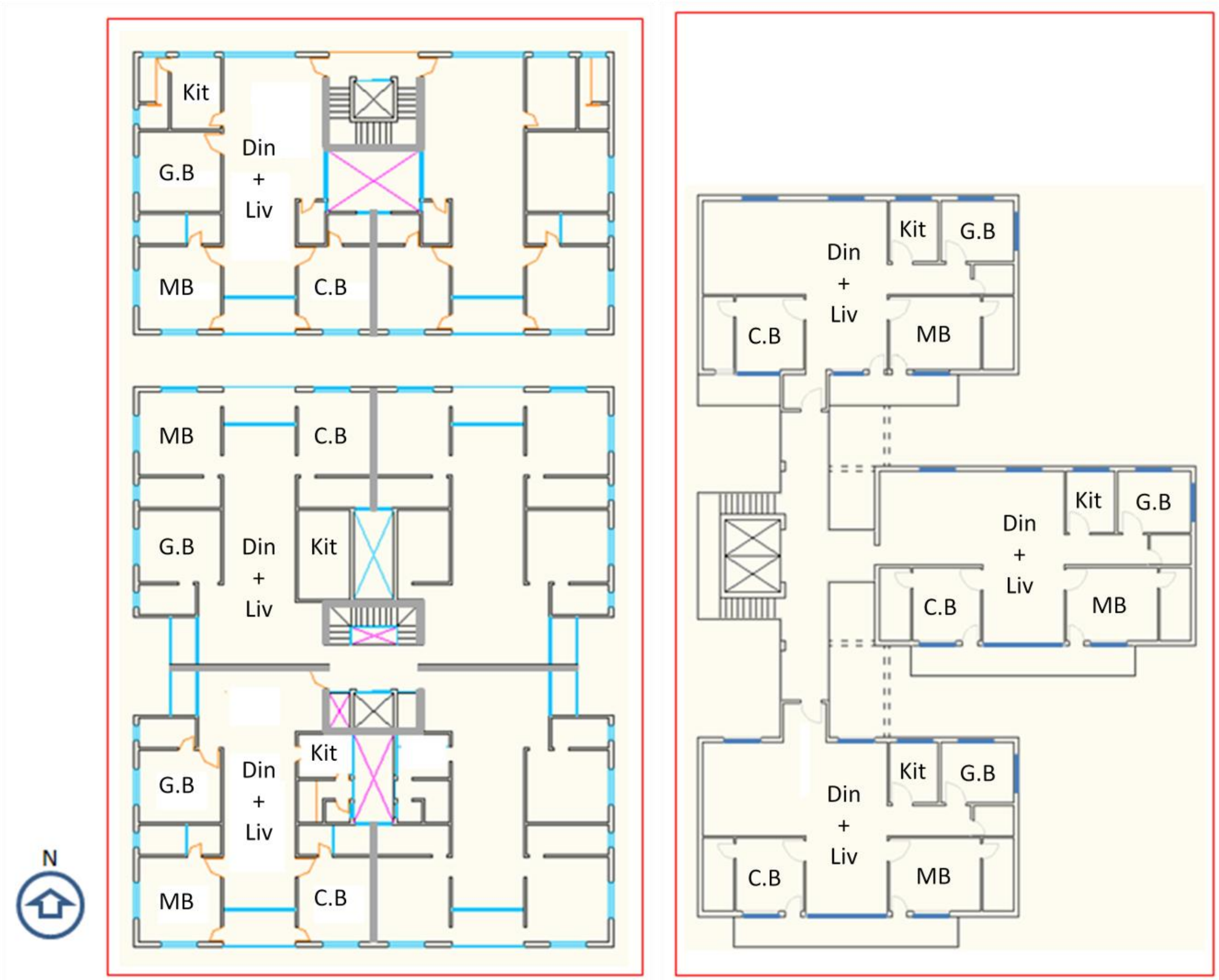


Figure-4.3: Floor plans of the studied apartment building under zoning scheme-1 (left) and zoning scheme-4 (right).

Figure-4.4: Floor plans of the studied apartment building under zoning scheme-2 (left) and zoning scheme-3 (right).

Floor plan under zoning scheme-2: the building under zoning scheme-2 Figure-4.4 (left) has mostly similar features to the one in zoning scheme-1. Only difference is that the middle dwelling unit can afford a veranda on the east side.

Floor plan under zoning scheme-3: Figure-4.4 (right) shows that the building under zoning scheme-3 has the following features that make it perform better than scheme-1 and scheme-2, in terms of solar radiation protection:

- All four dwelling units have 30% west/east facing exterior walls and therefore, they reduce more direct solar radiation than the units in zoning scheme-1 and zoning scheme-2.
- Moreover, due to space availability, all the units have verandas on south side to cut summer sun.

Floor plan under zoning scheme-4: Figure-4.3 (right) shows that the building under zoning scheme-4 has the following features that make it perform the best, in terms of solar radiation protection:

- All three dwelling units have 18% west and 18% east facing exterior walls.
- Like, scheme-3, in zoning scheme-4, all the units has verandas on south side.
- Moreover, there are no windows on any of the west facing exterior walls.

So, based on the review of the above mentioned features, in the four different floor plans, zoning scheme-4 seems to have greater possibility to reduce solar radiation. However, a set of simulations in EnergyPlus is done to calculate exact amount of Solar Beam Radiation received in all of these four various buildings.

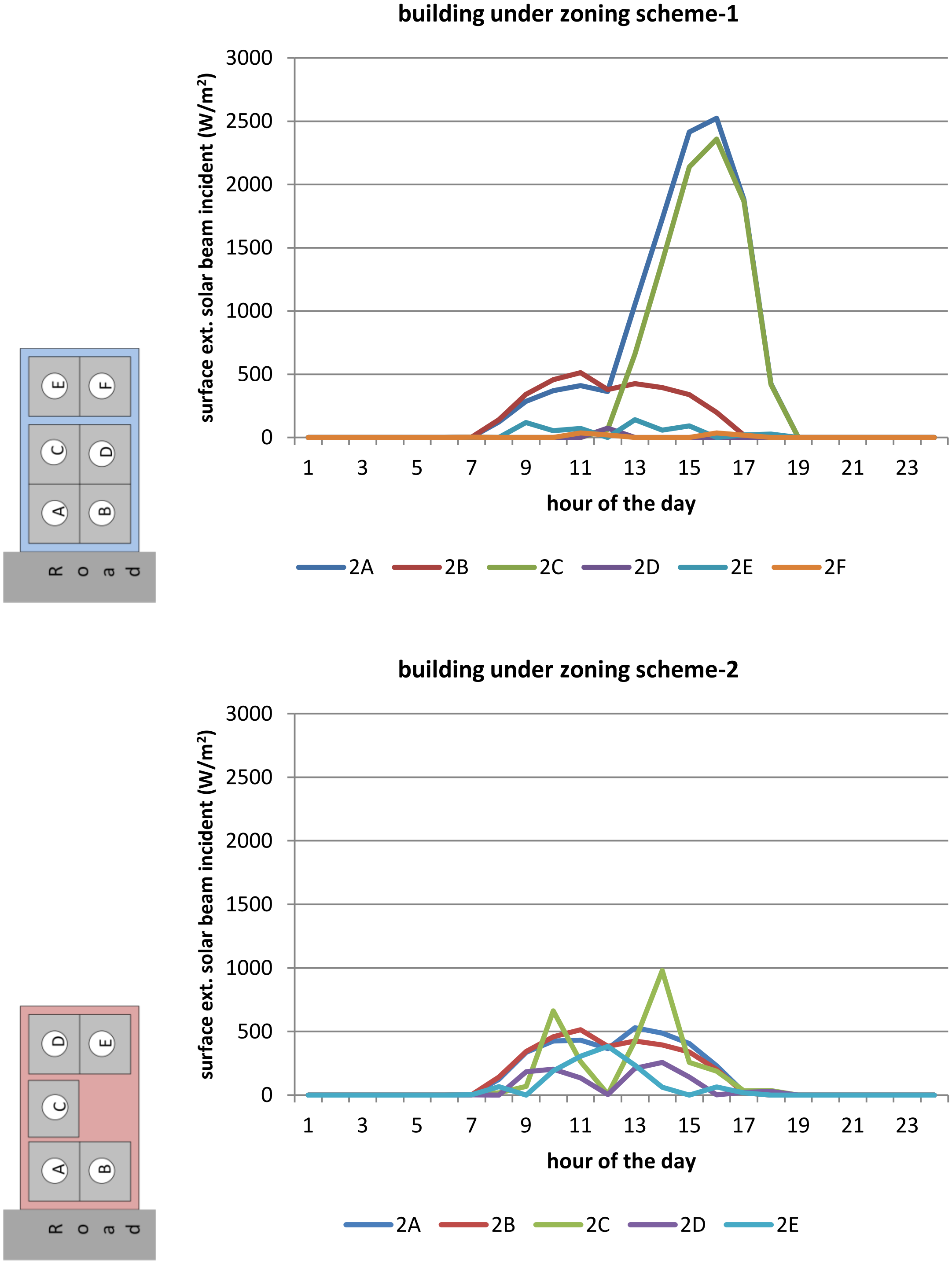


Figure-4.5-a: Hourly value of *solar beam radiation* (SESBI) on exterior surfaces of each dwelling unit. The chart on top represent the building under zoning scheme-1, and the chart at bottom represents the building under zoning scheme-2.

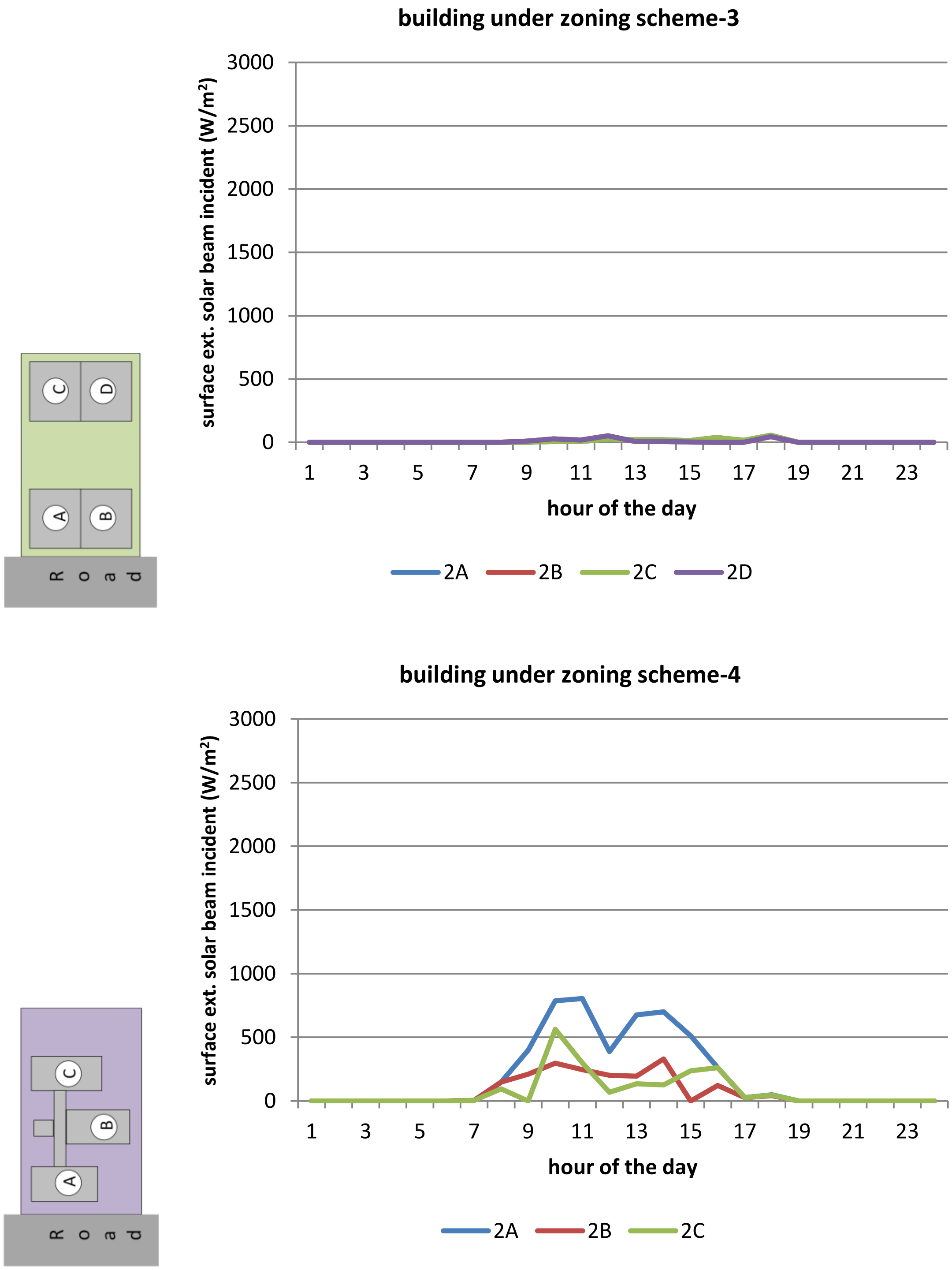
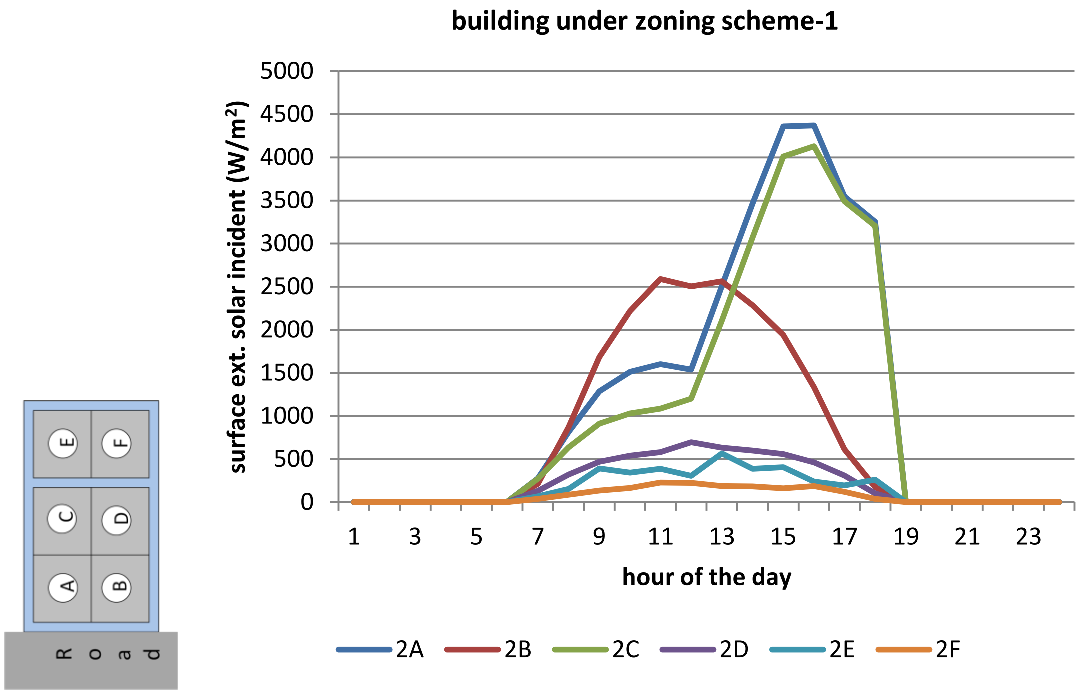


Figure-4.5-b: Hourly value of *solar beam radiation* on exterior surfaces of each dwelling unit. The chart on top represent the building under zoning scheme-3, and the chart at bottom represents the building under zoning scheme-4.



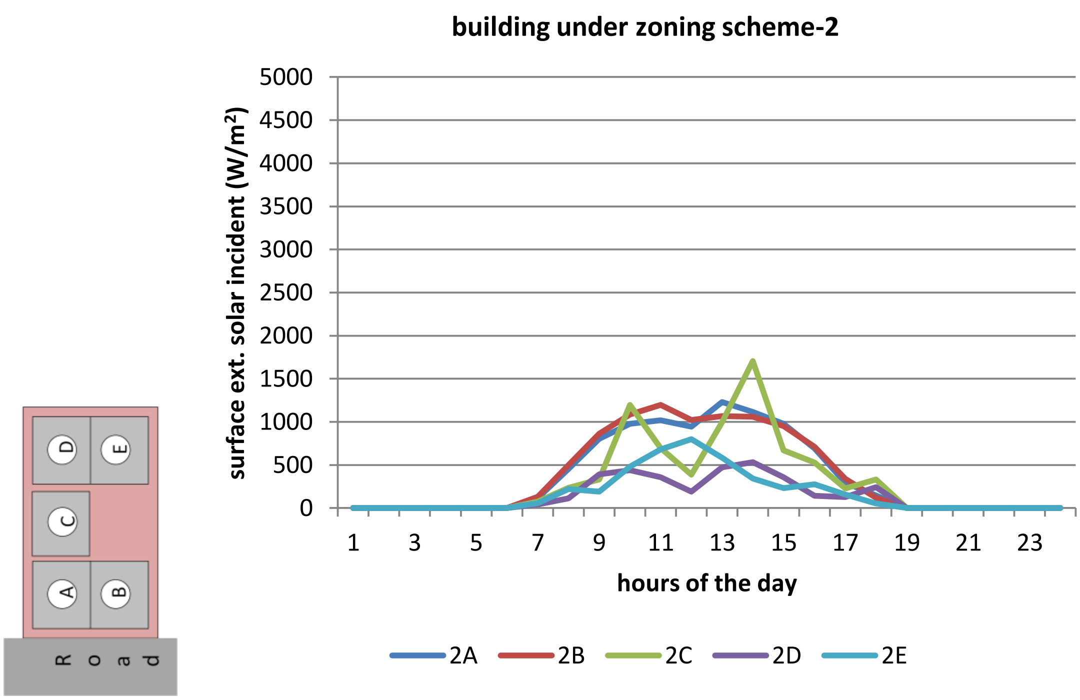
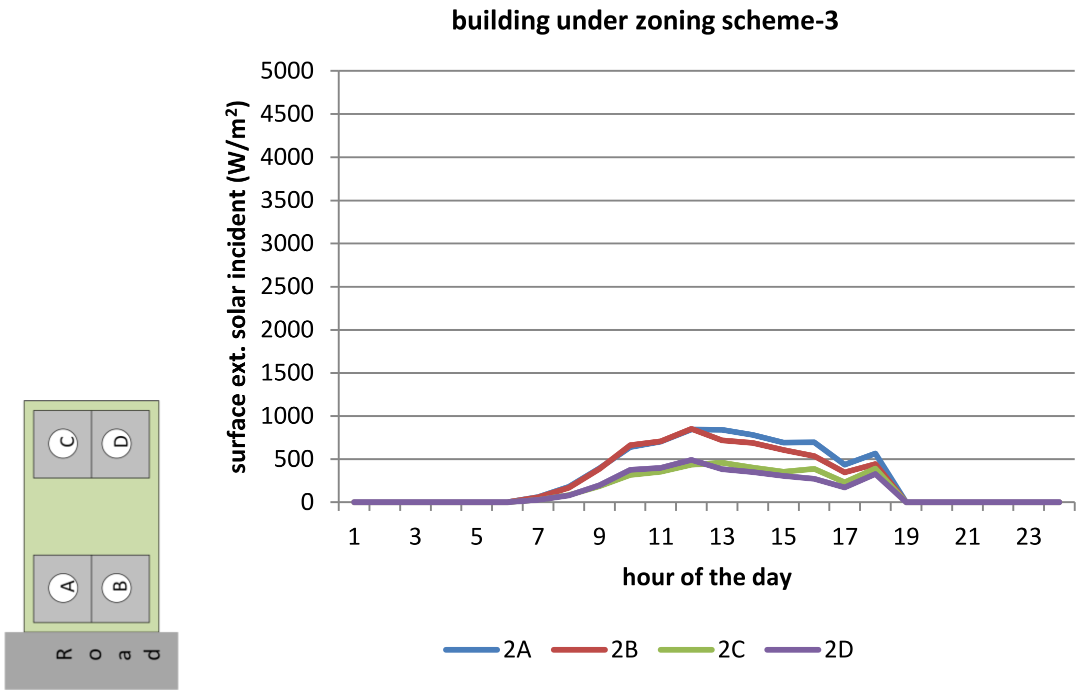


Figure-4.6-a: Hourly value of *total solar radiation* (SESI: beam + diffused + reflected from surroundings) on exterior surfaces of each dwelling unit. The top chart represent zoning scheme-1 and the bottom chart represent zoning scheme-2.



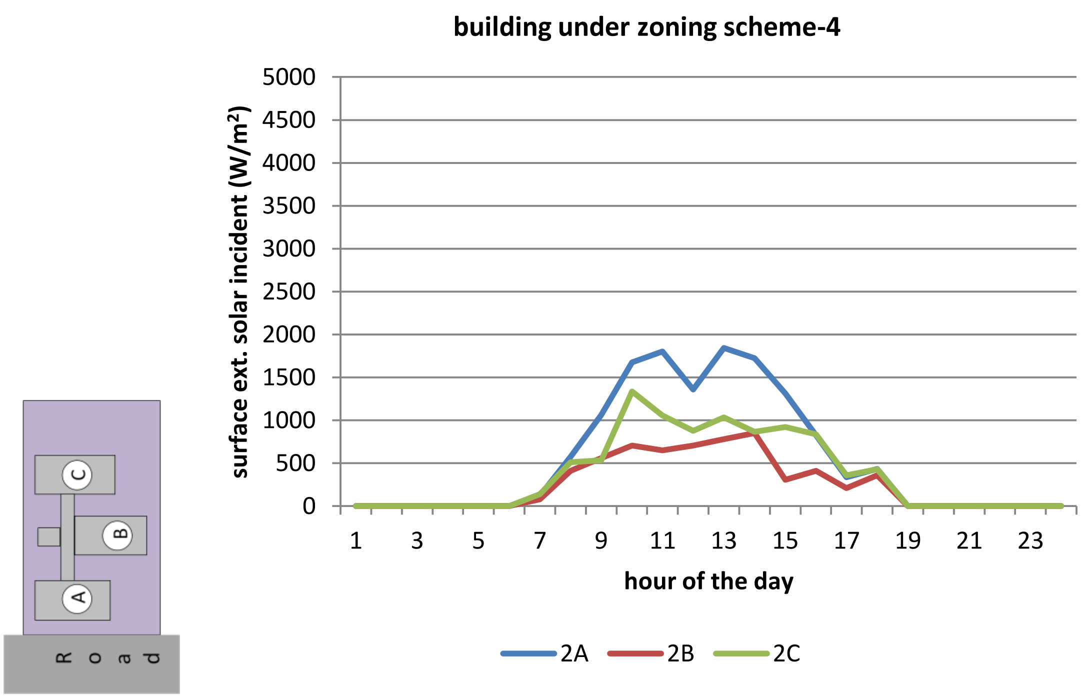


Figure-4.6-b: Hourly value of *total solar radiation* on exterior surfaces of each dwelling unit. The top chart represent zoning scheme-3 and the bottom chart represent zoning scheme-4.

4.1.2 Comparing the solar radiation data

According to Hachem (2011), the instantaneous solar radiation accounts for direct beam and diffuse radiation, as well as for radiation reflected from the ground and adjacent surfaces (Hachem, Athienitis, & Fazio, 2011). In EnergyPlus, direct solar beam radiation is presented as Surface Exterior Solar Beam Incident (SESBI) and the total solar radiation (beam + diffused + reflected from surroundings) are presented as Surface Exeterior Solar Incident (SESI). This research compares the four zoning schemes in terms of the SESBI (Figure-4.5-a, Figure-4.5-b) as well as SESI (Figure-4.6-a, Figure-4.6-b).

First, SESBI on the exterior surfaces of the dwelling units are calculated. As it was mentioned in the Methodology section, only dwelling units at the second floors are studied, and they are represented as 2A, 2B, 2C, etc. in the figures. The hourly values of SESBI are shown in Figure-4.5-a and Figure-4.5-b. The SESBI data represents only the direct solar radiation that reaches building facades, and does not consider diffuse sky radiation or reflected radiation from the surroundings. Therefore, it can be treated as a measure of shadow, meaning the following: as the amount of SESBI is lowered, the more shadows are achieved. So, the charts shown in Figure 4.5-a, and Figure 4.5-b will be searched to see which zoning scheme provides the least amount of SESBI.

According to the charts shown in the Figures 4.5-a, and 4.5-b, zoning scheme-3 provides the least amount of SESBI, hence it provides maximum shading. A more close up view of the chart for zoning scheme-3 shows that none of the dwelling units receive more than 50 W/m^2 in any hour of the day. The possible reasons are the following: i) south facades in all four dwelling units' are shaded by verandas, and ii) west and east facades in all four units' are shaded by the adjacent buildings.

However, having a shaded south façade and neighboring buildings on both east and west façade does not give same results (as it is for the units in zoning scheme-3) for the dwelling unit 2C in zoning scheme-1. The chart for zoning scheme-1 (Figure-4.5-a-top) shows that its 'dwelling unit-2C' receives higher SESBI (2400 W/m2 vs. 50 W/m2) than the units in zoning scheme-3. The possible reason behind these different results might be the building height difference. The former has taller neighboring buildings than the later one, and this might cause more shadow.

However, despite of higher neighboring buildings in zoning scheme-4, its units get higher SESBI (800 W/m2 vs. 50 W/m2) than the units in zoning scheme-3. Therefore, the building height of neighboring buildings is not the issue alone; rather it is the ratio of canyon geometry (height/width) of the alley-ways between neighboring buildings.

To visually check this, canyon geometries' impact on shading are simulated using the shadow feature presented by Google SketchUp. West facades of the bottom floors' are studied for 12:30pm. The results are shown in Figure-4.7. The Figure-4.7 shows that the canyon geometry under zoning scheme-4 is 2.75, and it does not provide any shadow; the canyon geometry under zoning scheme-3 is 11.25, and it provides shadow; the canyon geometry under zoning scheme-1 is 7.5, and it does not provide any shadow.

Therefore, optimum canyon geometry along with presence of veranda contributes to shading. Since zoning scheme-3 provides both the optimum canyon geometry and the scope to have veranda, it is the best zoning scheme in terms of controlling solar radiation.

4.1.3 Impact of solar radiation in the rise of indoor temperature

To quantify the zoning schemes' impact (through controlling solar radiation) on thermal comfort condition, west facing unit-2A in all zoning schemes are simulated in EnergyPlus. Since solar radiation through windows is more significant than solar radiation on opaque walls, these simulations calculate the amount of beam and diffuse solar radiation entering the zones through the exterior windows.

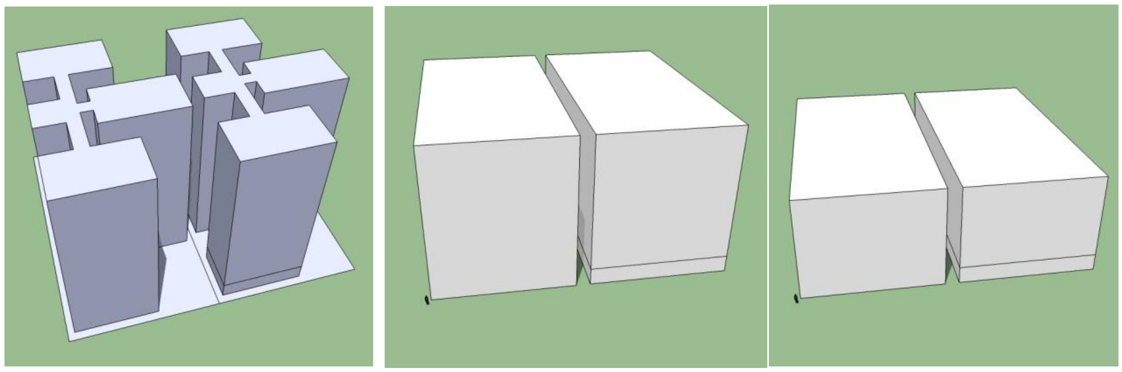


Figure-4.7: Canyon geometry with the ratio of 2.75 (left) causing no shadow; canyon geometry with the ratio of 11.25 (middle) causing shadows; Canyon geometry with the ratio of 7.5 causing no shadow.

Moreover, to calculate only the effect of solar radiation on indoor temperature, the indoor spaces are isolated from the introduction of outdoor warm temperature. Therefore, in these simulations, ventilation in the studied units is not considered.

The results are shown in Figure-4.8. The top chart shows solar radiation entering through windows (in Watts), and the bottom chart shows temperature difference in the dwelling unit under the zoning schemes. While zoning scheme-1 results in the highest amount of solar radiation intrusion, the remaining schemes almost equally reduce the solar radiation intrusion. The consequence is evident in the bottom chart which shows an average 1.4^{o}C temperature difference.

However, two sudden picks in indoor temperature were observed in Figure-4.8-bottom (one at 10:00am and the other at 5:00pm), which do not match with the solar radiation data (Figure-4.8-top). In order to understand the cause behind these sudden rises in indoor temperature, two more examinations were carried out: i) visual examination of hourly shadow patterns (created in SketchUp model) on building facades, and ii) examination of 'equipment schedule' and 'occupants activity schedule', two other sources of heat gain. Figure-4.9 shows the hourly shadow patterns on Unit-2A of zoning scheme-1, for April 5th (from sunrise to sunset); Table-4.2 shows the equipment and activity schedule created in EnergyPlus for unit-2A.

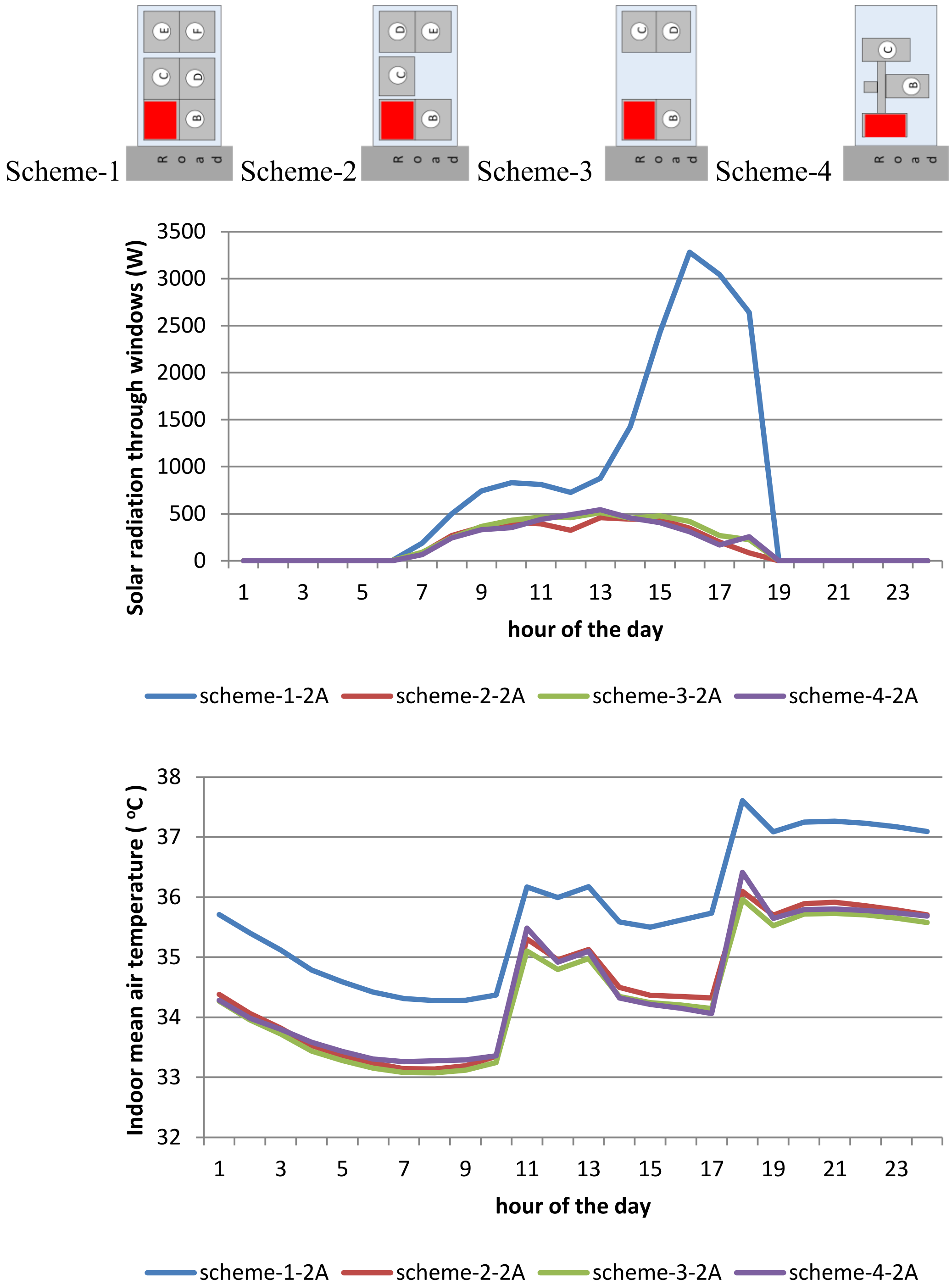


Figure-4.8: Solar radiation received through windows in unit-2A under four zoning schemes (top), and its impact in mean indoor temperature (bottom).

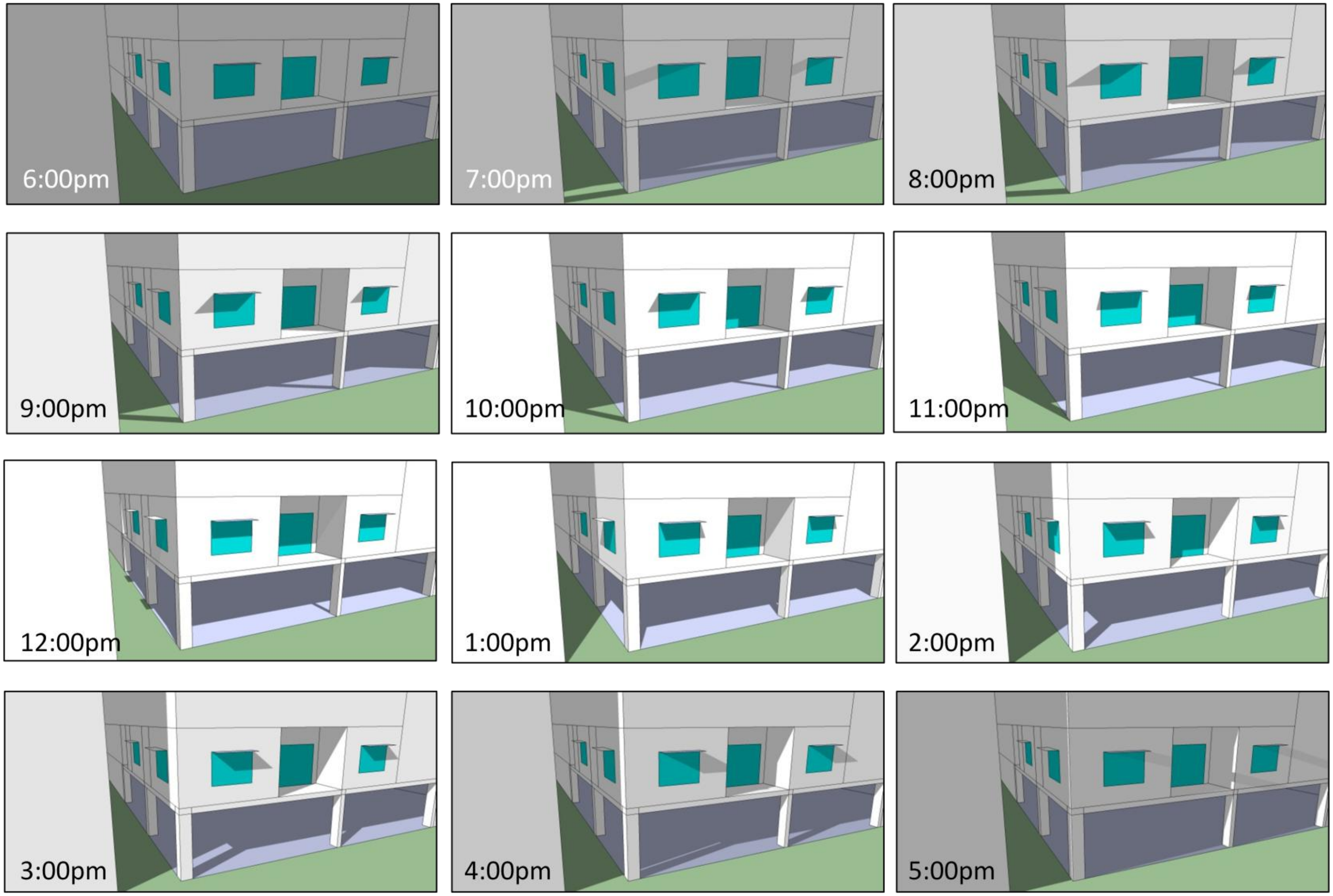


Figure-4.9: Hourly shadow patterns on facades in unit 2A, under zoning scheme-1.

Table-4.2: Equipment and activity schedule created in EnergyPlus.

Room type	Watts	End use sub category	Hours of use	
Bed room	350	TV + Personal Computer	Until 10:00	0
			Until 13:00	1
			Until 17:00	0
			Until 23:00	1
Living room	700	TV + Entertainment center	Until 10:00	0
			Until 14:00	1
			Until 17:00	0
			Until 23:00	1

Shadow patterns in Figure-4.9 do not show any sudden change in solar incident on the building facades. Table-4.2 shows that both at 10:00 o'clock and 17:00 o'clock, electrical equipments come into use and stays for several hours. Since they use either 350 watts or 700 watts, they cause those sudden rises in the indoor temperature. So, to get the isolated impact of solar radiation on indoor temperature, unit-2A was simulated where equipments were inactive (using equipment scheduling option in EnergyPlus). The results do not show any sudden rise in temperature as it was evident in Figure-4.8. Moreover, the results match with shadow patterns in Figure-4.9. Figure-4.10-top shows solar radiation incident on each of the windows in unit-2A, and Figure-4.10-bottom shows the resultant indoor temperature in each of the room in unit-2A. This figure, along with the shadow pattern on unit-2A (Figure-4.9) clearly shows how solar radiation causes temperature rise in the indoor spaces.

Similar simulations were performed for unit 2C for all four zoning schemes and the results show that zoning scheme-3 and zoning scheme-4 perform similarly, and they perform better than the others. Zoning scheme-1 performs the worst. The detail results are included in the appendix section.

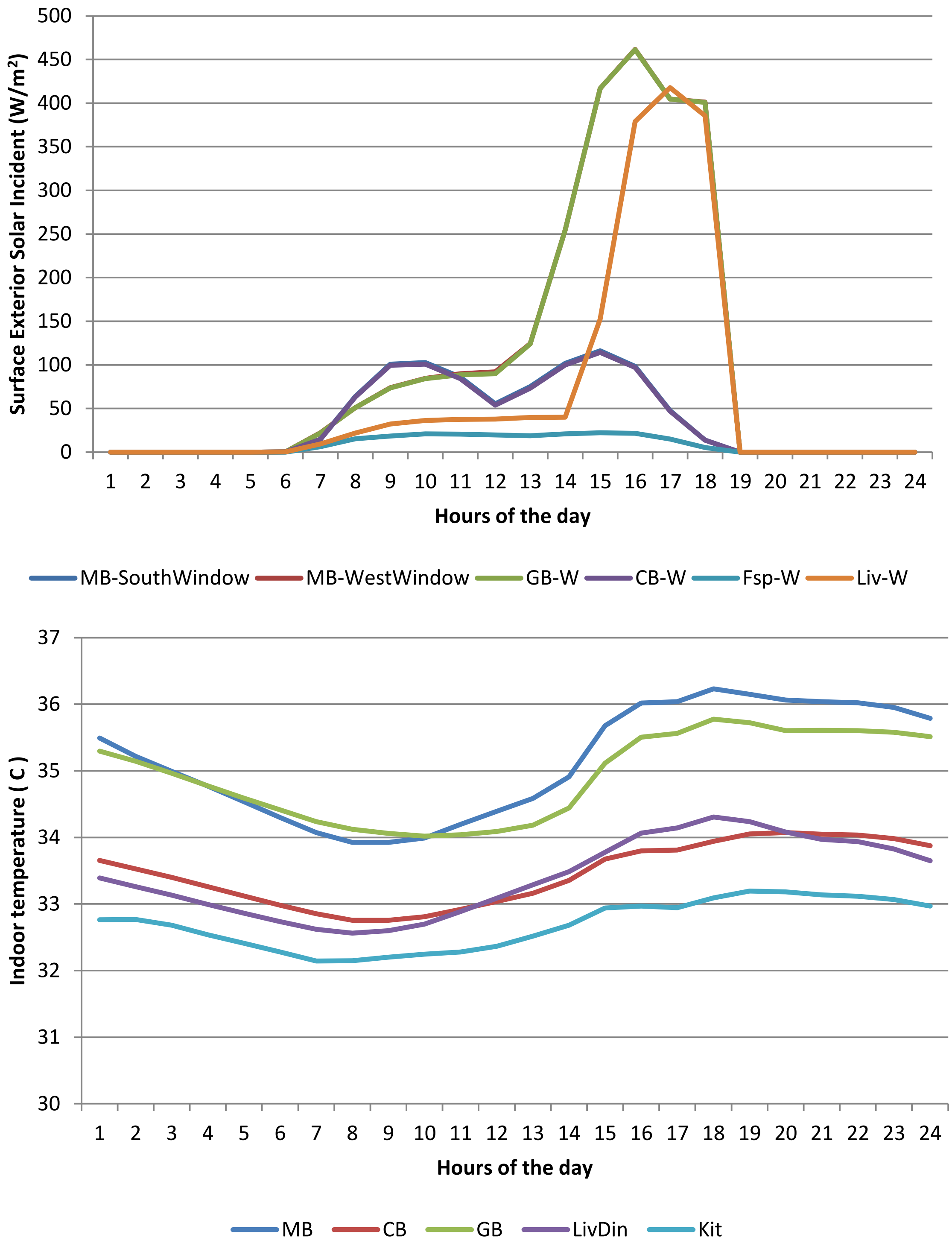


Figure-4.10: Solar radiation incident on each of the windows in unit-2A (top), and the resultant indoor temperature in each of the room in unit-2A (bottom).

So, in terms of controlling solar radiation on the building, zoning scheme-3 performs the best and zoning scheme-4 performs the second best; in terms of temperature reduction, their performance is similar.

4.2 PERFORMANCE OF DAY-LIGHT MAXIMIZATION

This research uses EnergyPlus for daylight calculation and gets the following three sets of data: i) internal illuminance (lx) in each room, ii) amount of heat (Joule) introduced to the space from electric light, and iii) rise in temperature due to this use of electric light.

Internal illuminance is calculated in a reference point, located at the center of each room, on work surface height (0.8m). All the bed rooms have a window to wall ratio (WWR) of 18%, and all the combined living and dining rooms have a window to wall ratio (WWR) of 56%. The glass materials in windows were considered as 6mm clear glass with a visible transmittance of 0.881. All the wall surfaces were considered as stucco, with a visible absorptance of 0.92; all the floor and ceiling surfaces were considered as concrete, with a visible absorptance of 0.65.

The electrical light fixtures in the EnergyPlus models were chosen based on the typical light fixture used by Dhaka's residents. Each of the bed rooms has two 60 Watts 48" tube light fixtures. The combined living and dining rooms have six 60 Watts 48" tube light fixtures. The fraction radiant (the fraction of heat from lights that goes into the zone as thermal radiation) of each of these lights is 72%, and the fraction visible (the fraction of heat from lights that goes into the zone as visible radiation) of each of these lights is 18%.

To compare the zoning schemes in terms of achieved internal illuminance, Figure-4.11 shows internal illuminance in the 2nd floor dwelling units for zoning scheme-1 and zoning scheme-4; Figure-4.12 shows internal illuminance in the 2nd floor dwelling units for zoning scheme-2 and zoning scheme-3. Within each room is shown the highest achieved internal illuminance (calculated for April 5th), and the time that the internal illuminance was calculated is also included. However, these time differences, mentioned across the four floor plans, make it difficult to compare the zoning schemes.

In order to view comparative pictures of internal illuminance among the four zoning schemes, hourly internal illuminance (lx) in all the bed rooms in unit-2A, for all four zoning schemes, are presented in four charts in Figure-4.13. Along with the internal illuminance (lx), the global horizontal illuminance (lx) is also shown in all four charts. The charts show that all the bed rooms in zoning scheme #2 and #3 get similar amount of internal illuminance. If compared with zoning scheme #2 and #3, internal illuminance is less in the master bed room (MB) and child bed room (CB) in zoning scheme-1, and it is high in the guest bed room (GB). For zoning scheme-4, internal illuminance is less in MB and CB (than scheme #2 and #3) but high in GB. For both scheme #1 and #4, internal illuminance in the guest bed is higher because the canyon geometries next to these bed rooms have a higher ratio of width/height.

Now, to analyze how much heat is added into the rooms by electrical light (to cover the lack of daylight), the following two sets of simulations were carried out: i) in one simulation, no electric light was used to cover the lack of daylight, and ii) in the other simulation, automated dimming option of electric light was introduced, and 'electrical lighting schedule' in EnergyPlus was set to be activated from sunrise to sunset. Both of these two cases were simulated without the presence of ventilation, so that no major heat transfer happens between the rooms and the outdoors.

For a better presentation of the impact of day-light on indoor temperature, the daylight as well as thermal simulation results of unit 2A and 2D of zoning scheme-3 are shown in two-axis line charts (Figure-4.14), where the right axis shows the heat introduced (Joule) from the use of electric light, and the left axis shows the rise in temperature. Zoning scheme-3 was chosen because zoning scheme-3 shows the best performance in solar radiation reduction and therefore should consequently provide the least internal illuminance in individual units.

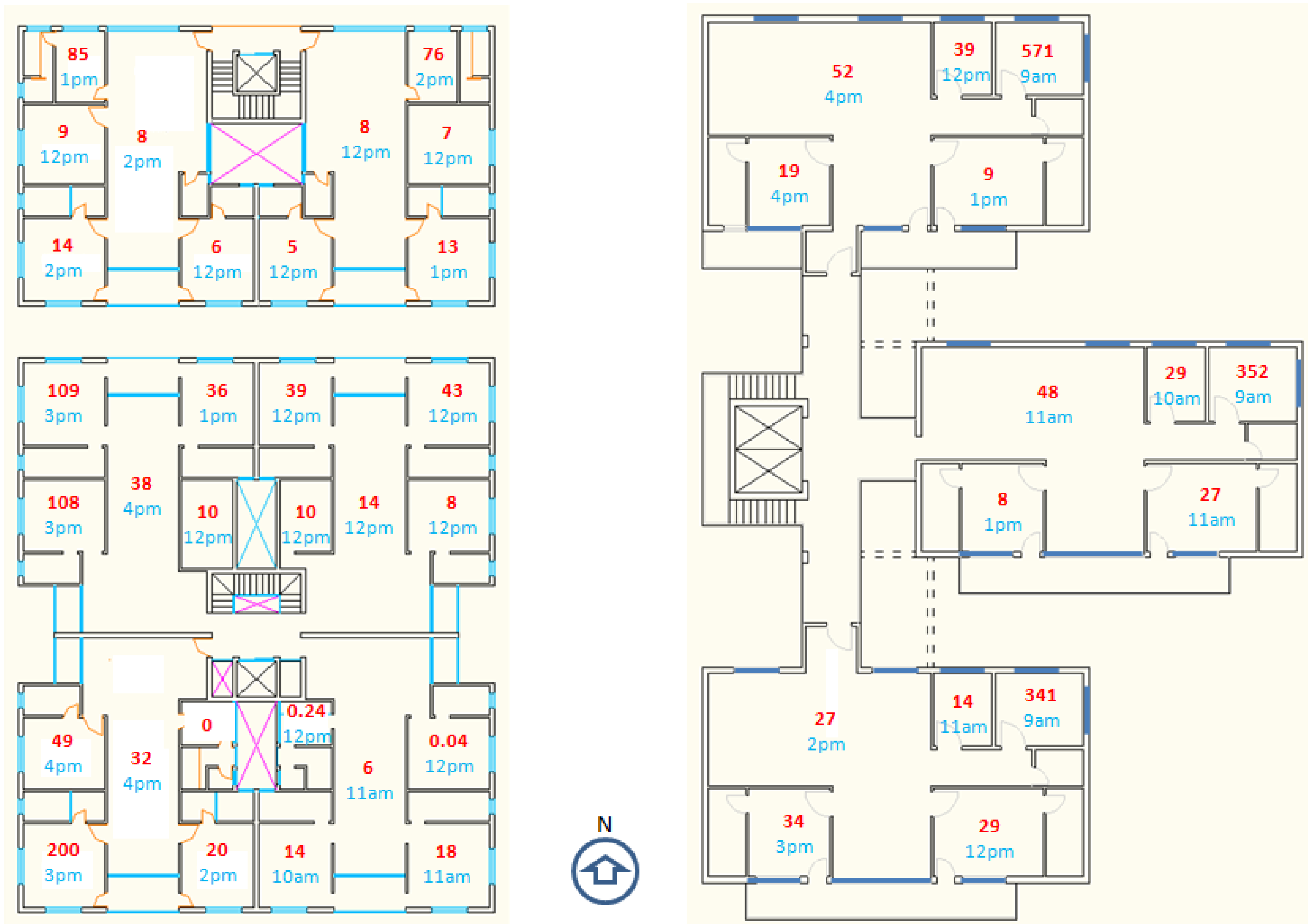


Figure-4.11: Internal illuminance (lx) in dwelling units at second floor, under scheme-1 (left) and scheme-4 (right).

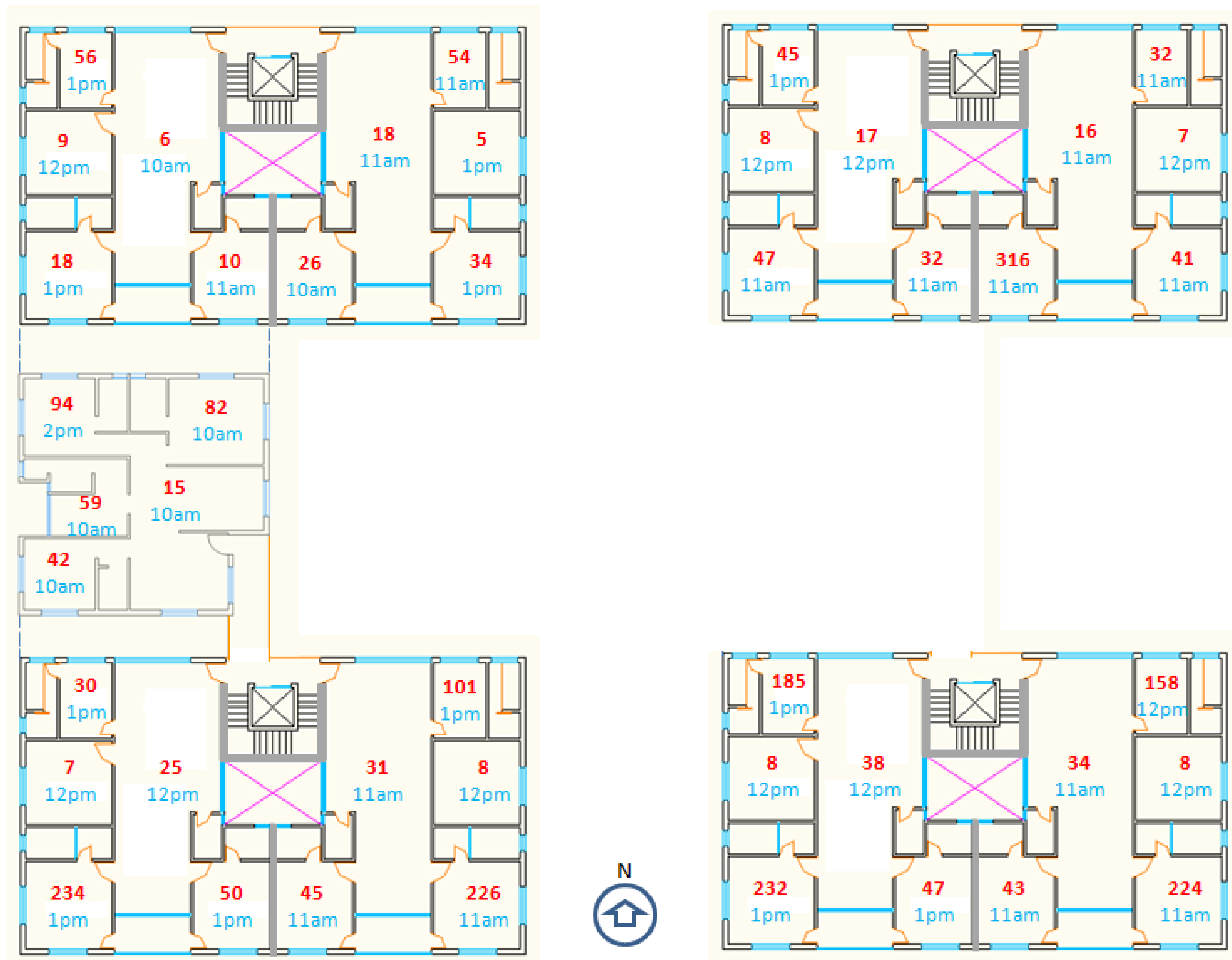


Figure-4.12: Internal illuminance (lx) in dwelling units at second floor, under scheme-2 (left) and scheme-3 (right).

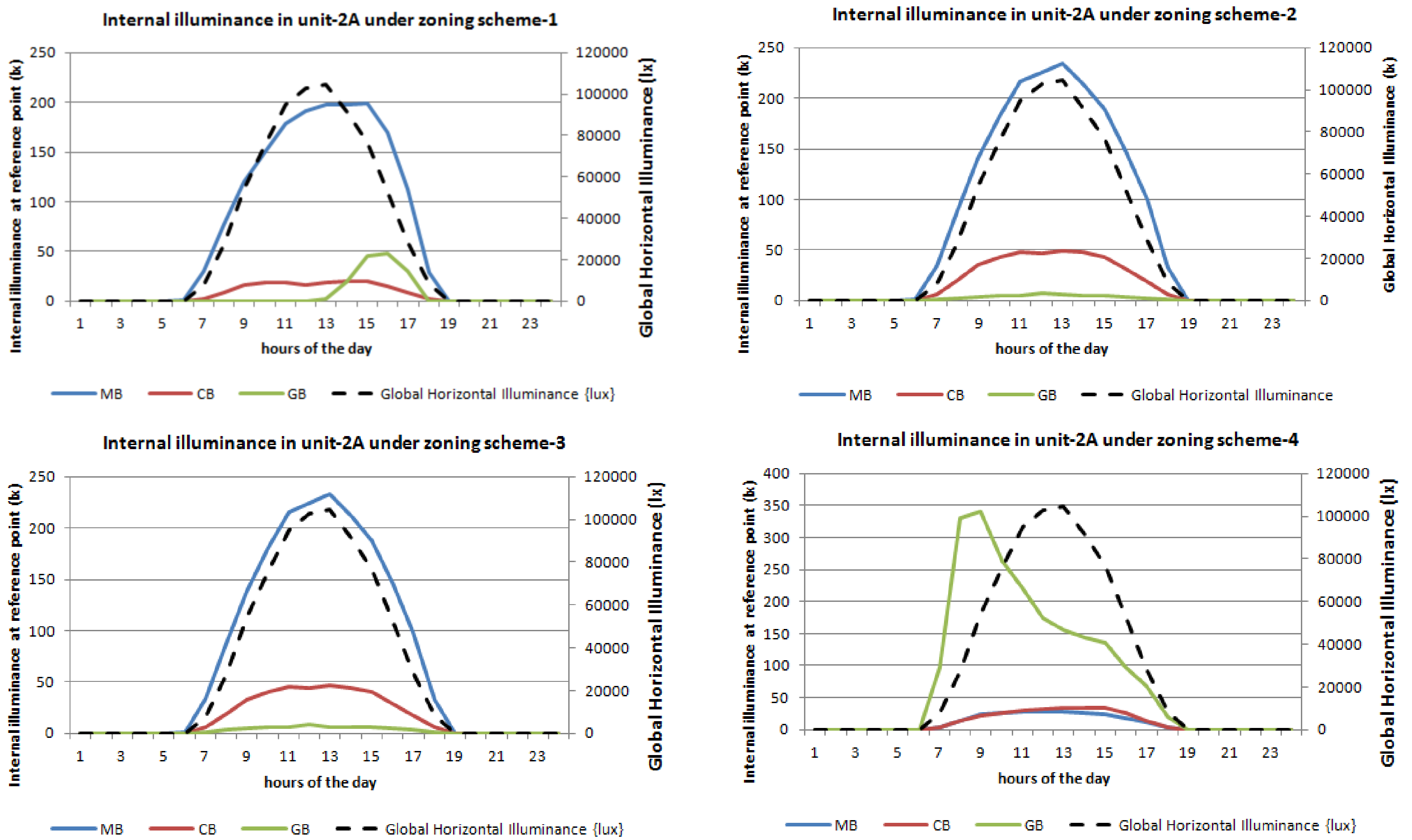
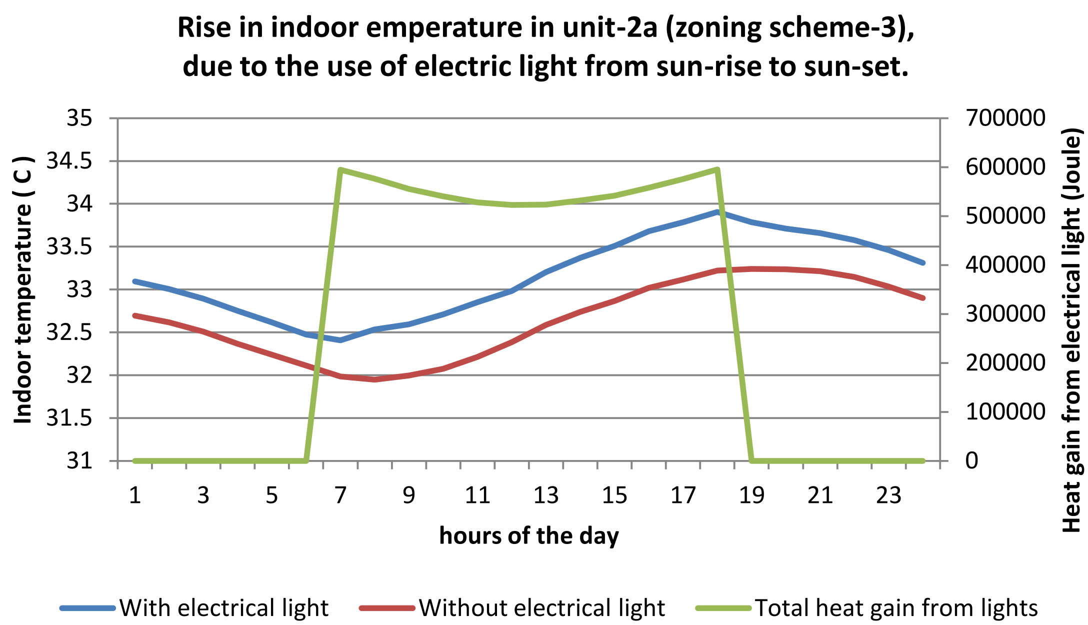


Figure-4.13: Hourly internal illuminance (lx) in Master Bed (MB), Child Bed (CB), and Guest Bed (GB), in unit-2A of each zoning scheme, along with hourly global horizontal illuminance (lx).



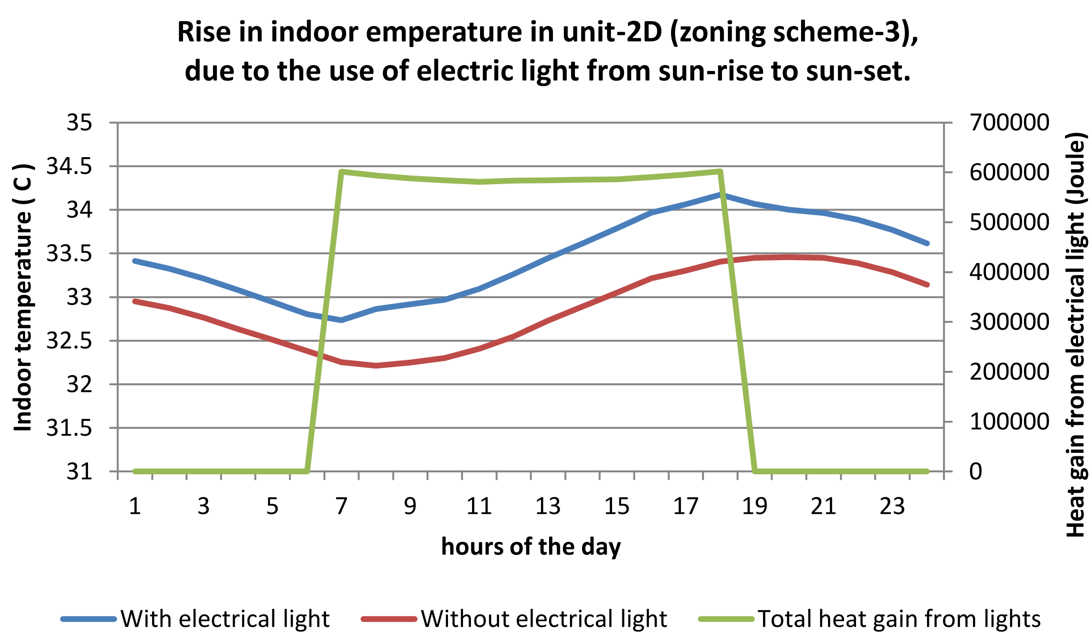


Figure-4.14: Heat gain from the use of electrical light (due to lack of daylight) and consequent rise in indoor temperature in unit 2A and 2D, under scheme-3.

In the following paragraphs, the average temperature rise (due to the use of electrical light) in each dwelling unit under each zoning scheme is described.

Zoning scheme-4: Similar simulations and calculations are done for zoning scheme-4. Under zoning scheme-4, in unit 2A, an average hourly temperature rise is 0.34^{o}C; in unit 2B, there is no temperature rise; and in unit 2C, it is 0.23^{o}C. So, the average temperature rise in zoning scheme-4 is 0.19^{o}C.

Zoning scheme-1: Under zoning scheme-1, in unit 2A, an average hourly temperature rise is 0.02^{o}C; unit 2B also experiences a temperature increase of 0.02^{o}C; in unit 2C, it is 0.41^{o}C; in unit 2D, it is 0.57^{o}C; in unit 2E, it is 0.56^{o}C; in unit 2F, it is 0.59^{o}C. So, the average temperature rise in zoning scheme-1 is 0.36^{o}C.

Zoning scheme-2: Under zoning scheme-2, in unit 2A, an average hourly temperature rise is 0.53^{o}C; in unit 2B, it is 0.52^{o}C; in unit 2C, it is 0.47^{o}C; in unit 2D, it is 0.55^{o}C; and in unit 2E, it is 0.56^{o}C. So, the average temperature rise in zoning scheme-2 is 0.53^{o}C.

Table-4.3 shows the average temperature rise in the second floor dwelling units under each zoning scheme. According to Table-4.3, scheme-4 performs the best, with an average temperature rise of 0.19^{o}C; the second best is scheme-1, with an average temperature rise of 0.36^{o}C; scheme-3 performs the second worst, with an average temperature rise of 0.42^{o}C; and scheme-2 performs the worst, with an average temperature rise of 0.53^{o}C.

Table-4.3: Average rise in indoor mean air temperature due to use of electrical light.

Zoning scheme	Average hourly rise in indoor air temperature due to use of electrical light
Zoning scheme-1	0.36°C
Zoning scheme-2	0.53°C
Zoning scheme-3	0.42°C
Zoning scheme-4	0.19°C

4.3 PERFORMANCE OF VENTILATION RATE MAXIMIZATION

To analyze the zoning schemes' impact on ventilation rate and consequent indoor temperature, two sets of simulations were carried out and compared. In one set, no ventilation (natural or mechanical) was allowed, and therefore, the temperature rise was due to solar load and electrical light load. In the other set, both all-day-ventilation and nigh-time ventilation were introduced. Table-4.4 shows average hourly ventilation rates in all units under all four zoning schemes.

Table-4.4: Average hourly ventilation rates in all dwelling units under all four zoning schemes.

Zoning scheme number	Ventilation rate in individual dwelling unit					
	2A	2B	2C	2D	2E	2F
#1	38.3	34.85	10.75	12.42	12.48	12.44
#2	34	33.93	28	26.9	43.5	
#3	30.19	30.57	30.19	30.49		
#4	24.57	20.03	20.05			

Table-4.4 shows that zoning scheme-2 and zoning scheme-3 provides an average hourly ventilation rate of 33 and 30 ACH. Zoning scheme-4 provides lower ventilation rate than the scheme 2 and 3 which is about 22 ACH. For unit 2A and 2B, zoning scheme-1 provides higher ventilation rate (36.6 ACH) than any of the units in other schemes. However, for the rest of the four units, zoning scheme provides lowest ventilation rate at 12 ACH.

Although it was expected that zoning schemes which allow more open space would provide higher ventilation rate, and zoning schemes which allow less open space would provide lower ventilation rate, this is not seen from Table-4.4. Rather, higher ventilation rate is also observed in denser context.

Unit 2A in scheme-1 experiences the highest ventilation rate (38 ACH) even though scheme-1 has the least open space to allow maximum airflow. The possible reason is that the south façade of 2A experiences positive wind pressure due to south wind, and its west façade experiences negative pressure due to its location in the alleyway. This pressure difference causes the higher ventilation rate.

This is true but opposite for unit 2C under scheme-1. Both its west façade and north façade experience the same amount of negative pressure, and therefore the ventilation rate is low (11 ACH). Figure-4.15 shows pressure difference in different facades of unit-2A and 2C of scheme-1.

Under zoning scheme-1, this higher pressure on south façade is due to its uninterrupted exposure to south wind from street-front. The incoming south wind has only smaller alleyway to pass through and therefore, it causes the high pressure on south facade. This is not the case in zoning scheme-4 which allows larger open spaces around the buildings. This allows the south wind to pass through without creating any large pressure on the south walls. Therefore, lower ventilation rate is observed in unit 2A and 2C under scheme-4.

Principally, the higher the ventilation rate, the better it is to flush out unwanted heat from indoor. In naturally ventilated spaces, the indoor temperature follows the outdoor temperature. Dhaka's average hourly temperature on April 5^{th} is 31.34^{o}C. With adequate ventilation rate, all the dwelling units' average hourly indoor temperature should be close to this temperature. To see whether the zoning schemes are providing adequate ventilation rate for the dwelling units, unit 2A and 2C were simulated in EnergyPlus. Table-4.5 shows solar heat gain, ventilation rates, and resultant average hourly indoor temperature in these units.

Under zoning scheme-1, both unit 2A and 2C have higher solar gain. 2A has higher ventilation rate and therefore achieves an average hourly indoor temperature of 31.5^{o}C; 2C has lower ventilation rate and therefore achieves an average hourly indoor temperature of 33.13^{o}C.

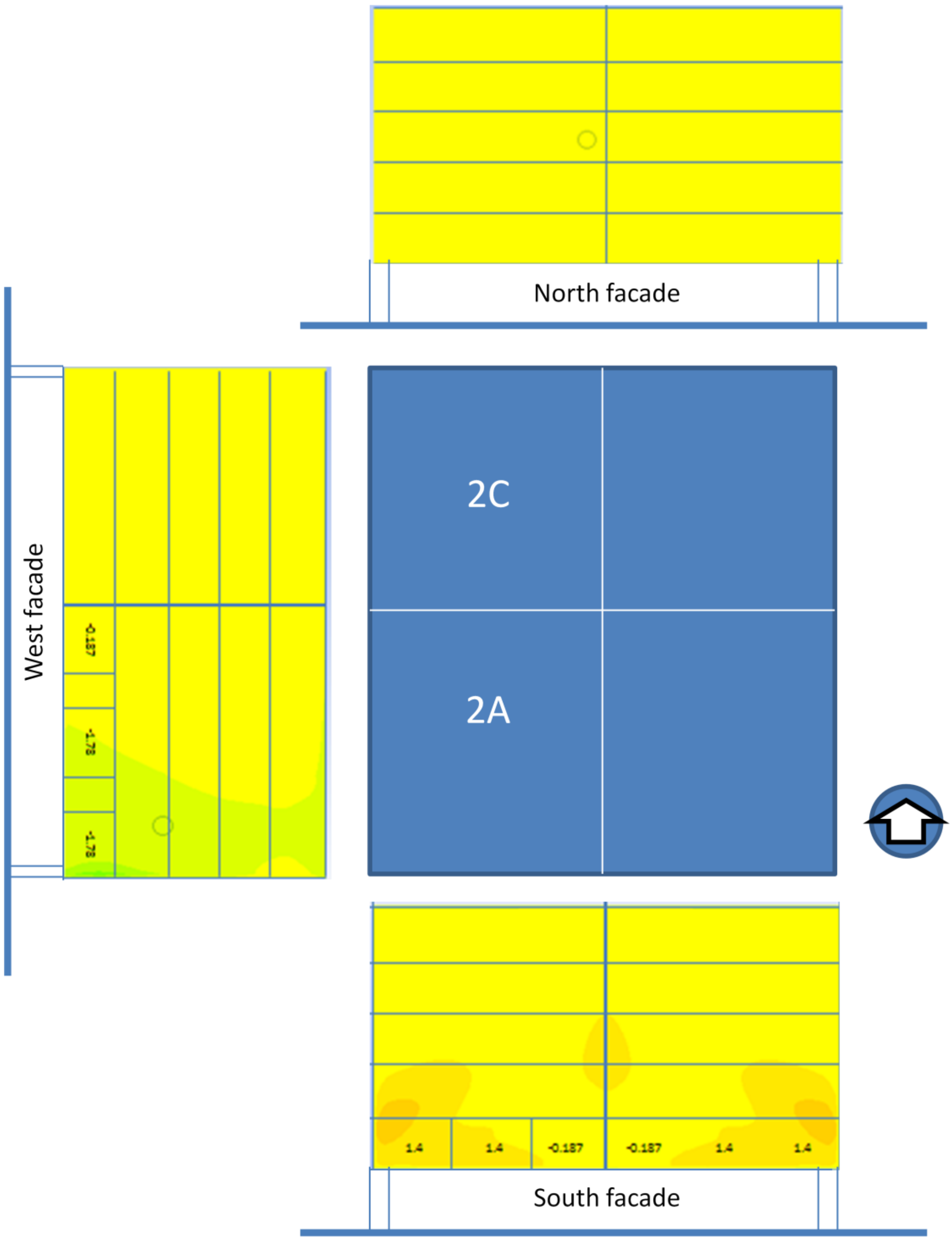


Figure-4.15: Pressure difference in different facades in apartment building (front part) under zoning scheme-1. (Green represents the lowest pressure, orange represents the highest pressure)

Table-4.5: Ventilation rates in dwelling units, with hourly solar gain (W/m^2) and average hourly indoor temperature (C).

Zoning scheme number	Dwelling unit number	Ventilation rate (ACH)	Average hourly solar gain (W/m^2)	Average hourly indoor temperature (C)
#1	2A	38	1188	31.5
	2C	11	1047	33.13
#2	2A	30	365	31.84
	2C	28	307	31.49
#3	2A	34	447	31.61
	2C	30	333	31.56
#4	2A	25	524	31.53
	2C	20	370	31.41

In each of the rest of the zoning schemes, unit 2A receives higher solar heat gain than unit 2C; however, with a little higher ventilation rate, unit 2A reduces the average hourly indoor temperature almost close to that in unit 2C.

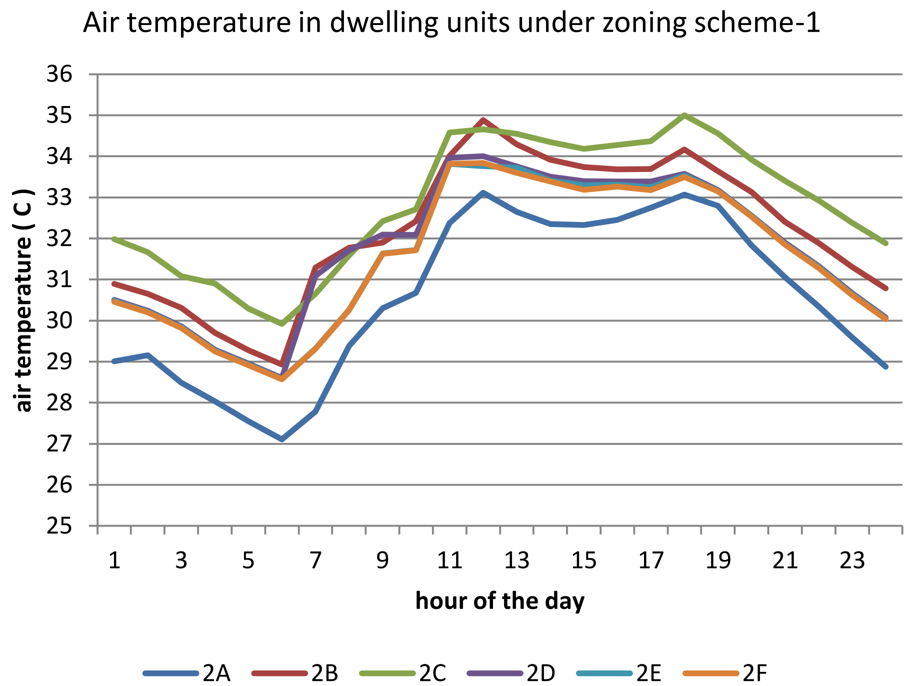
So, Table-4.5 shows that zoning scheme 2, 3, and 4 provides adequate ventilation rate to the apartment buildings to tackle its' solar heat gain. Zoning scheme-1 only provides adequate ventilation rate for two of its dwelling units; it allows low ventilation rates for the other four units and consequently causes high indoor temperature in those units.

4.4 COMBINED PERFORMANCE OF SOLAR PROTECTION, DAYLIGHT MAXIMIZATION, AND VENTILATION MAXIMIZATION

All the effects of solar protection, daylight maximization, and ventilation maximization should principally reduce the indoor temperature. Therefore, to analyze the zoning schemes' combined performance of solar protection, daylight maximization, and ventilation maximization, a comparison of indoor temperature in all units were performed. The results are shown in Table-4.6.

Table-4.6: Indoor temperature in individual dwelling units.

Zoning scheme number	average hourly indoor temperature (C) in individual dwelling unit					
	2A	2B	2C	2D	2E	2F
#1	30.54	32.2	32.84	31.80	31.58	31.56
#2	31.51	31.51	31.18	30.62	31.18	
#3	30.62	31.28	30.56	31.33		
#4	31.17	31.00	31.06			



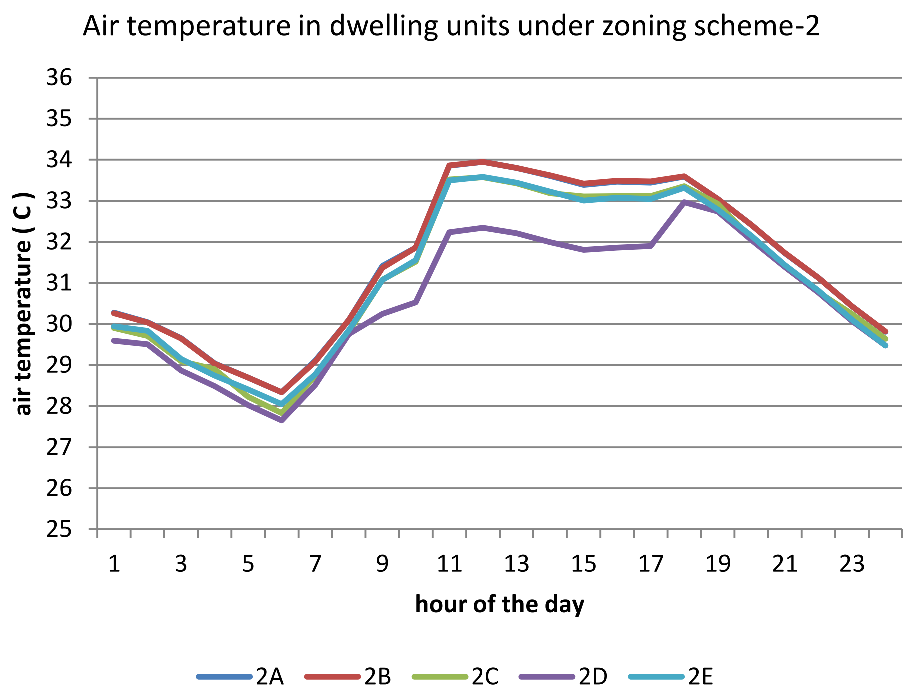
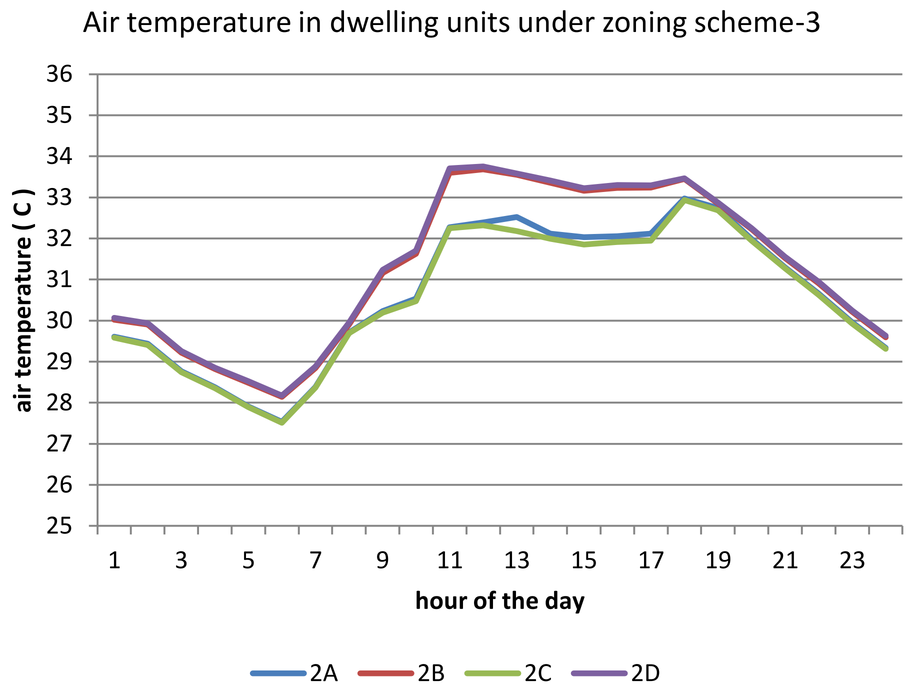


Figure-4.16-a: Hourly indoor temperature in dwelling units, under zoning scheme-1 (top) and under zoning scheme-2 (bottom).



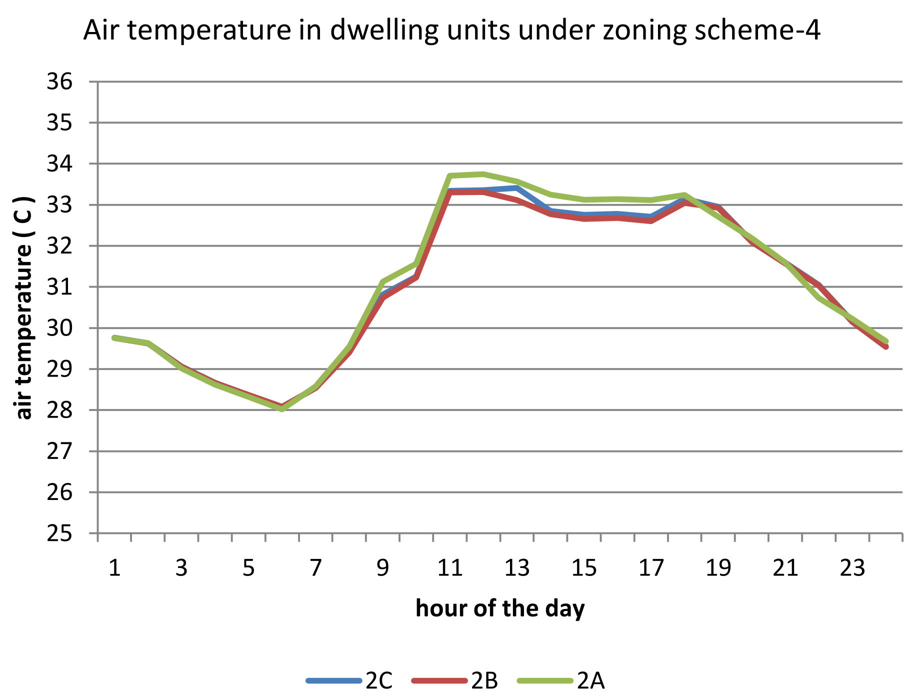


Figure-4.16-b: Hourly indoor temperature in dwelling units, under zoning scheme-3 (top) and under zoning scheme-4 (bottom).

Table-4.6 shows the average hourly value but it does not show which zoning scheme provide comfortable temperature for most of the day. To analyze this, 24 hours indoor temperature in all dwelling units are shown in Figure-4.16-a to Figure-4.16-b. From the figures, it is evident that zoning scheme-3 provides highest number of thermally comfortable hours. In all units, hours those experiences above 33^{o}C are presented in Table-4.7.

Table-4.7: Number of hours those experiences above 33^{o}C indoor temperature.

Zoning scheme number	Number of hours those experiences above 33^{o}C.					
	2A	2B	2C	2D	2E	2F
#1	1	10	11	9	9	9
#2	9	9	8	0	8	
#3	0	8	0	8		
#4	8	3	3			

So, Table-4.6 and Table-4.7 show that the average hourly value of indoor temperature is lower in zoning scheme-3 than the other three zoning schemes; half of its dwelling units experience zero hour of high temperature (above 33^{o}C) and other half experience eight hours of high temperature.

Table-4.6 and Table-4.7 also show that the average hourly value of indoor temperature is little higher in zoning scheme-4 than it is in zoning scheme-3; two of its dwelling units experience three hours of high temperature (above 33^{o}C) but the other one experiences eight hours of high temperature.

So, in terms of indoor temperature, zoning scheme-3 and zoning scheme-4 perform better than scheme 1 and 2 but among themselves, they are not too far from each other. Therefore, superiority between these two zoning schemes, in terms of thermal comfort, depends on their performance of providing air velocity in the dwelling units.

4.5 PERFORMANCE OF AIR VELOCITY MAXIMIZATION

Since acceptable ventilation rates are found in three of the zoning schemes, it is assumable that dwelling units under these zoning schemes will have adequate air velocity. However, it is crucial to see the pattern and magnitude of indoor air velocity within the individual dwelling units; because an adequate air velocity raises occupants' thermal comfort sensation. Table-4.8 shows an average air velocity in each dwelling unit, calculated at the center of the room, under all four zoning schemes. Figure-4.17 to Figure-4.20 show airflow pattern in each of the rooms, in each of the dwelling units, under all four zoning schemes.

Table-4.8: Average air velocity in individual dwelling units.

Zoning scheme number	Air velocity in individual dwelling unit					
	2A	2B	2C	2D	2E	2F
#1	0.56m/s	0.89m/s	0m/s	0m/s	0m/s	0m/s
#2	0.57m/s	0.82m/s	1.0m/s	0.57m/s	0.53m/s	
#3	0.78m/s	0.84m/s	0.77m/s	0.44m/s		
#4	0.41m/s	0.23m/s	0.37m/s			

So Table-4.8 shows that zoning scheme 2 and 3 provides higher air velocities than scheme 1 and 4. An average air velocity of 0.7m/s is found in dwelling units under both schemes 2 and 3. Zoning scheme-4 provides an average air velocity of 0.34m/s for its dwelling units, and scheme-1 provides an average velocity of 0.24m/s.

Literature review shows that, in Dhaka's context, tolerance to high temperature increases (2.2^{o}C) with an air velocity of more than 0.3m/s. Since all of the zoning schemes except scheme-1 have an average air velocity of more than 0.3m/s, higher temperature will be less stressful under these zoning schemes. However, these velocities were recorded for April 5th when average hourly outdoor velocity is 2.78m/s. So if the outdoor air velocity reduces in other times, zoning scheme 2 and 3 will perform better than zoning scheme-4.

Under scheme-1, although the average velocity in scheme-1 is 0.24m/s, only two units are getting higher than this velocity and the other four units are all getting 0.0m/s air velocity. Therefore, zoning scheme-1 performs the worst in terms of providing adequate air velocity.

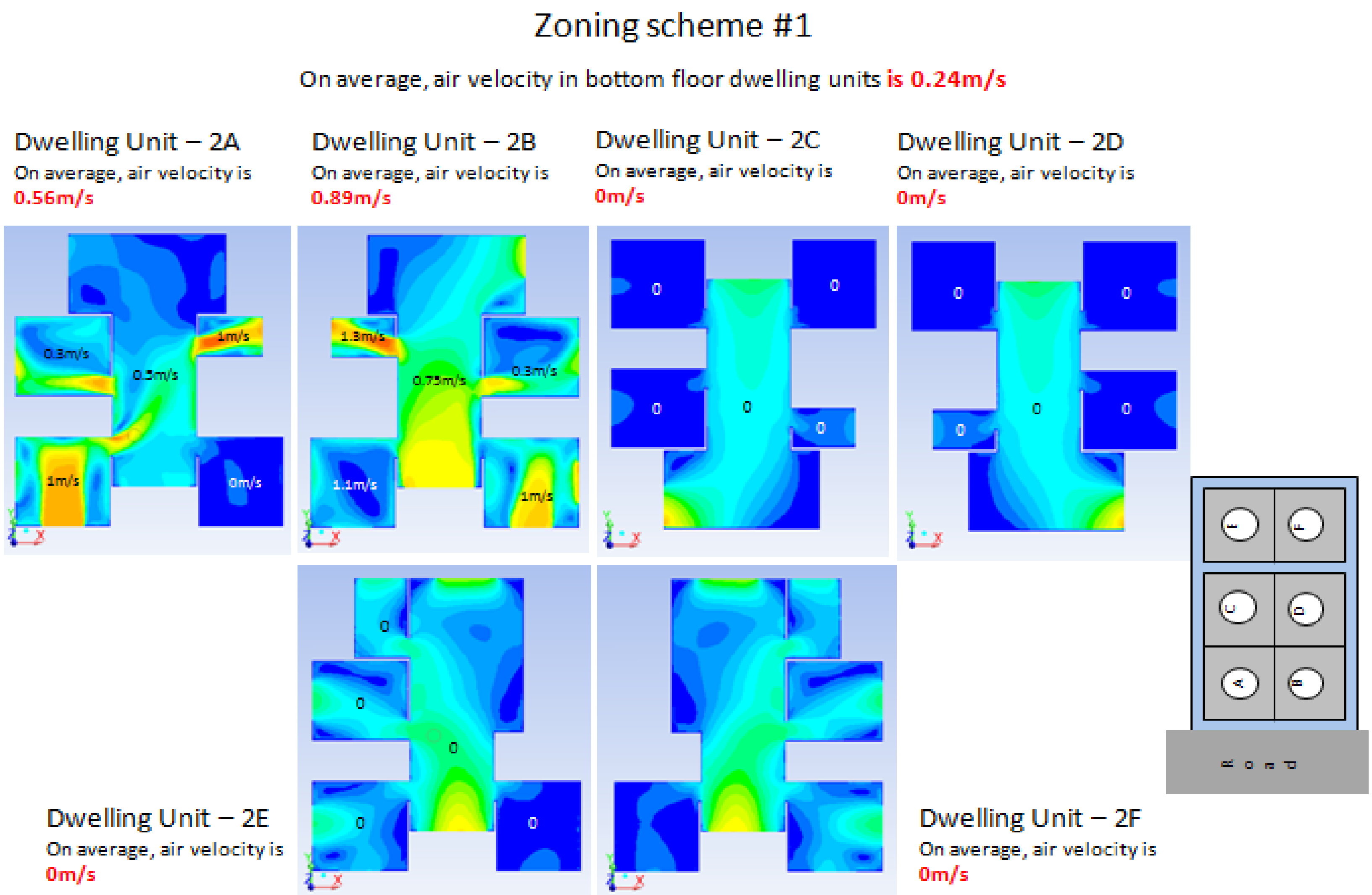


Figure-4.17: Air velocity in individual rooms in all six dwelling units under zoning scheme-1.

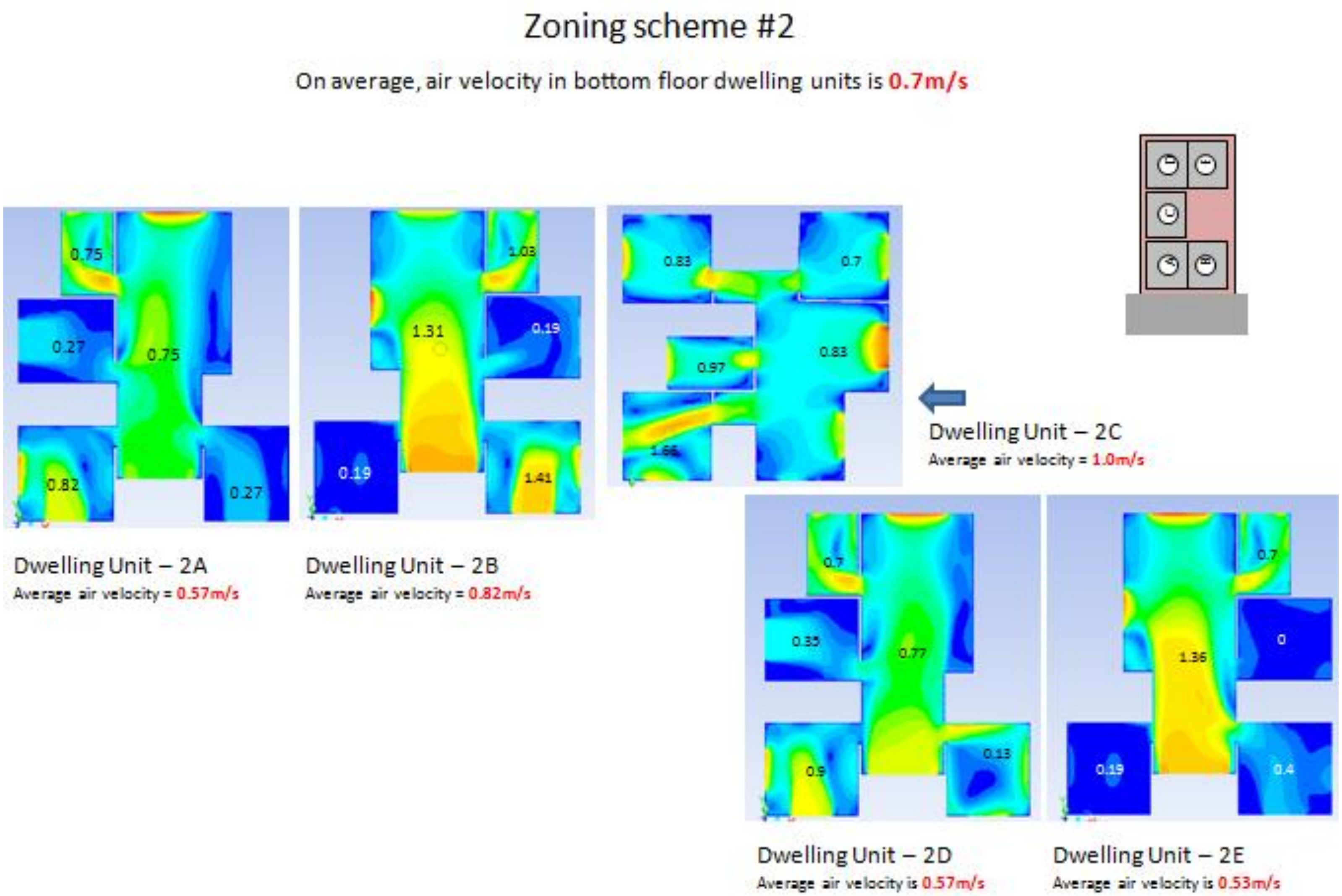


Figure-4.18: Air velocity in individual rooms in all five dwelling units under zoning scheme-2.

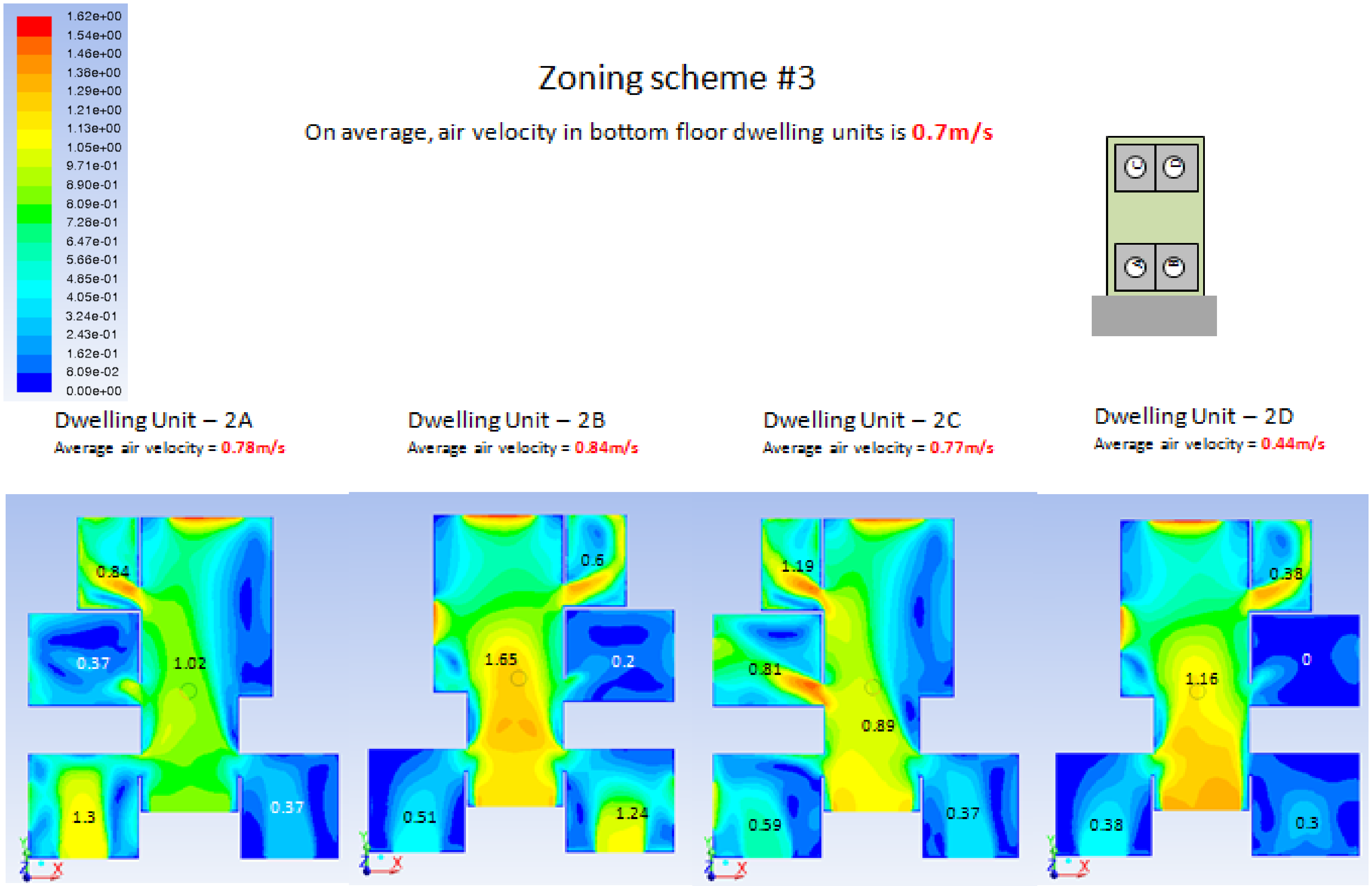


Figure-4.19: Air velocity in individual rooms in all four dwelling units under zoning scheme-3.

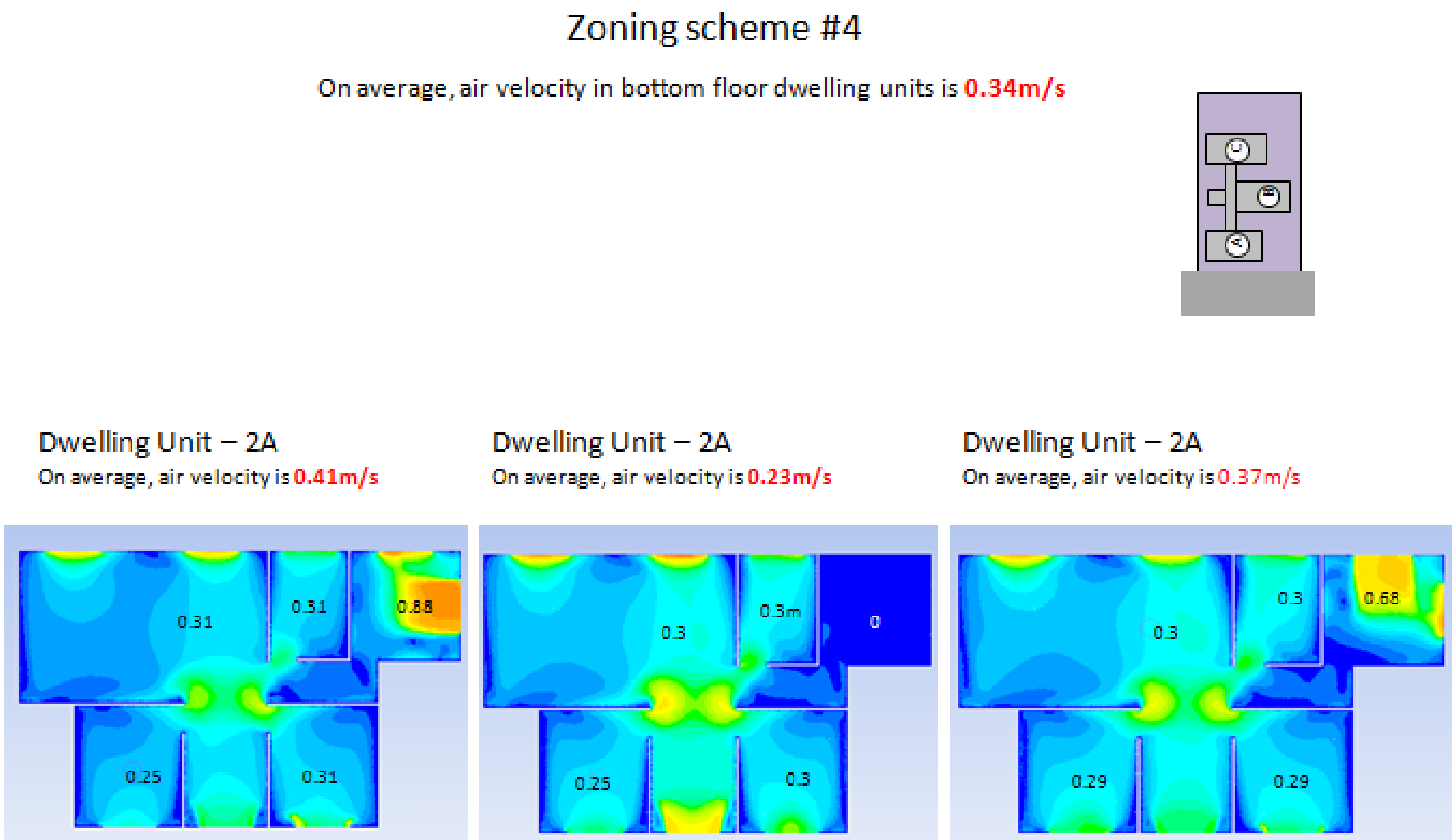


Figure-4.20: Air velocity in individual rooms in all three dwelling units under zoning scheme-4.

4.6 SUMMARY OF THE RESULTS

The summary of the results are shown in a tabulated format in Table-4.9. The table shows that zoning scheme-3 performs best in terms of solar radiation control, ventilation rate, air velocity enhancement, and it consequently provides lowest indoor temperature. However, it shows little higher mean radiant temperature than scheme-4, and shows higher temperature rise due to lack of daylight. Still, considering these two components' magnitude, zoning scheme-3 seems to be superior to the other three zoning schemes in terms of providing favorable thermal comfort conditions.

Table-4.9: Comparison between zoning regulations' performance.

Zoning scheme number	Average of hourly solar radiation	Temperature rise due to lack of daylight	Ventilation rate	Air velocity	Highest peak in indoor temperature	Highest peak in indoor mean radiant temperatu re
#1	1117 W/m^2	0.36°C	12 ACH	0.24m/s	34°C	33.75°C
#2	336 W/m^2	0.53°C	34 ACH	0.7m/s	33.5°C	32.5°C
#3	390 W/m^2	0.42°C	30 ACH	0.7m/s	33°C	32.5°C
#4	447 W/m^2	0.19°C	22 ACH	0.34m/s	33.4	32°C

5. CONCLUSION

5.1 DISCUSSION

The intention of this research is to find an appropriate zoning regulation scheme for Dhaka's non-conditioned apartment buildings (for a lot size of 1/3rd acre) which would provide favorable thermal comfort conditions without changing its existing density. This research analyzed two existing zoning schemes (one based on regulations of 1996, and the other based on the regulations of 2008) as well as two hypothetical zoning schemes. The hypothetical ones were studied because this research finds 1996 and 2008 regulations to be two extremes (in terms of allowing open space and building height), and therefore examination of in-between alternative zoning schemes seemed essential for this study. This research found one of the in-between schemes to be more appropriate to bring favorable thermal comfort conditions than the other three schemes.

The principal difference in the four zoning schemes is the percentage of lot area to be built on or allowable building footprint; and the four variations in allowable building footprints are: 80%, 70%, 60% and 50%. To maintain the existing density (FAR = 5 and density = 90 DU/Acre), buildings' heights were kept different in each of these zoning schemes; and the four height variations are: six-stories, seven-stories, nine-stories, and eleven-stories. Throughout this dissertation, these four various sets of zoning regulation components were discussed under the following four names: zoning scheme-1 (80% allowable footprint, 6-story height limit), zoning scheme-2 (70% allowable footprint, 7-story height limit), zoning scheme-3 (60% allowable footprint, 9-story height limit), and zoning scheme-4 (50% allowable footprint, 11-story height limit). Zoning scheme-1 and zoning scheme-4 represent Dhaka's zoning regulations of 1996 and 2008 respectively, and the zoning scheme-2 and zoning scheme-3 are the hypothetical ones. This research found zoning scheme-3 to be the most appropriate to bring favorable thermal comfort conditions in Dhaka's context.

The studied thermal comfort conditions included *indoor temperature*, *indoor mean radiant temperature*, and *indoor air velocity*. In an apartment building, these three conditions vary based on the variation in the following elements: amount of *solar radiation*, amount of *daylight*, and *ventilation rate*. This research showed how each of the zoning schemes resulted in different thermal comfort conditions in the apartment buildings due to receiving different amounts of the mentioned elements.

Solar radiation control: in terms of controlling solar radiation on the building, zoning scheme-3 performed the best and zoning scheme-4 performed the second best. Zoning scheme-3 protected maximum solar radiation because of the following two reasons: i) the higher ratio (height/width) of the canyon geometry in alleyways (due to setbacks and building height) provided ample shading to the west and east façade, and ii) with 60% allowable building footprint, the building had enough open space to have veranda on the south sides to protect south facing rooms. Scheme-4 performed little lower than scheme-3 because its ratio of canyon geometry is lower than scheme-3 and therefore could not cut similar solar radiation on east and west sides.

Daylight maximization: zoning schemes' daylight maximization performance was studied because zoning regulation, by allowing adequate internal illuminance, can reduce heat gain (from the use of electrical light) in buildings. Therefore, besides comparing the available internal illuminance (Lx) under each zoning scheme, heat introduction (from electrical light) and resultant temperature rises were compared. Results show that zoning scheme-4 provides maximum internal illuminance because it causes the lowest temperature rise (an average hourly value of 0.19^{o}C). Although zoning scheme-3 could allow the least amount of internal illuminance due to its highest level of solar control, the illuminance results does not agree with this. Under zoning scheme-3, an average hourly temperature rise of 0.42^{o}C was observed, and with this value, scheme-3 performs the second worst among the schemes in terms of internal illuminance. Zoning scheme-2 has the highest value of hourly temperature rise (0.53^{o}C) due to lack of daylight, and zoning scheme-2 has the second lowest value of hourly temperature rise (0.36^{o}C).

Ventilation rate maximization: although it was assumed that zoning schemes allowing higher open spaces (by lowering allowable building footprint) could provide higher ventilation rate, the results do not support this. Scheme 3 and 4 were found to have a better ventilation rate than scheme 1 and 4, providing an average ventilation rate of 33 ACH and 30 ACH respectively. Scheme 1 provides the least amount of ventilation rate (12 ACH) due to its compact and dense nature. Despite having the highest openness, zoning scheme-4 allows an average ventilation rate of 22 ACH. This is because the building-form and its surroundings created a lower pressure difference between windward and leeward facades.

Average indoor air velocity: zoning schemes' performance of providing air velocity linearly follows their performance of ventilation rates. Both zoning scheme 3 and 4 provide the highest rate of air velocity at 0.7m/s. Zoning scheme-1 provides the lowest average air velocity, where only two of its dwelling units get above 0.5m/s velocity and the rest of the four units get zero air velocity. In all three units in zoning scheme-4, the average air velocity is 0.34m/s. A 0.3m/s air velocity is crucial for temperature between 32^{o}C and 34^{o}C, which is the case in most of the dwelling units, because this velocity makes these high temperatures tolerable to the occupants. However, this 0.34m/s air velocity in zoning scheme-4 was observed based on an outdoor ventilation rate of 2.78m/s. So, if outdoor wind speed is lower than this level, zoning scheme-4 will not perform well. In this regard, zoning scheme 2 and 3 will perform better due to the presence of a much higher air velocity (0.7m/s).

Therefore, this research concluded that zoning scheme-3 is the most appropriate in terms of improving thermal comfort conditions, by providing a balance between solar protection, daylight maximization, ventilation rate maximization, and air velocity maximization.

5.2 VALIDITY OF THE HYPOTHESIS AND THE MAGNITUDE OF THE KEY RESEARCH FINDINGS

The research hypothesis was that ‘thermal comfort conditions in Dhaka’s non-conditioned apartment buildings can be improved by appropriate zoning regulations, without sacrificing existing density’.

Through simulation results, the research showed that for a constant density of a FAR of 5, a zoning scheme that allows 60% allowable building footprint (zoning scheme-3 in this research) provides better thermal comfort conditions than a zoning scheme that allow 80% allowable building footprint (zoning scheme-1 in this research).

The magnitude of this finding is described through Figure-5.1. Figure-5.1 shows that zoning scheme-3 provides favorable thermal comfort conditions for 50% of the studied units where as zoning scheme-1 cannot provide favorable thermal comfort conditions to any of the studied units. Moreover, in zoning scheme-3, 100% dwelling units have an air velocity of 0.7m/s whereas in zoning scheme-1, 66% dwelling units have a zero air velocity. Therefore, Figure-5.1 clearly shows that an appropriate zoning scheme can provide higher number of dwelling units with improved thermal comfort conditions.

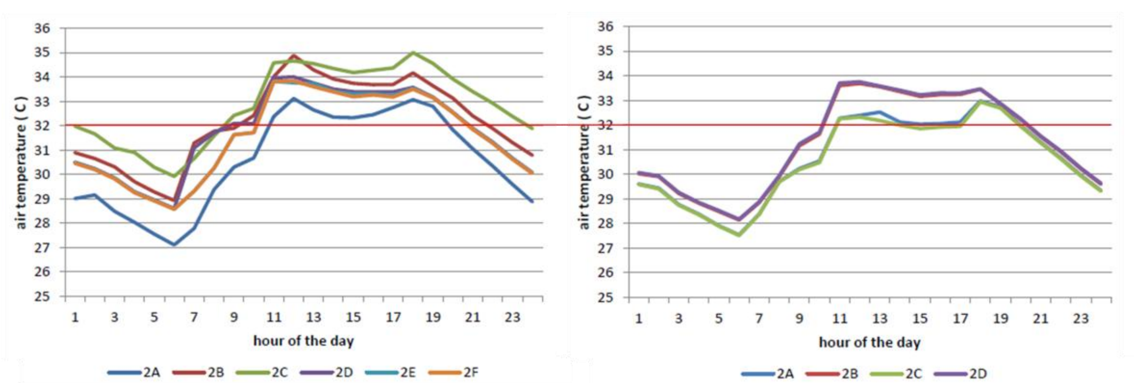


Figure-5.1: Comparison between indoor temperatures in dwelling units under zoning scheme #1 (left) and #3 (right).

5.3 SIGNIFICANCE OF THIS RESEARCH

The principal significance of this research is: it proves zoning regulations as an effective tool to improve thermal comfort conditions in non-conditioned apartment buildings. So far, zoning regulations have been used as strategy to assure solar access for passive heating and consequent energy reduction in buildings under colder climate. To the knowledge of this author, this research is the first of its kind that studied zoning regulations as form-giver and analyzes consequent thermal comfort conditions in the non-conditioned apartment buildings. Moreover, it analyzes the building in terms of individual dwelling unit scale which is rare in other studies.

The other major significance of this research is: it proves that favorable thermal comfort conditions can be achieved in high-density housing context, without sacrificing the existing density. Most of the other studies considered a reduction in density (in hot humid climate) or an increase in density (in colder climate) as the means to provide thermal comfort conditions. However, this is not practical in Dhaka or any other cities in the developing countries due to land scarcity and consequent agricultural land encroachment.

In terms of Dhaka’s context, the most relevant significance of this research lies in its potential to offer modification in Dhaka’s zoning regulations. The research findings suggest that the recent restrictions (2008) on allowable building footprint are overestimated. With a little more allowable footprint (60% vs. 50%), similar or higher improvement can be achieved in thermal comfort conditions. With this modification in zoning regulations, less tall buildings (9-stories vs. 11-stories) will be able to meet the thermal comfort requirement under the existing FAR. Beside improving thermal comfort conditions, this will also provide resource savings in the following manner: i) less use of mechanical means of cooling due to the reduction of thermally stressful hours, ii) by eliminating extra floors on top, higher cost of high-rise construction will be minimized, and iii) by reducing travel distances of elevators, daily energy consumption will be reduced.

Beside its significance in Dhaka's housing and planning context, this research offers its contribution to the following fields of study: i) energy-conscious urban planning, and ii) climate-responsive building-forms.

Energy-conscious urban planning: so far, most studies in energy-conscious urban planning have focused on the impact of density on transportation energy. Their findings promote increased density to reduce travel distance and consequent energy use. Studies also show that high density also raises energy use in buildings due to lack of solar and wind access in buildings. However, these studies have not considered how solar and wind access can be improved in this higher density development. This research shows that urban planning, through appropriate zoning regulations, can assure adequate solar and wind access in a moderately high density (90 DU/Acre) development and consequently reduce the energy use in buildings.

Climate-responsive building-forms: most studies on climate-responsive building-form were done in colder climates or hot arid climates. Fewer studies were done in hot humid climate. Moreover, these studies (in hot humid climates) hardly considered building-form in the context of a dense urban environment. This research shows climate responsiveness of four building-forms in the context of dense urban areas in a hot humid climate. These building-forms' performance of solar control, day-light maximization, ventilation maximization, and air velocity enhancement will be helpful to building design professionals to design better climate-responsive building-forms in the urban context of other hot humid cities.

So, providing a better understanding about how zoning regulations can affect thermal comfort conditions could improve the lives of people living in non-conditioned buildings under hot humid climates.

5.4 RECOMMENDATIONS FOR PLANNING AND ZONING REGULATIONS IN DHAKA CITY

Based on the findings, this research suggests the following recommendations for Dhaka's zoning regulations:

- The allowable building footprints for all lot sizes, mentioned in 2008 regulations, should be reevaluated and readjusted in terms of their impact on thermal comfort.
- Since thermal comfort is achievable without sacrificing existing density, the FAR for all lot sizes should be readjusted so that it allows the optimum (in terms of favorable thermal comfort conditions) allowable building footprint as well as the density existed prior to 2008 regulations.
- For a $1/3^{rd}$ acre lot, the allowable building footprint should be changed from 50% to 60% since the later provide better thermal comfort conditions.
- For better solar protection, the dimensions in setback rules should be governed by its orientation (north/south/east/west) rather than its location (front, back or sides of the lot); setbacks in south or north of a lot should be wider, and setbacks in west or east should be narrower.

5.5 LIMITATIONS OF THIS RESEARCH AND IMPLICATIONS FOR FURTHER RESEARCH

Limitations: The major limitations in this research are due to limitation in computing time and resource.

This research analyzed the four zoning schemes' impact on a limited number of building-forms, i.e., one building-form for each zoning scheme. A higher variation in building-forms would have increased the generalizability of the research findings.

The studied dwelling units were also limited to the 'dwelling units only on second floors'. Including dwelling units on other floors would make the validation of the research results stronger.

Methodological limitations include dependency on computer simulations alone. Comparing the results with data measured in real buildings would make the validation of the results stronger. The limitation regarding measured data is due to absence of samples for all four building-forms studied in this research.

The other limitation of this research is that only one day (the hottest day found in the weather file) of a year was analyzed. Since the year in the weather file is not the hottest year, it is hard to generalize that the zoning scheme-3 will assure the mentioned thermal comfort conditions for any of the hottest days in Dhaka's context. Moreover, some other days, with different outdoor temperature and wind velocity, need to be simulated to see whether zoning scheme-3 still performs the best, with a significant difference.

The major limitations in this research are due to limitation in computing time and resource. Therefore, in future researches, research-design could be different to address the limitations in computing time and resource.

Future research: Further studies are required to include more variations in building-forms. To manage the limitations of computing time and resource in the study of larger variation in building-forms, the research can change the scale of investigation; i.e., a larger variation in building-form can be studied in terms of individual building scale rather than in terms of individual dwelling unit scale.

Further research can be conducted to analyzing zoning schemes' impact on thermal comfort conditions in all dwelling units, in all four buildings. In such case, individual dwelling unit can be assumed as a single zone model rather than a multi-zone model, to overcome the computation time and resource.

Once samples of various building-forms are available, a further research could be conducted using experimental data along with the computer simulations. That would strongly validate the significance of zoning regulations on thermal comfort conditions in non-conditioned apartment buildings.

These future researches could find other possibilities to make zoning regulations more appropriate for bringing thermal comfort in non-conditioned apartment buildings.

REFERENCES

Ahmed KS (2003) Comfort in urban spaces: Defining the boundaries of outdoor thermal comfort for the tropical urban environments. *Energy and Buildings* 35(1): 103-110.

Ahmed ZN, & Khan N (2004) Evolution of house form in Dhaka city. *Global Built Environmental Review (GBER)* 3(3): 38-48.

Ahmed ZN (2010, May) *Building regulation changes: Effects on residential building design in Dhaka for energy efficiency*. Paper presented at the International Seminar on Well Being Indoors: Clima 2010, Clima, Turkey.

Al-Sallal KA (2001) The balanced synthesis of form and space in the vernacular house of Sana'a: Bioclimatic and functional analysis. *Architectural Science Review* 44(4): 419-427.

Ali ZF (2007) Comfort with courtyards in Dhaka apartments. *BRAC University Journal,* 4(2): 1-6.

Andolsun S, Culp CH, Haberl J, & Witte MJ (2011) EnergyPlus vs. DOE-2.1e: The effect of ground-coupling on energy use of a code house with basement in a hot-humid climate. *Energy and Buildings* 43(7): 1663-1675.

ANSYS Inc (2009) *ANSYS FLUENT 12.0.* Canonsburg, PA: Ansys Inc.

Artmann N, Manz H, & Heiselberg P (2008) Parameter study on performance of building cooling by night-time ventilation. *Renewable Energy* 33(12): 2589-2598.

Atmaca I, Kaynakli O, & Yigit A (2007) Effects of radiant temperature on thermal comfort. *Building and Environment* 42(9): 3210-3220.

Brager GS, & deDear RJ (1998) Thermal adaptation in the built environment: A literature review. *Energy and Buildings* 27(1): 83-96.

Caciolo M, Marchio D, & Stabat P (2009, July) *Survey of the existing approaches to assess and design natural ventilation and need for further developments.* Paper presented at the Eleventh International IBPSA Conference, Glasgow, Scotland.

Capeluto IG (2003) Energy performance of the self-shading building envelope. *Energy and Buildings* 35(3): 327-336.

Carrilho DG, Chen Q, Glicksman LR, & Norford LK (2002) Simulation of wind-driven ventilative cooling systems for an apartment building in Beijing and Shanghai. *Energy and Buildings* 34(1): 1-11.

Chakrabarti P (2008) *The Building Construction Act and Regulations*. Dhaka, Bangladesh: Law Book Publisher.

Chen Q Y, & Srebric J (2001) *How to verify, validate, and report indoor environment modeling CFD analyses*. Atlanta: ASHRAE

Cheng V, Steemers K, Montavon M, & Compagnon R (2006, September) *Urban form, density and solar potential*. Paper presented at the The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland.

Cheung JOP, & Liu CH (2011) CFD simulations of natural ventilation behaviour in high-rise buildings in regular and staggered arrangements at various spacings. *Energy and Buildings* 43(5): 1149-1158.

Cohen Y, Stanhill G, & Fuchs M (1983) An experimental comparison of evaporative cooling in a naturally ventilated glasshouse due to wetting the outer roof and inner crop soil surfaces. *Agricultural Meteorology* 28(3): 239-251.

Cook J (Ed.). (1998) *Passive cooling*. Cambridge, MA: The MIT Press.

Corbella OD, & Magalhães MAAA (2008) Conceptual differences between the bioclimatic urbanism for Europe and for the tropical humid climate. *Renewable Energy* 33(5): 1019-1023.

Cóstola D, & Alucci M (2007, September) *Pressure coefficient simulated by CFD for wind-driven ventilation analysis*. Paper presented at the Building Simulation, Beijing, China.

Cóstola D, Blocken B, & Hensen JLM (2009) Overview of pressure coefficient data in building energy simulation and airflow network programs. *Building and Environment* 44(10): 2027-2036.

Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Huang YJ, Pedersen CO, et al. (2001) EnergyPlus: Creating a new-generation building energy simulation program. *Energy and Buildings* 33(4): 319-331.

Crawley D. B., Pedersen C. O., Lawrie L. K., & Winkelmann F. C. (2000) EnergyPlus: Energy Simulation program. *ASHRAE Journal* 42 (4): 49-56.

David ML (2002) Computational aspects of nodal multizone airflow systems. *Building and Environment* 37(11): 1083-1090.

David MO (2003) Predicting indoor temperatures in closed buildings with high thermal mass. *Energy and Buildings* 35(9): 851-862.

Eftekhari MM, Marjanovic LD, & Pinnock DJ (2003) Air flow distribution in and around a single-sided naturally ventilated room. *Building and Environment* 38(3): 389-397.

Eli T (1986) Accuracy of schemes with nonuniform meshes for compressible fluid flows. *Applied Numerical Mathematics* 2(6): 529-550.

Emmanuel R, Rosenlund H, & Johansson E (2007) Urban shading - a design option for the tropics? A study in Colombo, Sri Lanka *International Journal of Climatology* 27(14): 1995-2004.

Franke J, Hellsten A, Schlünzen H, & Carissimo B (Eds.). (2007) *Best practice guideline for the CFD simulation of flows in the urban environment*. Brussels: COST Office.

Ghiaus C, & Allard F (Eds.). (2005) *Natural ventilation in the urban environment assessment and design*. London: Earthscan.

Givoni B (1994) Building design principles for hot humid regions. *Renewable Energy* 5(5-8): 908-916.

Givoni B (1992) Comfort, climate analysis and building design guidelines. *Energy and Buildings* 18(1): 11-23.

Graça GCCCd (2003) *Simplified models for heat transfer in rooms.* Unpublished Dissertation, University of California, San Diego.

Grosso M (1998) Urban form and renewable energy potential. *Renewable Energy* 15(1-4): 331-336.

Gu L (2007, September) *Airflow network modeling in EnergyPlus.* Paper presented at the Building Simulation, Beijing, China.

Hachem C, Athienitis A, & Fazio P (2011) Parametric investigation of geometric form effects on solar potential of housing units. *Solar Energy* 85(9): 1864-1877.

Hafiz R (2004) Comfort and quality of indoor and outdoor spaces of Dhaka: An analysis of urban planning and design. *Global Built Environmental Review (GBER)* 4(2): 61-70.

Hamdy IF, & Fikry MA (1998) Passive solar ventilation. *Renewable Energy* 14(1-4): 381-386.

Harlan SL, Brazel AJ, Prashad L, Stefanov WL, & Larsen L (2006). Neighborhood microclimates and vulnerability to heat stress. *Social Science & Medicine* 63(11): 2847-2863.

Hassan M, Ullah MS, & Gomes CD (2000, November) *Rural housing in Bangladesh : An inquiry into housing typology, construction technology & indigenous practices. (Co-Author)* Paper presented at the Intl Conference on Housing & Hazards and the Rural Community, Dhaka, Bangladesh.

Huang J, Winkelmann F, Buhl F, Pedersen C, Fisher D, Liesen R, et al. (1999, September) *Linking the COMIS multi-zone airflow model with the EnergyPlus building energy simulation program.* Paper presented at the Building Simulation, Kyoto, Japan.

Humphrey M (1970) A simple theoretical derivation of thermal comfort conditions. *Journal of the Institute of Heating and Ventilating Engineers* 33: 95–98. .

Islam AKMK (2003) *Patterns and changes of vernacular architecture in Bangladesg.* Unpublished thesis, The Royal Institute of Technology, Stockholm.

James LDJ, & McDonald BN (1999) *Texas municipal zoning law* (3rd ed.). Charlottesville, VA: Lexis Pub.

Jiang Y, Alexander D, Jenkins H, Arthur R, & Chen Q (2003) Natural ventilation in buildings: Measurement in a wind tunnel and numerical simulation with large-eddy simulation. *Journal of Wind Engineering and Industrial Aerodynamics* 91(3): 331-353.

Joseph CL (2000) Shading effects due to nearby buildings and energy implications. *Energy Conversion and Management* 41(7): 647-659.

Kamruzzaman M, & Ogura N (2007, November) *Apartment housing in Dhaka City: Past, present and characteristic outlook.* Paper presented at the Building Stock Activation, Tokyo, Japan.

Kensek K, Noble D, Schiler M, & Setiadarma E (1996) Shading mask: A teaching tool for sun shading devices. *Automation in Construction* 5(3): 219-231.

Knowles RK (2003) The solar envelope: Its meaning for energy and buildings. *Energy and Buildings* 35(1): 15-25.

Knowles RK, & Marguerite NV (1980) Solar access and urban form *AIA Journal* February: 42-49.

Knowles RL, Berry RD & Solar Energy Information Data Bank (U.S.) (1980) *Solar envelope concepts: Moderate density building applications: Final report, April 1980.* Golden, Colo: Solar Energy Information Data Bank.

Kota S, & Haberl JS (2009, November) *Historical survey of daylighting calculations methods and their use in energy performance simulations*. Paper presented at the Ninth International Conference for Enhanced Building Operations, Austin, TX.

Kristensen PE, Tang C, Reimann G, & Ismail AZ (2007, June) *Design strategies for energy efficiency in hot and humid climate: The case of the Zeo Building.* Paper presented at the International Conference on Sustainable Building Asia, Seoul, Korea.

Krüger E, & Givoni B (2008) Thermal monitoring and indoor temperature predictions in a passive solar building in an arid environment. *Building and Environment* 43(11): 1792-1804.

Kubota T, Chyee DTH, & Ahmad S (2009) The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. *Energy and Buildings* 41(8): 829-839.

Lechner N (2009) *Heating, cooling, lighting: Sustainable design methods for architects* (3rd ed.). Hoboken, NJ: John Wiley & Sons.

Lomas KJ (2007) Architectural design of an advanced naturally ventilated building form. *Energy and Buildings* 39: 166–181.

Mallick FH (1996) Thermal comfort and building design in the tropical climates. *Energy and Buildings* 23(3): 161-167.

M N A S (1997) Measurements of air change rates and air flow patterns in large single-cell buildings. *Energy and Buildings* 26(2): 175-182.

Mahtab-uz-Zaman QM, & Lau SSY (2000) City expansion policy versus compact city deman: The case of Dhaka. In M. Jenks & R. Burgess (Eds.), *Compact cities: Sustainable urban forms for developing countries*. New York: E. & F.N. Spon.

Mak CM, & Yik FWH (2002) A study of natural ventilation in a kitchen using Computational Fluid Dynamics (CFD). *Architectural Science Review* 45(3): 183-190.

Microsystems S (2008) *Climate consultant (5.1) [software]*. Santa Clara, CA: Sun Microsystems Inc.

Mohamed MF, Prasad D, & Tahir MM (2008, June) *A study on balcony and its potential as an element of ventilation control in naturally ventilated apartment in hot and humid climate*. Paper presented at the International Conference on Construction and Building Technology, Kuala Lumpur, Malaysia.

Muhaisen AS, & Gadi MB (2006) Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome. *Building and Environment* 41(3): 245-253.

Naz F (2008, October) *Energy efficient garment factories in Bangladesh*. Paper presented at the 25th Conference on Passive and Low Energy Architecture, Dublin, Ireland.

Nicol F, & Humphreys M (2010) Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment* 45(1): 11-17.

Oh JKW, & Haberl JS (1997, September) *New educational software for teaching the sunpath diagram and shading mask protractor*. Paper presented at the Building Simulation, Prague, Czech Republic.

Oke TR (1987). *Boundary layer climates*. New York: Methuen.

Olesen BW, & Brager GS (2004) A better way to predict comfort: The new ASHRAE standard 55-2004. *ASHRAE Journal* 46(8): 20-28.

Ossen DR, Ahmad MH, & Madros NH (2005, May) *Impact of solar shading geometry on building energy use in hot humid climates with special reference to Malaysia*. Paper presented at the SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, Subang Jaya, Malaysia.

Owen MS, & Kennedy HE (Eds.). (2009) *2009 ASHRAE handbook: Fundamentals (SI Edition).* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Perez YV, & Capeluto IG (2009) Climatic considerations in school building design in the hot–humid climate for reducing energy consumption. *Applied Energy* 86(3): 340-348.

Qingyan C (2009) Ventilation performance prediction for buildings: A method overview and recent applications. *Building and Environment* 44(4): 848-858.

Ramos G, & Ghisi E (2010) Analysis of daylight calculated using the EnergyPlus programme. *Renewable and Sustainable Energy Reviews* 14(7): 1948-1958.

Rashid M (no date) Housing at Uttara Model Town in Dhaka City. Retrived from http://www.lth.se/fileadmin/hdm/alumni/papers/hd2002/hd2002-01.pdf, October 2010.

Ratti C, Raydan D, & Steemers K (2003) Building form and environmental performance: Archetypes, analysis and an arid climate. *Energy and Buildings* 35: 49–59.

Selmi DP, & Kushner JA (2004) *Land use regulation: Cases and materials* (2nd ed.). New York: Aspen Publishers.

Seraj TM (2009) Housing problem and apartment development in Dhaka City. In S. U. Ahmed (Ed.), *Dhaka : Past Present Future*. Dhaka: The Asiatic Society of Bangladesh.

Shaviv E, Yezioro A, & Capeluto IG (2001) Thermal mass and night ventilation as passive cooling design strategy. *Renewable Energy* 24(3-4): 445-452.

So ATP, & Lu JWZ (2001) Natural ventilation design by computational fuid dynamics: a Feng-shui approach. *Architectural Science Review* 44(1): 61-69.

Sreshthaputra A (2003) *Building design and operation for improving thermal comfort in naturally ventilated buildings in a hot-humid climate.* Unpublished Dissertation, Texas A&M University, College Station.

Su Y, Riffat SB, Lin YL, & Khan N (2008) Experimental and CFD study of ventilation flow rate of a Monodraught™ windcatcher. *Energy and Buildings* 40(6): 1110-1116.

Sulivan R (1998) *Final report: Validation studies of the DOE-2 building energy simulation program*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Tabb P (1990) *The solar village archetype* Unpublished Dissertation, Architecture Association School of Architecture, London.

Tablada A, De TF, Blocken B, Carmeliet J, & Verschure H (2009) On natural ventilation and thermal comfort in compact urban environments – the Old Havana case. *Building and Environment* 44(9): 1943-1958.

Tsutsumi JI, Katayama T, Ishii A, He P, & Hayashi T (1996) Investigation and numerical simulation of the wind effects on thermal comfort in a house. *Journal of Wind Engineering and Industrial Aerodynamics* 60(0): 267-280.

Ubbelohde MS, & Loisos G (no date) The Ahmedabad Pol Hose: Courtyard strategies in a hot-dry/hot-humid climate. Retrived from www.coolshadow.com/images/research/Pol_House.pdf, July 2010.

U.S. Department of Energy, Energy Efficiency and Renewable Energy office (2010) *EnergyPlus Documentation: Input/Output Reference: The Encyclopedic Reference to EnergyPlus Input and Output*. Available from: http://apps1.eere.energy.gov/buildings/energyplus/pdfs/inputoutputreference.pdf, October 2009.

VanHooff T, & Blocken B (2010) Coupled urban wind flow and indoor natural ventilation modelling on a high-resolution grid: A case study for the Amsterdam ArenA stadium. *Environmental Modelling & Software* 25(1): 51-65.

Vickery BJ, & Karakatsanis C (1987) External pressure distributions and induced internal ventilation flow in low-rise industrial and domestic structures. *ASHRAE Transactions* 98(2): 2198-2213.

Wende W, Huelsmann W, Marty M, Penn-Bressel G, & Bobylev N (2010) Climate protection and compact urban structures in spatial planning and local construction plans in Germany. *Land Use Policy* 27(3): 864-868

Wong NH, & Chong AZM (2010) Performance evaluation of misting fans in hot and humid climate. *Building and Environment* 45(12): 2666-2678.

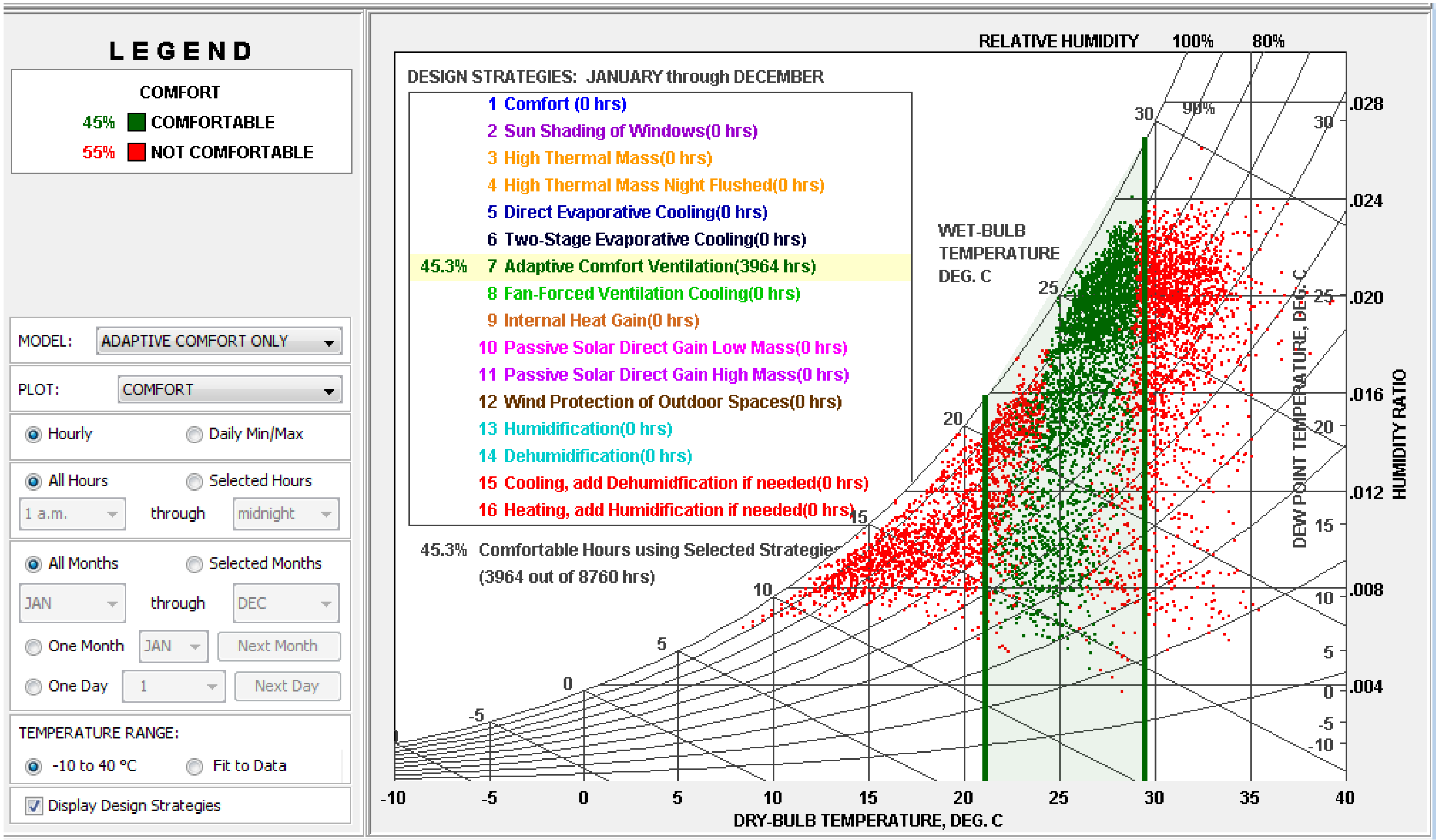
Wu YC, Yang AS, Tseng LY, & Liu CL (2011) Myth of ecological architecture designs: Comparison between design concept and computational analysis results of natural-ventilation for Tjibaou Cultural Center in New Caledonia. *Energy and Buildings* 43(10): 2788-2797.

Zhai Z, Hamilton SD, Huang J, Allocca C, Kobayashi N, & Chen Q (2000, September) *Integration of indoor and outdoor airflow study for natural ventilation design using CFD*. Paper presented at the 21st AIVC Annual Conference, “Innovations in Ventilation Technology”, The Hague, Netherlands.

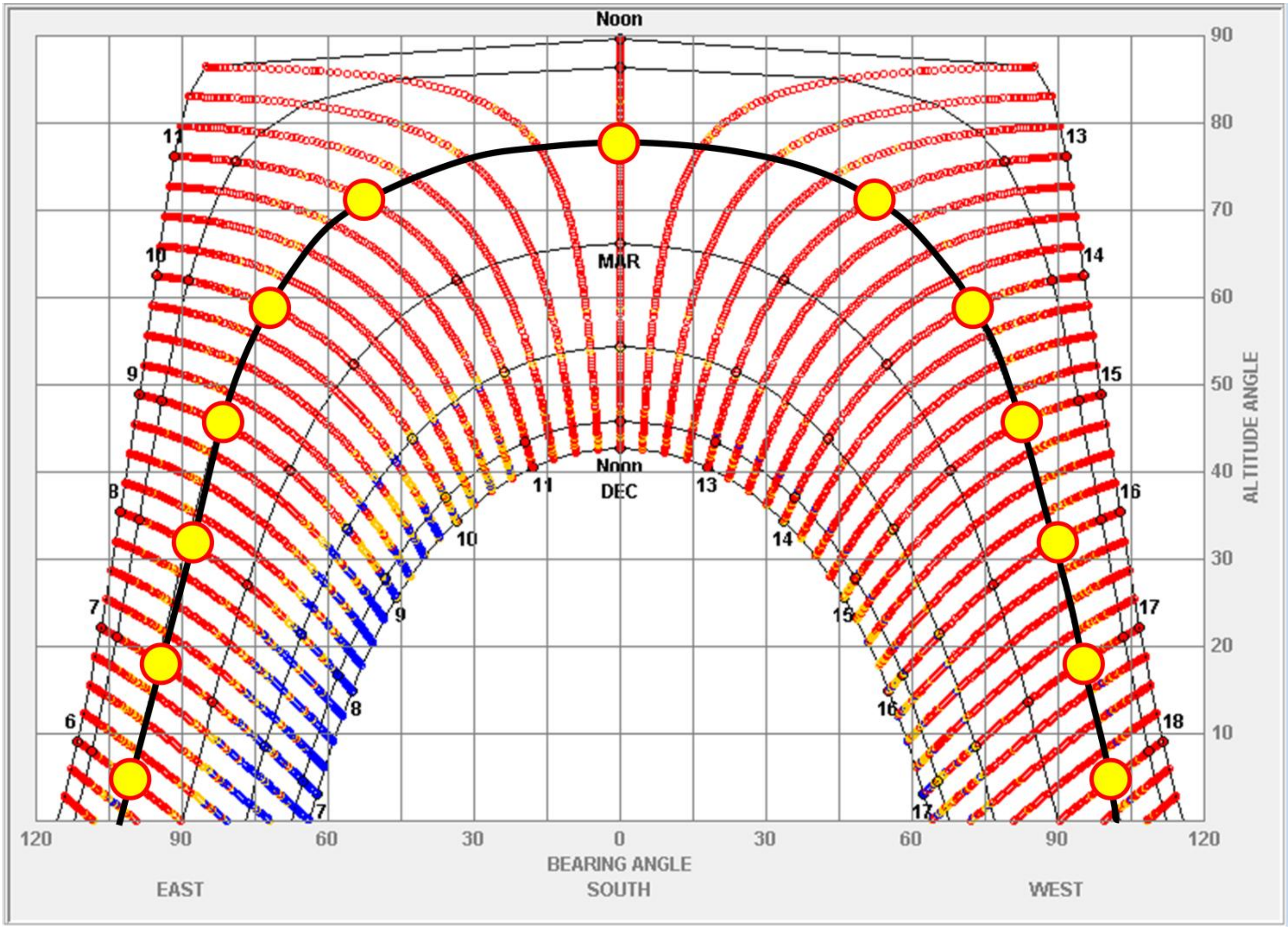
APPENDIX A

DETAILS ABOUT THE WEATHER INFORMATION FOR THE SIMULATIONS

Psychometric chart in terms of Dhaka's climatic conditions, using adaptive thermal comfort of ASHRAE-55-2004:



Sun-path diagram for Dhaka city:



Dhaka's weather information for April 5:

HH:MM	Dry Bulb Temperature {C}	Dew Point Temperature {C}	Relative Humidity {%}	Atmospheric Pressure {Pa}	Extraterrestrial Horizontal Radiation {Wh/m2}	Extraterrestrial Direct Normal Radiation {Wh/m2}	Horizontal Infrared Radiation Intensity from Sky {Wh/m2}	Global Horizontal Radiation {Wh/m2}
1:00	29.1	25	79	101200	0	0	404	0
2:00	28.6	24.8	80	101200	0	0	401	0
3:00	28	24.6	82	101200	0	0	398	0
4:00	27.5	24.4	83	101200	0	0	395	0
5:00	26.9	24.2	85	101200	0	0	391	0
6:00	26.4	24	87	100300	5	200	389	1
7:00	27.9	24	79	100300	212	1366	396	69
8:00	29.5	24	72	100300	525	1366	413	252
9:00	31	24	66	100300	807	1366	421	493
10:00	32.6	24	61	100300	1038	1366	430	684
11:00	34.1	24	56	100300	1202	1366	430	844
12:00	35.7	24	51	100300	1288	1366	439	908

Dhaka's weather information for April 5 (continued):

HH:MM	Dry Bulb Temperature {C}	Dew Point Temperature {C}	Relative Humidity {%}	Atmospheric Pressure {Pa}	Extraterrestrial Horizontal Radiation {Wh/m2}	Extraterrestrial Direct Normal Radiation {Wh/m2}	Horizontal Infrared Radiation Intensity from Sky {Wh/m2}	Global Horizontal Radiation {Wh/m2}
13:00	36.4	23.7	48	100200	1290	1366	443	924
14:00	37.2	23.3	45	100200	1208	1366	455	814
15:00	37.9	23	43	100200	1048	1366	459	689
16:00	36.3	23.7	48	100200	820	1366	451	483
17:00	34.6	24.3	55	100200	540	1366	442	260
18:00	33	25	63	100100	229	1366	433	75
19:00	32.1	25	66	100200	8	271	434	1
20:00	31.3	25	69	100200	0	0	434	0
21:00	30.4	25	73	100300	0	0	432	0
22:00	29.6	25	76	100300	0	0	431	0
23:00	28.7	25	80	100400	0	0	430	0
24:00:00	27.9	25	84	100400	0	0	437	0

Dhaka's weather information for April 5 (continued):

HH:MM	Direct Normal Radiation {Wh/m2}	Diffuse Horizontal Radiation {Wh/m2}	Global Horizontal Illuminance {lux}	Direct Normal Illuminance {lux}	Diffuse Horizontal Illuminance {lux}	Zenith Luminance {Cd/m2}	Wind Direction {deg}	Wind Speed {m/s}
1:00	0	0	0	0	0	0	180	3.6
2:00	0	0	0	0	0	0	180	3.4
3:00	0	0	0	0	0	0	180	3.2
4:00	0	0	0	0	0	0	180	3
5:00	0	0	0	0	0	0	180	2.8
6:00	0	1	0	0	0	0	180	2.6
7:00	48	61	7800	2800	7300	1450	180	3.3
8:00	267	149	27500	18300	20500	3100	180	3.9
9:00	453	226	54200	37300	32200	5330	180	4.6
10:00	531	280	76100	44700	42100	9020	180	3.9
11:00	599	317	94900	50800	50300	15440	180	3.3
12:00	609	334	102700	51700	54000	23370	180	2.6

Dhaka's weather information for April 5 (continued):

HH:MM	Direct Normal Radiation {Wh/m2}	Diffuse Horizontal Radiation {Wh/m2}	Global Horizontal Illuminance {lux}	Direct Normal Illuminance {lux}	Diffuse Horizontal Illuminance {lux}	Zenith Luminance {Cd/m2}	Wind Direction {deg}	Wind Speed {m/s}
13:00	624	334	104400	53200	54100	23640	180	2.1
14:00	564	314	91400	48300	48600	15610	180	1.5
15:00	531	281	76500	45500	41600	9230	180	1
16:00	422	230	53000	35000	32000	5500	180	1.5
17:00	270	153	28400	18600	21100	3200	180	2.1
18:00	55	66	8500	3200	8000	1580	180	2.6
19:00	0	1	0	0	0	0	180	2.6
20:00	0	0	0	0	0	0	180	2.6
21:00	0	0	0	0	0	0	180	2.6
22:00	0	0	0	0	0	0	180	2.6
23:00	0	0	0	0	0	0	180	2.6
24:00:00	0	0	0	0	0	0	180	2.6

Dhaka's weather information for April 5 (continued):

HH:MM	Total Sky Cover {.1}	Opaque Sky Cover {.1}	Visibility {km}	Ceiling Height {m}	Present Weather Observation	Present Weather Codes	Precipitable Water {mm}	Aerosol Optical Depth {.001}
1:00	0	0	4	77777	9	'999999999	52	0.042
2:00	0	0	4	77777	9	'999999999	52	0.042
3:00	0	0	4	77777	9	'999999999	51	0.042
4:00	0	0	4	77777	9	'999999999	50	0.042
5:00	0	0	4	77777	9	'999999999	50	0.042
6:00	0	0	4	77777	0	'999999919	49	0.042
7:00	0	0	4	77777	9	'999999999	49	0.042
8:00	0	0	4	77777	9	'999999999	49	0.042
9:00	0	0	4	77777	0	'999999919	49	0.042
10:00	0	0	4	77777	9	'999999999	49	0.042
11:00	0	0	4	77777	9	'999999999	49	0.042
12:00	0	0	4	77777	0	'999999919	49	0.042

Dhaka's weather information for April 5 (continued):

HH:MM	Total Sky Cover {.1}	Opaque Sky Cover {.1}	Visibility {km}	Ceiling Height {m}	Present Weather Observation	Present Weather Codes	Precipitable Water {mm}	Aerosol Optical Depth {.001}
13:00	0	0	4	77777	9	'999999999	48	0.042
14:00	0	0	4	77777	9	'999999999	47	0.042
15:00	0	0	4	77777	0	'999999919	46	0.042
16:00	0	0	4	77777	9	'999999999	48	0.042
17:00	0	0	4	77777	9	'999999999	50	0.042
18:00	0	0	4	77777	0	'999999919	52	0.042
19:00	0	0	4	77777	9	'999999999	52	0.042
20:00	0	0	4	77777	9	'999999999	52	0.042
21:00	0	0	4	77777	9	'999999999	52	0.042
22:00	0	0	4	77777	9	'999999999	52	0.042
23:00	0	0	4	77777	9	'999999999	52	0.042
24:00:00	0	0	4	240	0	'999999919	52	0.042

Dhaka's weather information for April 5 (continued):

HH:MM	Snow Depth {cm}	Days Since Last Snow	Albedo {.01}	Liquid Precipitation Depth {mm}	Liquid Precipitation Quantity {hr}
1:00	899	9	0.1	0	1
2:00	899	9	0.1	0	1
3:00	899	9	0.1	0	1
4:00	899	9	0.1	0	1
5:00	899	9	0.1	0	1
6:00	899	9	0.1	0	1
7:00	899	9	0.1	0	1
8:00	899	9	0.1	0	1
9:00	899	9	0.1	0	1
10:00	899	9	0.1	0	1
11:00	899	9	0.1	0	1
12:00	899	9	0.1	0	1

Dhaka's weather information for April 5 (continued):

HH:MM	Snow Depth {cm}	Days Since Last Snow	Albedo {.01}	Liquid Precipitation Depth {mm}	Liquid Precipitation Quantity {hr}
13:00	899	9	0.1	0	1
14:00	899	9	0.1	0	1
15:00	899	9	0.1	0	1
16:00	899	9	0.1	0	1
17:00	899	9	0.1	0	1
18:00	899	9	0.1	0	1
19:00	899	9	0.1	0	1
20:00	899	9	0.1	0	1
21:00	899	9	0.1	0	1
22:00	899	9	0.1	0	1
23:00	899	9	0.1	0	1
24:00:00	899	9	0.1	0	1

APPENDIX B

DETAILS ABOUT THE MODEL FOR ENERGYPLUS SIMULATION

Building:

Field	Units	Obj1
Name		Untitled
North Axis	deg	0
Terrain		City
Loads Convergence Tolerance Value		0.04
Temperature Convergence Tolerance Value	deltaC	0.4
Solar Distribution		FullInteriorAndExteriorWithReflections
Maximum Number of Warmup Days		25

Run Period:

Field	Units	Obj1
Name		
Begin Month		4
Begin Day of Month		5
End Month		4
End Day of Month		5
Day of Week for Start Day		UseWeatherFile
Use Weather File Holidays and Special Days		Yes
Use Weather File Daylight Saving Period		Yes
Apply Weekend Holiday Rule		No
Use Weather File Rain Indicators		Yes
Use Weather File Snow Indicators		Yes
Number of Times Runperiod to be Repeated		

Run period control- special days:

Field	Units	Obj1
Name		April 5
Start Date		04/05
Duration	days	1
Special Day Type		SummerDesignDay

Different schedules:

Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	Obj7
Clothing Sch	Air Velo Sch	WindowVentSched	Work Efficiency Sch	INTERMITTENT-1 BedRm Equipment	INTERMITTENT-2 LivingRm Equipment	Activity Schedule MasterBed
Any Number	Any Number	Fraction	Any Number	Fraction	Fraction	Any Number
Through: 01/31	Through: 12/31	Through: 02/28	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31
For: AllDays	For: AllDays	For: AllDays	For: ALlDays	For: Sunday Monday Tuesday wednesday Thursday	For: Sunday Monday Tuesday wednesday Thursday	For: Sunday Monday Tuesday Wednesday Thursday
Until: 24:00	Until: 24:00	Until: 24:00	Until: 24:00	Until: 17:00	Until: 11:00	Until: 7:00
0.66	0.137	0	0.08	0	0	77
Through: 02/28		Through: 10/30		Until: 23:00	Until: 14:00	Until: 9:00
For: AllDays		For: AllDays		1	1	180
Until: 24:00		Until:24:00		Until: 24:00	Until: 17:00	Until: 15:00
0.52		1		0	0	0
Through: 10/31		Through: 12/31		For: AllOtherDays	Until: 23:00	Until: 18:00
For: AllDays		For: AllDays		Until: 10:00	1	77
Until: 24:00		Until: 24:00		0	Until: 24:00	Until: 23:00
0.316		0		Until: 13:00	0	108
Through: 11/30				1	For: AllOtherDays	Until: 24:00
For: AllDays				Until: 17:00	Until: 10:00	77
Until: 24:00				0	0	For: AllOtherDays
0.52				Until: 24:00	Until: 14:00	Until:10:00
Through: 12/31				1	1	77
For: AllDays					Until: 17:00	Until: 11:00
Until: 24:00					0	180
0.66					Until: 24:00	Until: 14:00
					1	0
						Until: 17:00
						77
						Until: 24:00
						0

Different schedules (continued):

Obj8	Obj9	Obj10	Obj11	Obj12	Obj13	Obj14
Activity Schedule ChildBed	Activity Schedule Livingroom	Individual Apartment LIGHTING	Individual Apartment Living OCCUPANCY	Individual Apartment Mbed OCCUPANCY	Individual Apartment Cbed OCCUPANCY	Shading Transmittance Schedule
Any Number	Any Number	Fraction	Fraction	Fraction	Fraction	Fraction
Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31
For: Sunday Monday Tuesday Wednesday Thursday	For: Sunday Monday Tuesday Wednesday Thursday	For: WeekDays	For: WeekDays	For: WeekDays	For: WeekDays	For: WeekDays
Until: 7:00	Until: 11:00	Until: 6:00	Until: 11:00	Until: 9:00	Until: 9:00	Until: 24:00
77	0	0	0	1	1	0
Until: 9:00	Until: 14:00	Until: 7:00	Until: 14:00	Until: 15:00	Until: 15:00	
180	108	0.5	0.25	0	0	
Until: 15:00	Until: 17:00	Until: 17:00	Until: 17:00	Until: 18:00	Until: 17:00	
0	0	0	0	0.5	1	
Until: 17:00	Until: 23:00	Until: 19:00	Until: 23:00	Until: 23:00	Until: 19:00	
77	108	0.5	0.5	0.5	0	
Until: 19:00	Until: 24:00	Until: 24:00	Until: 24:00	Until: 24:00	Until: 24:00	
0	0	1	0	1	1	
Until: 24:00	For: AllOtherDays	For: AllOtherDays	For: AllOtherDays	For: AllOtherDays	For: AllOtherDays	
99	Until: 10:00	Until: 2:00	Until: 10:00	Until: 11:00	Until: 11:00	
For: AllOtherDays	0	0.5	0	1	1	
Until:10:00	Until:14:00	Until: 17:00	Until: 14:00	Until: 14:00	Until: 14:00	
77	108	0	1	0	0	
Until: 11:00	Until: 17:00	Until: 19:00	Until: 17:00	Until: 17:00	Until: 17:00	
180	0	0.5	0.25	1	1	
Until: 14:00	Until: 24:00	Until: 24:00	Until: 24:00	Until: 24:00	Until: 24:00	
0	108	1	1	0	0	
Until: 17:00						
77						
Until: 24:00						
0						

Material selected for the model to be simulated:

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6
Name		C4 - 4 IN COMMON BRICK	A1 - 1 IN STUCCO	C10 - 6 IN HW CONCRETE	F18 Terrazzo	ASHRAE 90.1-2004_Sec 5.5-2_Roof Insulation_1	1.375in-Solid-Core
Roughness		Rough	Smooth	MediumRough	Rough	MediumRough	Smooth
Thickness	m	0.1014984	0.025389841	0.152704797	0.0254	0.125	0.034925
Conductivity	W/m-K	0.7264224	0.6918309	1.729577	1.8	0.049	0.1525
Density	kg/m3	1922.216	1858.142	2242.585	2560	265	614.5
Specific Heat	J/kg-K	836.8	836.8	836.8	790	836.8	1630
Thermal Absorptance		0.9	0.9	0.9		0.9	0.9
Solar Absorptance		0.76	0.92	0.65		0.7	0.92
Visible Absorptance		0.76	0.92	0.65		0.7	0.92

Window material selected for the model to be simulated:

Field	Units	Obj1
Name		CLEAR 6MM
Optical Data Type		SpectralAverage
Window Glass Spectral Data Set Name		
Thickness	m	0.006
Solar Transmittance at Normal Incidence		0.775
Front Side Solar Reflectance at Normal Incidence		0.071
Back Side Solar Reflectance at Normal Incidence		0.071
Visible Transmittance at Normal Incidence		0.881
Front Side Visible Reflectance at Normal Incidence		0.08
Back Side Visible Reflectance at Normal Incidence		0.08
Infrared Transmittance at Normal Incidence		0
Front Side Infrared Hemispherical Emissivity		0.84
Back Side Infrared Hemispherical Emissivity		0.84
Conductivity	W/m-K	0.9
Dirt Correction Factor for Solar and Visible Transmittance		
Solar Diffusing		

Construction features selected for the model to be simulated:

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6
Name		Interior Floor	Exterior Wall	Interior Wall	Exterior Roof	Interior Door	Exterior Window
Outside Layer		F18 Terrazzo	A1 - 1 IN STUCCO	A1 - 1 IN STUCCO	ASHRAE 90.1-2004_Sec 5.5-2_Roof Insulation_1	1.375in-Solid-Core	CLEAR 6MM
Layer 2		C10 - 6 IN HW CONCRETE	C4 - 4 IN COMMON BRICK	C4 - 4 IN COMMON BRICK	C10 - 6 IN HW CONCRETE		
Layer 3		A1 - 1 IN STUCCO	C4 - 4 IN COMMON BRICK	A1 - 1 IN STUCCO	A1 - 1 IN STUCCO		
Layer 4			A1 - 1 IN STUCCO				
Layer 5							
Layer 6							
Layer 7							
Layer 8							
Layer 9							
Layer 10							

Occupant related information for the EnergyPlus model:

Field	Units	Obj1	Obj2	Obj3	Obj4
Name		MB-people	GB-people	DL-people	CB-people
Zone or ZoneList Name		MB	GB	Living-dining	CB
Number of People Schedule Name		Individual Apartment Mbed OCCUPANCY	Individual Apartment Cbed OCCUPANCY	Individual Apartment Living OCCUPANCY	Individual Apartment Cbed OCCUPANCY
Number of People Calculation Method		People	People	People	People
Number of People		2	1	4	1
People per Zone Floor Area	person/m2				
Zone Floor Area per Person	m2/person				
Fraction Radiant		0.33	0.33	0.33	0.33
Sensible Heat Fraction		autocalculate	autocalculate	autocalculate	autocalculate
Activity Level Schedule Name		Activity Schedule MasterBed	Activity Schedule ChildBed	Activity Schedule Livingroom	Activity Schedule ChildBed
Carbon Dioxide Generation Rate	m3/s-W	0.0000000382	0.0000000382	0.0000000382	0.0000000382
Enable ASHRAE 55 Comfort Warnings		No	No	No	No
Mean Radiant Temperature Calculation Type		ZoneAveraged	ZoneAveraged	ZoneAveraged	ZoneAveraged
Surface Name/Angle Factor List Name					
Work Efficiency Schedule Name		Work Efficiency Sch	Work Efficiency Sch	Work Efficiency Sch	Work Efficiency Sch
Clothing Insulation Schedule Name		Clothing Sch	Clothing Sch	Clothing Sch	Clothing Sch
Air Velocity Schedule Name		Air Velo Sch	Air Velo Sch	Air Velo Sch	Air Velo Sch
Thermal Comfort Model 1 Type		Fanger	Fanger	Fanger	Fanger
Thermal Comfort Model 2 Type					
Thermal Comfort Model 3 Type					

Electrical lighting related information for the EnergyPlus model:

Field	Units	Obj1	Obj2	Obj3	Obj4
Name		MB-light	GB-light	DL-light	CB-light
Zone or ZoneList Name		MB	GB	Living-dining	CB
Schedule Name		Individual Apartment LIGHTING	Individual Apartment LIGHTING	Individual Apartment LIGHTING	Individual Apartment LIGHTING
Design Level Calculation Method		LightingLevel	LightingLevel	LightingLevel	LightingLevel
Lighting Level	W	120	120	360	120
Watts per Zone Floor Area	W/m2				
Watts per Person	W/person				
Return Air Fraction		0	0	0	0
Fraction Radiant		0.72	0.72	0.72	0.72
Fraction Visible		0.18	0.18	0.18	0.18
Fraction Replaceable		1	1	1	1
End-Use Subcategory		General	General	General	General
Return Air Fraction Calculated from Plenum Temperature		No	No	No	No
Return Air Fraction Function of Plenum Temperature Coefficient 1					
Return Air Fraction Function of Plenum Temperature Coefficient 2	1/K				

Electrical equipment related information for the EnergyPlus model:

Field	Units	Obj1	Obj2	Obj3	Obj4
Name		MB-ElecEquip	GB-ElecEquip	DL-ElecEquip	CB-ElecEquip
Zone or ZoneList Name		MB	GB	Living-dining	CB
Schedule Name		INTERMITTENT-1 BedRm Equipment	INTERMITTENT-1 BedRm Equipment	INTERMITTENT-2 LivingRm Equipment	INTERMITTENT-1 BedRm Equipment
Design Level Calculation Method		EquipmentLevel	EquipmentLevel	EquipmentLevel	EquipmentLevel
Design Level	W	250	350	700	350
Watts per Zone Floor Area	W/m2				
Watts per Person	W/person				
Fraction Latent		0	0	0	0
Fraction Radiant		0.3	0.3	0.3	0.3
Fraction Lost		0	0	0	0
End-Use Subcategory		Computer	Computer and Music system	Entertainment station	Computer and Music system

AirflowNetwork Simulation control:

Field	Units	Obj1
Name		NaturalVentilation-2A
AirflowNetwork Control		MultizoneWithoutDistribution
Wind Pressure Coefficient Type		Input
AirflowNetwork Wind Pressure Coefficient Array Name		0 Degrees
Height Selection for Local Wind Speed Calculation		ExternalNode
Building Type		LowRise
Maximum Number of Iterations	dimensionless	500
Initialization Type		ZeroNodePressures
Relative Airflow Convergence Tolerance	dimensionless	0.0001
Absolute Airflow Convergence Tolerance	kg/s	0.000001
Convergence Acceleration Limit	dimensionless	-0.5
Azimuth Angle of Long Axis of Building	deg	0
Ratio of Building Width Along Short Axis to Width Along Long Axis		0.865

Details about window opening:

Field	Units	Obj1
Name		WiOpen1
Air Mass Flow Coefficient When Opening is Closed	kg/s-m	0.001
Air Mass Flow Exponent When Opening is Closed	dimensionless	0.667
Type of Rectanguler Large Vertical Opening (LVO)		NonPivoted
Extra Crack Length or Height of Pivoting Axis	m	0
Number of Sets of Opening Factor Data		2
Opening Factor 1	dimensionless	0
Discharge Coefficient for Opening Factor 1	dimensionless	0.5
Width Factor for Opening Factor 1	dimensionless	0
Height Factor for Opening Factor 1	dimensionless	1
Start Height Factor for Opening Factor 1	dimensionless	0
Opening Factor 2	dimensionless	1
Discharge Coefficient for Opening Factor 2	dimensionless	0.6
Width Factor for Opening Factor 2	dimensionless	1
Height Factor for Opening Factor 2	dimensionless	1
Start Height Factor for Opening Factor 2	dimensionless	0
Opening Factor 3	dimensionless	0

VITA

Saiful Islam received his Bachelors of Architecture degree in Architecture from Ahsanullah University of Science and Technology, Dhaka, Bangladesh in September 2000. He received his Master of Architecture degree in Architecture from the University of Texas at San Antonio, San Antonio, TX in December 2005. After that, he joined the Department of Architecture at Texas A&M University in August 2006 and received his Doctor of Philosophy degree in December 2011. His research interest includes natural ventilation, energy efficient building design in humid tropics, relationship between zoning regulations and thermal comfort.

He can be reached at the following address:

College of Architecture
3137 TAMU
Langford Bldg. A, Room 122
College Station, TX 77843-3137
Email: saif1509@neo.tamu.edu