



KTH Architecture and
the Built Environment

Passive Design Features for Energy-Efficient Residential Buildings in Tropical Climates: the context of Dhaka, Bangladesh

Tahmina Ahsan

Stockholm 2009

KTH, Department of Urban Planning and Environment
Division of Environmental Strategies Research - fms

Kungliga Tekniska högskolan

ABSTRACT

This study aimed at identifying passive design features through extensive literature study that can be incorporated in residential buildings to make them energy efficient. The study also aimed at identifying changes in the design process that can affect energy efficiency in residential buildings. It has analyzed the design features of typical residential buildings representative of upper middle income households in Dhaka through a case study conducted in Dhaka. It also analyzed the present electric energy use for cooling and lighting typical residential buildings of upper middle income households in Dhaka and the possible energy savings by adopting certain energy efficient features in the case study building. It also distinguishes the different roles of developers, architects, interior designers, land owners (clients) and residents that can act as a barrier in achieving energy efficiency in residential buildings.

The findings from this study indicate that doubling the thickness of external walls on east and west, use of hollow clay tiles instead of weathering course for roofs and use of appropriate horizontal overhang ratios for all four orientations can reduce the cooling load of the case study building by 64% and hence reduce the total energy use of the building by 26%. Finally it can be concluded that the process of designing energy efficient residential buildings is not a 'one-man's show'. Architects, developers, interior designers and clients are the other actors who can bring a change in the design practice.

Keywords: *Energy- efficient; passive design features; residential building; tropical climate*

ACKNOWLEDGEMENT

First and foremost, I would like to thank and express my sincere gratitude to my supervisor Örjan Svane, Research Leader and Associate Professor at Environmental Strategies Research Group- fms, KTH- Royal Institute of Technology. Without his help, suggestions and constructive criticism, I would not have been able to come this far. I am indebted to him for his patience and continuous support throughout the period of this study. I would also like to thank him for he moral support and encouragements at the final stage of this study.

I am grateful to the Swedish Institute for granting me the MKP scholarship (Master of Key personnel in Developing Countries). Without this scholarship it would have been utterly impossible to live in Sweden for two years.

I would like to express my heartfelt thanks to Ms. Sofia Norlander, Master's Programme Coordinator and Mr. Peter Brokking, Programme Coordinator for EESI for always being there to help in all sorts of administrative work. I would also like to express my gratitude to Dr. Tigran Haas, UPD Program Director for his inspiration and encouraging words.

I would like to thank my friend Sarah Bashneen for helping me during the survey of the case study building in Dhaka. She not only introduced me to the flat owners and tenant in the case study building, but also offered her assistance while I made notes, interviewed the households and took photographs. Without her help, I would have never been able to have access to the case study building. Thanks also go out to my friends Mohammad Moniruzzaman and Sonya Afrin for helping me out in Dhaka and sending me some documents and cost estimates.

I would also like to thank Professor Qazi Azizul Mowla in BUET, Dhaka for giving me his thesis and Professor Mohammad Ali Naqi, Head of the Department of Architecture, Stamford University Dhaka for encouraging me to earn a Master's Degree.

My friends Atiq Uz Zaman, Himanshu Sanghani and Kedar Uttam in Stockholm have provided assistance in numerous ways. They have given me constrictive criticism and valuable suggestions to help me improve my thesis. My uncle Svein Erik Maubach has helped me by meticulously by proof reading all the drafts.

I am thankful to my students Al Imran, Dipu, Kamal Hosain, Maumita Saha, Mudassir Hossain, Nazmuch Sakib, Shahabuddin Mahmud and Sharmin Aktar in the Department of Architecture at Stamford University Dhaka. They have painstakingly gone through the trouble of taking photographs and sending them to me amidst their studies.

I am grateful to my husband for his support, criticism and endurance all the way. Last, but not the least, I would especially like to thank my parents, sister and brother who have always prayed for me and without their support I would not have accomplished anything.

TABLE OF CONTENTS

ABSTRACT.....	ii
ACKNOWLEDGEMENT	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES.....	vii
LIST OF TABLES	x
ACRONYMS	xi
1 INTRODUCTION.....	1
1.1 Problem formulation	1
1.1.1 General problem	1
1.1.2 Specific problem	1
1.1.3 Research problem	2
1.2 Aims	3
1.3 Significance and limitations	4
1.3.1 Expected contribution from this study.....	4
1.3.2 Scope and Limitations of the research.....	5
2 CONTEXT- SITUATIONAL SETTING OF PROBLEMS IN DHAKA.....	6
2.1 Dhaka's energy situation	6
2.2 Climate of Dhaka	6
2.3 Residential buildings and energy efficiency	9
3 THEORETICAL FRAMEWORK.....	11
3.1 Energy efficient residential buildings	11
3.2 Basic principles in energy efficient building design.....	11
3.3 Planning aspects	11
3.3.1 Site analysis	11
3.3.2 Building form.....	12
3.3.3 Building orientation	12
3.3.4 Room orientation and arrangement	13
3.3.5 Landscaping	15
3.4 Building Envelope.....	16
3.4.1 External wall.....	16
3.4.2 Thermal insulation	17
3.4.3 Building material	18

3.4.4	Roof	18
3.4.5	. Windows	22
4	METHODOLOGY.....	35
4.1	Research Methodology	35
4.2	Case study methodology	35
4.2.1	Research design	35
4.2.2	Selection of case study	36
4.2.3	Issues investigated/ units of analysis	36
4.2.4	Data gathering strategies	37
4.2.5	Evaluation and analysis of the data	37
4.2.6	Validation of results.....	37
4.2.7	Generalization	38
5	RESULTS: CASE STUDY FINDINGS AND DATA ANALYSIS.....	39
5.1	An overview of the case study building	39
5.2	Design features of the case study building	41
5.2.1	Planning aspects of the case study building	41
5.2.2	Building envelope.....	54
5.2.3	Aspects provided by the developer	63
5.3	Energy usage of the case study flats	63
5.3.1	Total energy usage	63
5.3.2	Energy usage for cooling	65
5.3.3	Energy usage for lighting	68
6	DISCUSSION	72
6.1	Energy efficient design features	72
6.2	Energy use of the flats in the case study on adoption of the energy efficient features .	73
6.3	Barriers in adopting energy efficiency in residential buildings.....	74
6.3.1	Barriers related to designing energy efficient buildings.....	74
6.3.2	Recommendations for overcoming barriers	77
7	CONCLUSION AND RECOMMENDATION.....	78
	APPENDICES	80
	Appendix 1. Benefits of green roofs	80
	Appendix 2. Total energy use of all the flats	81
2.1.	Total energy use of Unit A2	81
2.2.	Total energy use of Unit A3	81

2.3.	Total energy use of Unit B2.....	82
2.4.	Total energy use of Unit B4.....	83
2.5.	Total energy use of Unit B5.....	83
2.6.	Total energy use of Unit C1.....	84
2.7.	Total energy use of Unit C5.....	85
	Appendix 3. Number of lights in all the Units of the case study	86
	building.....	86
3.1.	Number of lights in each room of Unit A2	86
3.2.	Number of lights in each room of Unit A3	86
3.3.	Number of lights in each room of Unit B2.....	87
3.4.	Number of lights in each room of Unit B4.....	87
3.5.	Number of lights in each room of Unit B5.....	88
3.6.	Number of lights in each room of Unit C1.....	88
3.7.	Number of lights in each room of Unit C5.....	89
	REFERENCES.....	90

LIST OF FIGURES

Fig. 1. Location of Dhaka, Bangladesh.....	7
Fig. 2. Seasonal wind direction at Dhaka based on wind speed data.	8
Fig. 3. Duration of solar radiation received on the facade.....	14
Fig. 4. External wall construction.....	17
Fig. 5. Secondary roof system construction.	21
Fig. 6. Roof structures under investigation (uniform width of 75 mm) (material: 1-RCC, 2-WC, 3-HCT, 4-air).....	22
Fig. 7. Overhang design	25
Fig. 8. (Left) Residential building model with a void ratio of 0% (with six apartments)	27
Fig. 9. (Right) Residential building model with a void ratio of 50 % (with six apartments).....	27
Fig. 10. Standard cube components of a residential building model.....	28
Fig. 11. Particle flowing out through the lower opening (indicated by motion blurs).	29
Fig. 12. Orientation of openings.....	30
Fig. 13. Deflection by projecting slabs.....	31
Fig. 14. Louvered door.....	31
Fig. 15. Benefit of jalousie window: unrestricted openness in open position.....	32
Fig. 16. Benefit of jalousie window: restrict rain penetration.....	32
Fig. 17. Benefit of roof overhang	32
Fig. 18. Wing wall outside window.....	33
Fig. 19. Air-damming action of parapet	33
Fig. 20. Location of the case study building in Lalmatia, Dhaka	39
Fig. 21. The Case Study Building.....	40
Fig. 22. Location of different units in the case study apartment	41
Fig. 23. Site plan of the case study building	42
Fig. 24. Two fifty feet width roads flanked on the western and southern side of the case study building.....	42
Figs. 25 and 26. The case study building and the building next to it on the eastern side	43
Figs. 27 and 28. Case study building and the building next o it on the northern side.....	43
Figs. 29 and 30. Narrow space between the case study building and the building next to it on the east.....	43

Fig. 31 and 32. Compactness of the case study building.....	44
Fig. 33. Typical floor plan showing the longer axis oriented towards the north-south direction.	45
Fig. 34. Dining space of Unit C5.....	47
Fig. 35. TV in living room of Unit A3.....	47
Fig. 36. TV in living room of Unit A2.....	47
Fig. 37. TV in dining space of Unit B4.....	48
Fig. 38. TV in masterbed of Unit B5	48
Figs. 39 and 40. Change in plans of unit A3 (left) and A2 (right).....	48
Fig. 41. Floor plan of Unit B4.....	49
Fig. 42. Floor plan of Unit B5.....	49
Fig. 43. Two layers of curtain and A.C in master bed (located on west) of Unit B2.....	51
Fig. 44. Two layers of curtain in living room of Unit B4	51
Fig. 45. Two layers of curtain in living room of Unit B5	51
Fig. 46. Bed sheet behind curtain in master bedroom of Unit B5.....	52
Fig. 47. Bed sheet behind curtain in study of Unit B5	52
Fig. 48. A.C in master bedroom of Unit B5	52
Fig. 49. A.C in living room of Unit B5.....	52
Fig. 50. A.C in living room of Unit B4.....	52
Fig. 51. Potted plants inside the boundary wall.....	53
Fig. 52. Potted plants on the roof.....	53
Figs. 53 and 54. Plants outside the boundary wall	53
Fig. 55. Facing brick on front facade	54
Fig. 56. Community room on roof.....	55
Fig. 57. Clothes hung on roof	55
Figs. 58 and 59. Details of sliding window (50% openable with grill and insect net)	56
Fig. 60. Windows on west facade	58
Fig. 61. Big windows from skirting to lintel on the west facade.....	58
Fig. 62. Bedroom on east side of Unit A3.....	59
Fig. 63. Living room on east side of Unit A3	59
Fig. 64. Living room on east side of Unit C1	59
Fig. 65. Bedroom on east side of Unit C1.....	59
Fig. 66. Living room on east side of Unit C5	60

Fig. 67. Bedroom on east side of Unit C5.....	60
Fig. 68. Two windows in master bed of Unit C5.....	60
Fig. 69. Two windows in master bed of Unit C1.....	60
Fig. 70. Two windows in master bed of Unit C5.....	60
Figs. 71 and 72. Central light well.....	61
Fig. 73. Four out of six lights indicated by arrows in the dining space of Unit B4	70
Fig. 74. Spot lights to highlight a mural in the foyer space of Unit A3	70

LIST OF TABLES

Table 1. Income groups in Dhaka City Corporation.....	3
Table 2. Climate chart of Dhaka for 2003.....	8
Table 3. Under-heated, comfortable and over-heated periods in Dhaka	9
Table 4. Description of Tested Cases for Independent Variable	25
Table 5. Occupancy pattern	46
Table 6. Orientation of rooms in all flat types (A, B and C)	50
Table 7. Window to floor area ratio (WFR) and window to wall area ratio (WWR) of rooms in Flat type A.....	56
Table 8. Window to floor area ratio (WFR) and window to wall area ratio of rooms (WWR) in Flat type B.....	57
Table 9. Window to floor area ratio (WFR) and window to wall area ratio (WWR) of rooms in Unit type C.....	57
Table 10. Shading device analysis of Flat Type A using the method developed by Oseen <i>et al.</i> (2006).....	62
Table 11. Shading device analysis of Flat Type B using the method developed by Oseen <i>et al.</i> (2006).....	62
Table 12. Shading device analysis of Flat Type C using the method developed by Oseen <i>et al.</i> (2006).....	62
Table 13. Appliances used by the different households.....	64
Table 14. Monthly total energy use	65
Table 15. Break-up of monthly total energy use	65
Table 16. Energy used for cooling	66
Table 17. Energy use of air conditioners based on their capacity, type, usage and power rating. 66	
Table 18. A.C usage pattern	67
Table 19. Different types of lights and energy used for lighting.....	68
Table 20. Energy use of lights based on their type, usage and power rating	69
Table 21. Energy efficient design features	72
Table 22. Reduced energy use of the flats.....	73

ACRONYMS

AC	Air Conditioner
BBS	Bangladesh Bureau of Statistics
CFD	Computational Fluid Dynamics
CFL	Compact Fluorescent Light
DSF	Double Skin Facade
GHG	Green House Gas
GW	Giga Watt
GWh	Giga Watt Hour
HCT	Hollow Clay Tiles
HVAC	Heating Ventilation and Air Conditioning
MW	Mega Watt
OHR	Overhang Ratio
PPD	Percentage People Dissatisfied
RCC	Reinforced Cement Concrete
SBS	Sick Building Syndrome
TV	Television
U	Coefficient of heat transmission
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
WC	Weathering Course
WFR	Window Floor-area Ratio
WWR	Window Wall-area Ratio

1 INTRODUCTION

1.1 Problem formulation

1.1.1 General problem

Bangladesh is a small but one of the most densely populated countries in the world. About 150 million people live in 58000 square kilometres (Saleque, 2008). Dhaka, the capital of Bangladesh, has come to be known as a fast growing megacity of South Asia in recent times. It began with a manageable population of 2.2 million in 1975, which reached 12.3 million in 2000. Dhaka city's population is expected to grow at a rate of 3.6% annually and reach a total of 21.1 million in 2015 (United Nations, 1999).

The energy infrastructure of Bangladesh is quite small, insufficient and poorly managed (Temple in Mozumder and Marathe, 2007). Bangladesh has small reserves of oil and coal, but natural gas resources are very large (Alam *et al.*, 2004). In Bangladesh, 82% of electricity generated is from natural gas, 9% from oil, 4% from hydro and 5% from coal (Tuhin, 2008). In 2004, Bangladesh's installed electric generation capacity was 4.7 GW (USAID, 2007).

According to Tuhin (2008), only 42.09% of the population is served with electricity and per capita electricity use is only 169.92 kWh. Overall, the country's generation plants have been unable to meet system demand over the past decade (Alam *et al.*, 2004). The demand for electricity is growing at a rate of 10% per year (USAID in Mozumder and Marathe, 2007) without any well-designed plan to meet the demand. The average generation capacity of power in 2008 was about 3771 MW per day, whereas the average peak demand of national power was about 4200 MW (Saleque, 2008). Saleque (2008) also adds that during summer, when the maximum temperature ranges from 30°C to 38°C, the average peak demand can increase from 4200 MW to 5500 MW. This deficit leads to extensive load shedding. Other problems in the Bangladesh's electric power sector include high system losses, delays in completion of new plants, low plant efficiencies, erratic power supply, electricity theft, blackouts, and shortages of funds for power plant maintenance (Alam *et al.*, 2004).

1.1.2 Specific problem

According to BBS (2008), the electricity used by the industrial, residential, commercial and other sectors in the year 2006-2007 was about 21181 GWh. Out of this, 42% was used by the residential sector alone (BBS, 2008). Rahman and Mallick (n.d) represent the sector wise use of electricity in Dhaka City as industrial (46%), residential (45%), commercial (7%) and others (2%).

Much of the increased demand for electricity is due to the increased standard of living (People's Report 2004-2005, 2006) among the wealthier income groups. One of the major factors in the increased use of electricity by the higher income group is the use of air conditioning units, which has only recently become quite popular (Hancock, 2006). Special assistant to the chief adviser for the power and energy ministry, M Tamim at a press briefing in 2008 said that air conditioners in Dhaka city alone use around 400MW of electricity. Cheung *et al.* (2005) have stated that the

increase in electricity use by the Chinese residential sector during the summer months has been caused by the growing demands for air conditioning systems. Vangtook and Chirarattananon (2007) have acknowledged that air conditioners are increasingly used in hot and humid regions to attain thermal comfort. However, they argue that air conditioning is highly energy intensive and suggest developing alternative energy efficient means to achieve comfort.

Reza (2008) notes that Dhaka city, with a growth rate of 4.34%, adds half a million people to its population each year. He also states that to accommodate the growing population, the city would need at least 10 million new units/flats by the year 2015 and Dhaka would not be able to cater the energy needs of these new units.

Moreover, a study of the regulations in the national building code of Bangladesh shows that the building codes do not address the issues of energy efficiency in any building category. Architects and developers of residential buildings, too, have not considered ways in which energy use can be reduced.

The specific problems that signify the importance of energy-efficiency in residential buildings are as follows:

- high-energy use of residential buildings in Dhaka,
- growing population and rising number of apartments,
- increased standard of living that would further add to energy usage and
- interrupted power supply due to power deficits.

1.1.3 Research problem

1.1.3.1 *Research questions*

The questions that attempt to be answered in order to achieve the goals of this research include:

1. What are the passive design features that can be incorporated in residential buildings of Dhaka to make them energy-efficient ?
2. What are the possible energy savings by adopting these energy efficient features?
3. What is the present electric energy use for cooling and lighting typical residential buildings inhabited by upper middle income households in Dhaka?
4. What are the different roles of developers, architects, interior designers, clients/land owners and residents that can act as a barrier in achieving energy efficiency in the residential buildings of Dhaka?

1.1.3.2 *Delimitations*

In terms of the various categories of buildings that are there in Dhaka, the study was delimited to multi-unit residential buildings.

Jones (1998) has concluded that energy use in modern buildings occur in five phases, namely, manufacture of building materials, transportation of building materials to the site, on-site construction activities, the operational phase, (running of the building) and finally, the

demolition process of buildings and recycling of building materials. This study confined itself in considering energy use at the operational phase of the building.

The study was oriented towards the residential buildings inhabited by upper middle-income groups in Dhaka. According to Islam and Shafi (2008) the monthly salary range for upper middle-income groups in the year 2004 was 420 to 840 US \$ (Table 3). He has also stated that the upper middle-income groups constitute about 10% of the population of Dhaka city. This thesis is delimited to this upper middle-income group, since they use more and more energy as they have increased their standard of living and are becoming increasingly accustomed to the use of air conditioners. Henning (2007) has outlined that one of the main reasons for the increasing electricity demand for air conditioning use in the residential sector is the increased living standards. For instance, the improvements of living standards in the metropolitan zone of China had caused an 80% increase in the use of air conditioners in residential buildings by the year 2000 in that zone (Aixing in Yu *et al.*, 2008). Vangtook and Chirarattananon (2007) have elaborated that typically one air conditioner is initially installed in the main bedroom of a house; with increase in disposable income, the household would add a second, a third and possibly more units to other bedrooms and common rooms.

The study is restricted to making new residential buildings energy-efficient and does not consider the existing housing stock because of two reasons. First, Dhaka is rapidly urbanizing and the construction of new buildings is extensive. Second, better design of new buildings could result in a 50% reduction in energy use, whereas, appropriate design intervention in the existing stock of buildings could yield an energy reduction of 25% (Clarke and Maver, 1991).

Table 1. Income groups in Dhaka City Corporation

Income Group (Monthly household income in taka)		Dhaka City Corporation 2004 %
Hardcore Poor	< 2500	25
Moderate Poor	2500-5000	15
Lower Middle	= 5000-10,000	20
Middle Middle	= 10,000-25,000	20
Upper Middle	= 25,000-50,000	10
Lower Upper	= 50,000-100,000	7
Upper Upper	100,000+	3

Source: Islam and Shafi, 2008. US \$ 1= 59.50 Bangladeshi Taka

1.2 Aims

The aim of this study is to analyze the criteria for energy efficiency, resulting in a series of feasible passive design solutions that can make a contribution in the field of architecture, towards the knowledge of developing and designing energy-efficient residential buildings. The study also

aims at identifying changes in the design process that can affect energy efficiency in residential buildings.

1.3 Significance and limitations

1.3.1 Expected contribution from this study

Worldwide, 30% to 40% of all primary energy is used in buildings (UNEP, 2007). Since the building sector is a major user of electricity, it is essential to evolve energy efficient building designs that can be used to provide thermal comfort. Buildings also account for a significant amount of carbon dioxide emissions (UNECE, 2008). In low-income countries, the residential sector represented 90 per cent of all carbon dioxide emissions from buildings in 2002 (UNECE, 2008).

Energy efficiency is crucial, especially for a country like Bangladesh where the demand for electricity, as already stated, is growing at a rate of 10% per year. However, the generation of power has not grown to match the growing demand. If buildings are made energy efficient, the energy saved can be utilized in serving the rest of the population; children in regions without access to electricity would not use lanterns to study if poverty does not prevent them from using electricity, industries would not face massive disruption in their production and economic activities would function without any disturbances. Chowdhury *et al.* (2006) assert that increased energy efficiency in buildings can provide financial benefits through reduced electricity bills and have a role in reducing total societal energy use. The arguments put forth by Janssen (2004) for improved energy efficiency in residential buildings focus on:

- Reduced energy costs to users
- Security of energy supply
- Cheaper than investing in increased energy capacity
- Improved comfort
- Lower GHG emissions, which mean a major contribution to climate change strategies and helping to achieve the Kyoto Protocol target.

As energy use is largely determined by the density of layout, location, orientation, etc. of the original design, architects and builders have great influence in saving energy. It is high time that government of Bangladesh formulates a building code to ensure energy efficient residential buildings to combat the energy crisis in the country.

This study is expected to provide the following benefits to the development of residential buildings in Bangladesh:

1. The study will improve the understanding of a typical residential building in Dhaka (case study building), including its energy use.
2. The study will determine the amount of electric energy used for cooling and lighting in typical residential buildings of Dhaka.
3. The study will provide guidelines to assist architects for designing energy-efficient residential buildings in Dhaka.

1.3.2 Scope and Limitations of the research

The study is limited in the sense that it was not possible to identify a very good example of an energy-efficient residential building in a similar climatic context as of Bangladesh from which energy efficiency criteria could be studied. Instead, the identification of energy efficient design features depended on an extensive literature study. Another limitation has been the time of the year when the case study was surveyed. As it was winter in Dhaka during the time of survey, it was not possible to measure micro climatic data inside the building. While analyzing energy efficient design principles for residential buildings, theoretical limitation was given to passive features that can be addressed through design and incorporated at the initial design stage of the buildings. Furthermore, only those kinds of measures are considered, that can be addressed through design or by bringing about a change in the design practice. The study considers energy use of electrical appliances to find out the energy used for cooling and lighting. However, it does not consider the efficiency or the possible improvements in efficiency of these devices; it considers only replacing them by passive techniques. Habits and behavioural patterns that cannot be influenced by design and are related to energy efficiency have not been dealt in this study.

2 CONTEXT- SITUATIONAL SETTING OF PROBLEMS IN DHAKA

2.1 Dhaka's energy situation

Frequent power disruption and load shedding in Dhaka, over four hours a day, amid hot and humid conditions have made the life of city people miserable. Recently, residents have alleged that they are experiencing one to three-hour long power cuts, four to five times a day on an average (The Daily Star, 2009). The load-shedding situation continues to worsen as the excessive heat drives people to use more electricity at homes and offices. According to the report of Dhaka Mirror (2009), the power situation in Bangladesh has taken a serious turn due to the inadequate generation of electricity. The country has been experiencing a shortfall of about 1200 MW of electricity against the demand of 4500 MW (Dhaka Mirror, 2009). Dhaka alone is being provided with 1185 MWs against a demand for about 1800 MWs. It is assumed that this demand would rise to 2200 MWs during the peak summertime, from mid March to mid October when electricity use goes up to its highest level because of hot weather as well as a huge need for irrigation.

2.2 Climate of Dhaka

It is important to analyze the climate scenario for Dhaka and understand the typical thermal behaviour of buildings. Knowledge on the thermal behaviour of the building envelope is crucial to control the amount of heat that goes into a building space. Buildings will cause thermal discomfort if an effective strategy is not adopted to reduce the extra heat going into it. According to Zain *et al.* (2007), factors that influence thermal comfort in humans include outdoor air temperature, relative humidity and airflow. Various strategies also need to be adopted to facilitate air flow because it has been observed by Zain *et al.* (2007) that if there is no air flow, occurrence of thermal comfort is only 44% occurrences in temperatures below 28.69 °C but an air flow of 0.7 m/s can improve the occurrence of thermal comfort to 100%.

Dhaka is located in central Bangladesh at 23°42'0"N 90°22'30"E (Fig. 1). The climate of Dhaka can be categorized as tropical monsoon type with an annual average temperature of 25 °C and monthly means varying between 18.5 °C in January and 29 °C in April. The climate is characterized by high temperatures, high humidity most of the year, and distinctly marked seasonal variations in precipitation (Table 1). According to meteorological conditions the year can be divided into four seasons, pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November) and winter (December–February).



Fig. 1. Location of Dhaka, Bangladesh

Source: World Atlas Travel

The pre-monsoon or summer season is generally hot and sunny. The hottest month is April. Mean monthly maximum temperature hovers around 33-34°C and the mean monthly minimum varies around 21-22°C. Approximately 15% of the annual rainfall occurs in this season. During summer, winds are mainly from the southwest (Fig. 2).

The monsoon or rainy season is characterized by high rainfall, humidity and cloudiness. About 80% of the annual rainfall occurs in this period. The month of June is cool due to the cooling effect of the rains. This season experiences mean maximum temperatures of around 31°C and mean minimum temperatures of around 25.5 °C. Humidity is around 85%. During the monsoon or rainy season, winds are from the southeast.

The post-monsoon is the transition period from monsoon to winter. In the post-monsoon season, the rainfall and relative humidity decreases along with the wind speed. In this period, the prevailing wind direction is from the northeast.

The winter or dry season is characterized by its low temperature, low humidity and clear blue skies. The coldest month is normally January. Mean monthly maximum temperature lingers around 26°C and the mean monthly minimum varies between 11-13 °C. About 5% of the annual rainfall occurs in this season. In winter, the general wind direction is from the northwest.

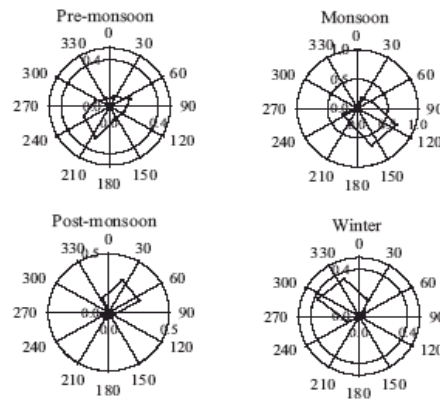


Fig. 2. Seasonal wind direction at Dhaka based on wind speed data.

Source: Khan, S.I., Mahfuz, M.U., Aziz, T. & Zobair, N. M. 2002

Table 2. Climate chart of Dhaka for 2003

Month	Temperature (°C)				Relative humidity (%)	Average precipitation (mm)	Wind			Average sunlight (hours)	Radiation (kWh/m²)
	Average		Record				Speed (Knots)	Direction (degrees)	Direction (cardinal)		
	Min	Max	Min	Max							
Jan	12	22	8	27	75	0	7	270	W	5	3.55
Feb	17	28	14	32	66	25	12	360	N	7	4.31
March	19	30	13	34	65	96	10	180	S	7	5.21
April	24	34	18	36	71	123	15	230	SW	8	5.61
May	24	33	20	36	73	140	25	310	NW	7	5.29
June	26	31	22	36	82	473	15	180	S	2	4.66
July	26	32	23	35	80	191	12	130	SE	5	4.48
Aug	27	32	24	35	79	202	10	140	SE	5	4.50
Sept	25	32	23	34	83	264	10	180	S	3	4.24
Oct	25	31	23	34	81	134	10	180	S	5	4.13
Nov	19	30	14	32	67	0	8	310	NW	8	3.90
Dec	16	26	13	29	67	45	8	50	N	7	3.59

Source: Bangladesh Meteorological Department

Ahmed (1987) has compared diurnal temperature variations with the levels of monthly comfort zones in Dhaka to identify ‘over-heated’ and ‘under-heated’ periods. She has defined under-heated period as all hours that have temperatures below the comfort range, whereas over-heated periods include all hours with temperatures above the comfort range. Ahmed (1987) concludes that identification of these periods enables the designer to pay special attention to the specific periods that do not fall in the comfort zone. Table 2 has been adopted from Ahmed’s PhD thesis. (1987). It shows the duration of the over-heated and under-heated in the course of a year for Dhaka. It can be concluded that the overheated periods that cause discomfort persist for 10 hours a day on average (10 am in the morning to 8 pm at night).

Table 3. Under-heated, comfortable and over-heated periods in Dhaka

	Hour											
Month	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-0
Jan												
Feb												
March												
April												
May												
June												
July												
Aug												
Sept												
Oct												
Nov												
Dec												

Colour Index:

Under-heated periods	Comfortable periods	Over-heated periods
----------------------	---------------------	---------------------

Source: Ahmed, 1987

2.3 Residential buildings and energy efficiency

The residential buildings provided by the developers in Dhaka do not focus on energy efficiency. In fact, the government of Bangladesh has not adopted building energy codes in any form for building construction, despite the recognized fact that worldwide, 30%-40 % of all primary energy is used in buildings (UNEP, 2007). By observing most of the residential buildings in Dhaka, it seems architects and developers are still not aware of the role they can play in designing energy efficient buildings. Architects are under constant pressure from the developers and clients to design multi-unit residential buildings with maximum space utilization, more bedrooms per flat/unit and good project economy. They therefore concentrate mainly on unit/flat size per building, provision of more bedrooms per flat/unit, kitchen complex (kitchen,

kitchen balcony, storeroom, maid's room and maid toilet) and provision of one car parking for each flat/unit and treatment of the front facade.

Designs of apartments, in general, are not responsive to the requirements of Dhaka's tropical climate. Residential buildings are designed without giving due importance to the parameters that are responsible for enabling thermal comfort without much dependence on energy use. Dependence on artificial lighting and ventilation is common in all apartments. Furthermore, energy use in the residential sector is increasing dramatically due to the improvements of living standards. The increase in electricity use by the residential sector particularly in hot and humid periods has been caused by the growing demand for air conditioners to provide thermal comfort for the occupants (Wong and Li, 2007)

3 THEORETICAL FRAMEWORK

3.1 Energy efficient residential buildings

Well-designed energy efficient buildings maintain the best environment for human habitation while minimizing the cost of energy. According to the Development and Land Use Policy Manual for Australia (2000), the objectives of energy efficient buildings are to improve the comfort levels of the occupants and reduce energy use (electricity, natural gas, etc) for heating, cooling and lighting. United Nations (1991) defines energy efficient buildings to have the minimum levels of energy inputs. Janssen (2004) claims that an improvement in energy efficiency is considered as any action undertaken by a producer or user of energy products, that decreases energy use per unit of output, without affecting the level of service provided.

3.2 Basic principles in energy efficient building design

It is evident from the above section that energy efficiency in buildings is vital for many reasons. Having justified the needs for energy efficiency it is now important to focus on the basic principles that can bring about energy efficiency in residential buildings of Dhaka. An extensive literature review consisting of different journals, books, researches and related websites was undertaken to establish the basic passive principles for designing energy efficient residential buildings. Below is the list of aspects for energy efficient residential buildings that has been arrived at from the literature review and is based on the context of Dhaka:

1. Planning aspects:
 - Site analysis
 - Building form
 - Building orientation
 - Room orientation
 - Landscaping
2. Building envelope:
 - External wall
 - Thermal insulation
 - Building material
 - Roof
 - Windows
 - Size
 - Orientation
 - Shading device
 - Natural ventilation
 - Daylight

3.3 Planning aspects

3.3.1 Site analysis

Analysis of the building site should be made to determine the following:

1. Wind breaks

Wind breaks are not desirable in tropical climates as they impede desirable breezes. Instead, it is desirable to have air movement. However, dense housing developments and proliferation of built structures in Dhaka do not leave a scope for choosing a portion of the site without windbreaks. Generally, plots are not surrounded by open spaces or green spaces in Dhaka.

2. Shade from existing buildings and trees

Watson and Labs (1983) recommend placing a building in such a way that it gets shading from existing trees and landmasses. The building can be sited to the east of such feature to reduce solar gain during afternoons when the sun is low. UNEP (2006) warns that improper planning of the site can result in 'heat island effect'. Such effects according to UNEP (2006) can be alleviated by reducing the total paved area on the site and shading the paved surfaces.

As already mentioned above, surrounding buildings in Dhaka are at very close proximity to plots. Hence, buildings constructed get shade from existing landmasses in almost all cases. Buildings, however, do not get shade from surrounding trees due to the absence of green spaces.

The above mentioned criteria do not directly generate reductions in energy use. Instead, they provide air movement for ventilation if wind breaks are absent and help to keep buildings cool through the shade provided by surrounding buildings.

3.3.2 Building form

Gut and Ackerknecht (1993) have suggested forms with large surfaces rather than compact buildings as large surfaces favour ventilation and heat emission at night-time. The building forms should thus be open, outward oriented and built on slits. Givoni (1998) states that building form largely depends on whether the building is planned to be air-conditioned or if it is intended to rely on natural ventilation. He recommends a compact shape for the building dwelled by people who are determined to use air conditioners and open forms for naturally ventilated buildings. Compactness of the building minimizes the surface area of the building envelope, resulting in a reduction of the heat gain through the envelope.

It might not be possible to design open, outward buildings in constricted sites as of Dhaka and where maximum utilization of land for profitability is the main objective. Most residential buildings in Dhaka are compact. The compactness of residential buildings is attributed to the fact that land is exploited to its utmost capacity, without leaving any open space. Prior to the establishment of Dhaka City Building Construction Act-2008, only 15% of a plot was left vacant as setback space. Now, after the new rules got underway, 32.5% of a plot (smallest size, about 135 square metres) is said to be left open for green space.

3.3.3 Building orientation

Properly oriented buildings take advantage of solar radiation and prevailing wind. According to Gut and Ackerknecht (1993), the longer axis of the building should lie along east-west direction for minimum solar heat gain by the building envelope.

Wong and Li (2007) performed field measurements and computational energy simulations to examine the effectiveness of passive climate control methods such as building orientation in residential buildings of Singapore. Their results state that the best orientation for a building in Singapore with its tropical climate is for the longer axis of the building to lie along east-west direction. They also conclude that the cooling load for a residential building can be reduced to 8% -11% by following this orientation.

The passive design feature on orienting the longer axis of the building towards east- west direction, as suggested Wong and Li is not always possible, especially due to actual orientation of the site, that is, when the site itself is longer on the west and east sides. Such cases are outside the influence of the developer and the architect. In such cases, the west facade needs more attention because it heats up in the afternoon and important rooms such as bedrooms are generally used later during the day when residents return from office. The east side is less problematic as it warm only in the morning when only few households occupy the major rooms. The west facade can be treated by locating auxiliary spaces, kitchen and staircase to minimize solar heat gain and Openings should be avoided on the west and if they cannot be avoided, they should be adequately shaded by using verandahs.

It should also be noted that the orientation requirement for wind flow can conflict with the requirement for solar protection. Mowla (1985) points out that solar geometry cannot be changed, skilful use of elements such as roof overhang or wall-projecting wing can change the direction of air flow and also give shade.

Fortunately, orientation requirement for solar protection does not conflict with wind flow in Dhaka as wind flow is from the southwest (summer), southeast (monsoon), northeast (post monsoon and northwest (winter); whereas, for solar protection, the west facade should not have openings on the west.

3.3.4 Room orientation and arrangement

According to Gut and Ackerknecht (1993), the arrangement of rooms depends on their function and according to the time of the day, they are in use. Watson and Labs (1983) have claimed that a house can be made more energy efficient if it is planned according to solar orientation and prevailing wind direction. However, they did specify how much energy saving is possible through such planning.

Overheating due to solar radiation is the prominent problem in Dhaka for most of the year, especially during the day. Table 2 showed the duration of overheated periods for Dhaka in the course of a year and Fig. 3 shows the duration and orientation of solar radiation received on a facade in Dhaka. This relationship between the duration and orientation of solar radiation was investigated by Mowla (1985) by using the sun-path diagram and shadow angle protractor. The aim while designing for Dhaka is prevention of overheating and provision of wind flow from the climatic point of view.

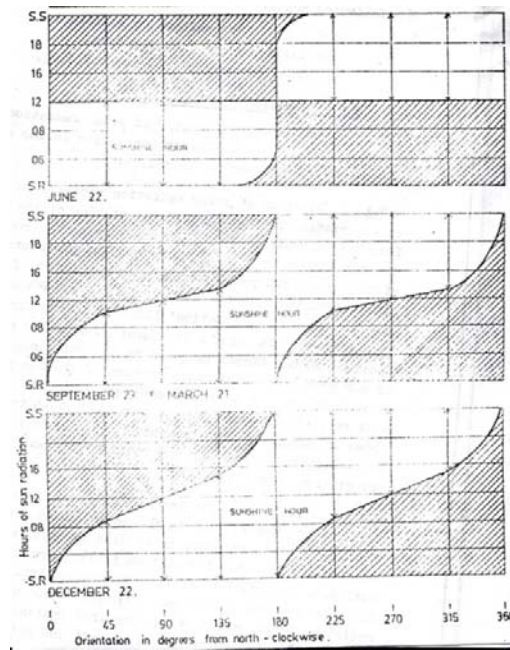


Fig. 3. Duration of solar radiation received on the facade

Source: Mowla, Q.A. 1985.

Givoni (1998) points out that cross-ventilation can be used to enable faster cooling and better ventilation. He stresses that building layout which provides good potential for cross-ventilation is more appropriate for developing countries in hot-humid regions where the vast majority of people cannot afford to buy air conditioners. He recommends a spread out building with openable windows to facilitate cross-ventilation.

The option of spread-out or open outwards building for Dhaka was already discussed in section 2.3.3. It can be easily implemented if the developer and client are prepared to:

- sacrifice some floor area that would have otherwise contributed to the area of the unit or flat and that would ultimately not add to the price of the unit or flat.
- accept higher construction costs because of increased surface area.

According to Mowla (1985), eastern facades in Dhaka get morning sun throughout the year amounting to almost 700 W/ m^2 (Mowla, 1985). He advises that rooms which are used later during the day can be arranged on the east side as they are warm in the morning and cool down in the afternoon. Mowla (1985) furthermore claims that western facades get afternoon sun with a radiation of about 700 W/ m^2 throughout the year. He suggests placing rooms that are used in the morning on the west side as they are cooler in the morning and heat up in the afternoon. He also stresses that southern facades in summer, does not get any sun through out the day. However, in summer, northern facade gets low altitude morning and evening sun. He claims that rooms facing north and south remain relatively cool if provided with adequate shading.

According to Gut and Ackerknecht (1993) in *Climate Responsive Building: Appropriate Building Construction in Tropical and Subtropical Regions*:

"Bedrooms can be located on the east side where it is coolest in the evening. Rooms which are in use for most times of the day, such as living rooms should be located on the northern side. Stores and other auxiliary spaces should be located on the disadvantaged side, mainly on the western sides. Provided the kitchen is used during morning and midday hours, it can be located on the west side as well. Rooms with high internal heat load, such as kitchens, should be detached from the main rooms."

When designing a multi-unit residential building, architects design one unit and use the 'mirror command' to copy the plan of one unit in a definite position. The Mirror command in AutoCAD (computer application for architectural drawings) allows mirroring selected objects in drawings by picking them and then defining the position of an imaginary mirror line using two points. Architects misuse this command and do not consider the consequences. Though the design of the original unit may have proper orientations, it fails to meet the orientation requirements as soon as it is 'mirrored'.

The usual trend for orientation of rooms in residential buildings of Dhaka is to give maximum priority to master bedroom followed by other bedrooms. Though dining spaces are used most frequently as will be seen in the case study building in Chapter Five, dining spaces are rarely given importance. Living spaces are also not given due importance. Dining spaces are centrally located and perform more as circulation space. Owing to its central location and compactness of building form, dining spaces do not get adequate daylight and natural ventilation. The planning guidelines proposed by Mowla (1985) and Gut and Ackerknecht (1993) are applicable for the context of Dhaka as they do not present any conflict with the functional, symbolic and socio-cultural aspects.

3.3.5 Landscaping

Raeissi and Taheri (1999) acknowledge the beneficial effects of trees. They state that plantation of trees can result in energy saving, reduction of noise and pollution, modification of temperatures and relative humidity and psychological benefits on humans. Their study on proper tree plantation for energy saving concludes that the cooling loads of a house can be reduced by 10%- 40% by appropriate tree plantation. They also note that trees can act complementary to window overhangs, as they are better for blocking low morning and afternoon sun, while overhangs are better barriers for high noon sunshine. The study by Simpson and Macpherson (1996) is in agreement with that of Raeissi and Taheri. Simpson and Macpherson (1996) have shown that tree shades can reduce annual energy for cooling by 10% -50%.

Even though appropriate tree plantation can bring significant amount of energy savings, this design principle can only be applicable in buildings of Dhaka if adequate space is left open either as a set back area or as designated green space. Setback rules according to the Dhaka City Building Construction Act for a typical plot size of 335 square metre is 1.5 m, 2 m and 1.25 m at the front, back and two sides respectively. These dimensions are not adequate enough to plant big trees that can provide shade.

3.4 Building Envelope

3.4.1 External wall

As the main goal in building design of tropical climates is reduction of direct heat gain by radiation through openings and reduction of internal surface temperature, the building should be designed with protected openings and walls (Gut and Ackerknecht, 1993). The walls can be protected by designing the roof so that it extends far beyond the line of walls and has broad overhanging eaves.

Gut and Ackerknecht (1993) argue that the outer surface of the external wall should be reflective and light coloured. The findings by Cheung *et al.* (2005) also support Gut and Ackerknecht's views on reflective and light coloured external walls. Cheung *et al.* (2005) had conducted a study to reduce the cooling energy for high-rise apartments through an improved building envelope design. They had identified six passive thermal design strategies, namely, insulation, thermal mass, colour of external walls, glazing systems, window size and shading devices. This section will consider their study on external wall; the findings from the investigations on the remaining passive design strategies will be discussed gradually in the designated sections. Their study shows that annual cooling has an almost linear relationship to the solar absorptance (amount of solar energy that passes into a material) of the external surfaces. Energy savings were found to be high with lower solar absorptance. A 30% reduction in solar absorptance can achieve a 12% saving in annual required cooling energy. They concluded that 12% saving on cooling energy could be obtained from using white or light colour external wall finishes. However, most residential buildings in Dhaka are already light- coloured, with only a very few exceptions. Choice of building colour depends mostly on architects and in few cases, on clients.

Mathur and Chand (2003) believe that thermal resistance of a wall can be increased by introducing an air cavity. Similarly, Mallick (1996) asserts that variation in wall thickness can make a considerable difference in the comfort level of houses in tropical climates.

The field measurements and computational energy simulations to examine the effectiveness of passive climate control methods such as facade construction in a typical 14 storey residential building of Singapore by Wong and Li (2007) depict similar views as of Mallick (1996). Wong and Li (2007) from their study concluded that the use of thicker construction on east and west external walls (Fig. 4) can reduce the solar radiation heat gain and hence, the cooling load can be reduced by 7%-10 % when the thickness of external wall is doubled (229 mm concrete hollow block instead of 114 mm concrete hollow block).

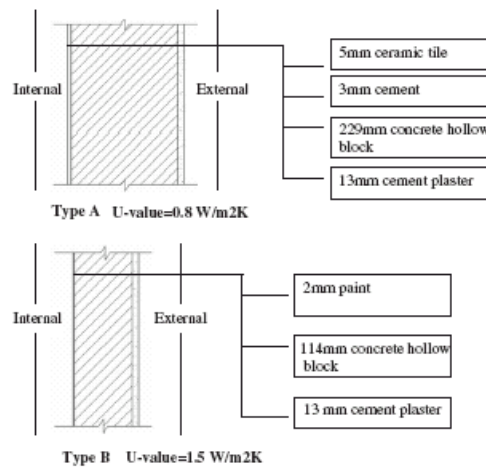


Fig. 4. External wall construction

Source: Wong, N.H and Li, S. 2007.

Residential buildings in Dhaka have 125 mm thick external walls made of brick to make most of the floor area and to reduce construction costs. It should be noted that older buildings had thicker walls ranging from 250 mm to 500mm. With the advent of multi-unit residential buildings due to increasing pressure on building land and structural system, thick walls were replaced with 125 mm walls. The design option put forward by Wong and Li uses concrete for external walls, but concrete is expensive in Dhaka. The local building material for external walls in Dhaka is burnt brick and it is much cheaper when compared to the cost of concrete. According to Gut and Ackerknecht (1993), the transmittance value or U value (measurement of heat transfer through a given building material) of 250 mm hollow concrete block whitewashed externally is 1.7 W/m². The U value of a 280 mm brick wall (115 mm brick + 50 mm air gap + 115 mm brick) including an air cavity of 50 mm and whitewashed externally is also 1.7 W/m². These U values suggest that energy savings from using brick instead of using concrete should be roughly the same as calculated by Wong and Li. Hence, for Dhaka's context 280 mm brick walls including an air cavity of 50 mm can be used instead of hollow concrete blocks on east and west facades.

3.4.2 Thermal insulation

According to Bolatturk (2008), thermal insulation is one of the most effective energy conservation measures for cooling and heating in buildings because it reduces heat transfer to and from the buildings. However, this view portrayed by Bolatturk (2008) seems to conflict with those of Gut and Ackerknecht (1993) and Yang and Hwang (1993). They state that thermal insulation has very little efficiency in warm-humid zones because the ambient air temperature inside and outside the building is same due to the free flow of air. Yang and Hwang (1993) have added that in warm and humid regions, condensation might occur and this would demean the thermal performance of the building envelope and cause mildew problems. Moreover, Gut and Ackerknecht (1993) also note that thermal insulation has a dual nature. It reduces daytime excess heat entering a building, but averts the building from cooling down at night. According to them,

this dual nature makes insulation unsuitable for buildings with natural climate control. These contradictions need to form a consensus. Perhaps the solution lies in first determining the cooling load at the design stage and then deciding whether this cooling load would be reduced by employing thermal insulation in the building or by using passive means of control.

Tham (1993) in his study of various energy conservation strategies obtained results that do not encourage wall insulation. His study concludes that by adding 50 mm of polystyrene as wall insulation, only 1.7 % reduction in total energy use is achieved. He also suggests that if savings in operation cost were compared to the cost of installation, wall insulation would not be economically feasible. This finding, yet again conflicts with the results of Bolatturk (2008) and Cheung (2005).

Considering all the contradictions and the conclusion put forth by Tham (1993) and the fact that thermal insulations are not available in Bangladesh, the option for thermal insulation as an efficient design feature has not been considered in this study.

3.4.3 Building material

It has already been mentioned that this study focuses only on the energy used by a building during the operation stage. It will not consider the energy used in manufacturing the building materials and transporting the building materials from the production plant to the site. Neither will it consider the energy used in on-site construction activities and the energy used in the demolition of the building and the recycling of their parts.

Gut and Ackerknecht (1993) recommend using the following building materials in tropical climates:

1. Burnt clay bricks can be used in tropical climates because they have good thermal resistance and good regulating property against humidity.
2. Timber has good thermal resistance and is a good regulator of humidity.
3. Matting of bamboo, grass and leaves are good because they are not airtight and allow proper ventilation.

As discussed in the previous section, burnt clay bricks are common building materials in Dhaka. Though timber was once used as a vernacular building material, it is no longer used because of the costs involved in seasoning timber. Bamboo, grass and leaves are temporary building materials and are not used in urban settings.

3.4.4 Roof

The roof is an important element of design when it comes to conserving energy because this part of the building receives most of the solar radiation and its shading is not easy. Vijaykumar *et al.* (2007) claim that Indian concrete roofs in single or two storey buildings with 150 mm thickness of reinforced cement concrete (RCC) and a weathering course (WC) having 75–100 mm thick lime brick mortar, account for about 50%- 70% of total heat transmitted into the occupant zone and are responsible for the major portion of electricity bill in air-conditioned buildings. Nahar and Sharma in Tang and Etzion (2004), Vijaykumar *et al.* (2007) and Alvarado and Martinez

(2008) conclude that the heat entering into the building structure through roof is the major cause for discomfort in case of non air-conditioned building or the major load for the air-conditioned building. However, Gut and Ackerknecht (1993) argue that this is true for single storied buildings and the top floor of multi-storied buildings. In Dhaka, most residential buildings are six-storied; the roof area is therefore very much smaller than that of the external walls. Conduction heat gain through the roof in Dhaka is thus smaller than that through external walls and windows.

Concerning roof shape, Gut and Ackerknecht (1993) note that warm-humid regions should have pitched roofs to drain off heavy rains. However, the scenario in urban areas of Bangladesh is contrary to their statement. In Dhaka, residential buildings have flat roofs for many reasons. The roofs are used as community space and for hanging laundry. As the residential buildings are mostly six-storied, roofs are flat for aesthetic reasons. Gut and Ackerknecht (1993) also suggest that roofs should have large overhangs to protect the walls and openings from radiation and precipitation; they should be made of lightweight materials with a low thermal capacity and high reflectivity. The roofs in Dhaka, however, are not lightweight; instead, they are made of concrete to be able to withstand tropical storms and severe weather. Gut and Ackerknecht (1993) claim that roofs cannot be kept cool if there are any obstructions that prevent the airflow along the roof surfaces. They recommended that parapet walls along the roof should not be high and solid and should not create a stagnant pool of hot air. However, Gut and Ackerknecht do not indicate figures to explain how much they actually mean by 'high'. Parapet walls in roofs of Dhaka are always solid and they are about 1 m high so that they can be used as railings. Perforated screen walls can be used as parapet walls to eradicate their solidity and thereby allowing airflow along the roof surface.

Alvarado and Martinez (2008) studied the impact of a simple and passive cooling system in reducing thermal loads of one- storied roofs. Their results demonstrate that the aluminium–polyurethane insulation system with an optimal orientation reduces the midpoint temperature of a cement-based roof significantly. The results also exhibit that the roof insulation system can reduce the typical thermal load by over 70% while effectively controlling thermal fluctuations. However, Garde *et al.* (2004) and Suehrcke *et al.* (2008) have differing views. Garde *et al.* (2004) found that in tropical climates, intermediate roof insulation can only decrease the air temperature inside a dwelling by few degrees. Suehrcke *et al.* (2008) concludes that roof insulation may hinder the desired night-time cooling. Moreover, the application of such roofs in Dhaka would not be spatially and culturally appropriate as roofs are used as community spaces. Roofs of residential buildings in Dhaka can be designed with a lightweight reflective canopy or canopy made of temporary building materials like bamboo 2-3 metres above the concrete roof. Such a shelter can shade the roof, prevent solar radiation on the concrete roof and will not hinder the functional use of the roof as in the case of the proposal by Alvarado and Martinez.

Akbari in Vijaykumar *et al.* (2007) has shown that passive roof cooling systems like coating the rooftop with highly reflective coatings can reduce the heat transmission across the roof by 20% – 70%. However, the deterioration of roof coating reflectivity over time is a major setback. For tropical countries like Bangladesh, which are dust prone, the cooling benefit of a roof surface with high solar reflectance can decrease with time as the surface accumulates dust and deposits.

However, Levinson *et al.* (2005) suggests that washing the dirt off the reflective roofs can almost completely restore its original reflectivity.

Green roofs have been increasingly investigated in order to determine how they could improve the quality of the urban environment. Teemusk and Mander (2009) have described green roofs as consisting of the following layers: a water-proofing membrane, a drainage layer, a filter membrane, a substrate layer and plants; the composition and thickness of this substrate layer is decisive. The benefits of green roofs as claimed by Teemusk & Mander (2009) are presented in Appendix 1.

Wong *et al.* (2003) in their study on life cycle cost analysis of rooftop gardens in Singapore state that despite the availability of materials and suitability of climate in Singapore, many developers are often held back from including rooftop gardens in the design brief mainly by concerns pertaining to initial costs. In their study, life cycle cost analysis of two major roof types, inaccessible and accessible have been assessed. Accessible roof gardens are known as intensive green roofs and are found in Singapore's local building developments. These roof gardens are accessible by people and are used as parks or building amenities. Hence, they usually incorporate paving and seating areas. Their increased weight, higher capital cost, intensive planting and higher maintenance requirements characterize intensive green roofs. Inaccessible roof gardens, on the other hand, are known as extensive green roofs. They are not designed for public use; instead they are mainly developed for aesthetic and ecological benefits. They are distinguished by being low cost, lightweight (50–150 kg/m²) and with thin mineral substrates. Minimal maintenance is required and inspection is performed one to two times per year. Wong *et al.* (2003) have estimated that the initial cost of extensive roof system, intensive green roof (shrubs) and intensive green roofs (trees) are \$89.86, \$178.93, \$197.16/m², respectively, while that of exposed flat roofs and built-up roofs are \$49.35 and \$131.60/m². Their findings imply that the initial costs of roof gardens vary with the type of structure and on the selections of plantings placed on the rooftop. Their calculations show that only extensive green roofs bring about positive net savings. They argue that even though extensive green roof costs much higher initially, the life cycle cost is greatly reduced. The simulations results of the study conducted by Wong *et al.* (2003) reveal that an extensive green roof could reduce energy use of the building and achieve a net savings of 14.6%. Net energy savings of intensive green roof is not more than 4% and is therefore not significant. They also conclude that by considering these energy savings, extensive green roof does not cost more than conventional flat roof. The energy saving mentioned for both green roofs is likely to be dependent on the number of storeys, but, the authors do not point out the number of storeys in each type of building with the roof gardens.

Patterson in Wong *et al.* (2003) also states that even though first costs of green roof range from three to six times the cost of a typical roofing system, in the long-term, green roofs may be less expensive and outperform conventional roofing. Lippiatt and Boyles (2001), in favour of green roofs, note that a short-lived, low first-cost product is often not the cost-effective alternative. According to them, a higher first cost may be justified many times over for a durable product with minimal maintenance.

Despite the benefits that have been discussed about roof gardens, there are disadvantages of roof gardens that need to be considered before they are planned. Gut and Ackerknecht (1993) have reflected upon the following disadvantages of roof gardens:

- They add a heavy load on the roof structure.
- Reliable waterproofing of the roof is not easy to achieve.
- Roof gardens reduce heat emission at night.
- Draining channels and outlets may get clogged.
- High water use of roof gardens should be considered in regions with scarcity of water.

From the discussion above on green roofs, it can be concluded that extensive green roofs are more energy efficient than intensive green roofs. Extensive green roofs, however, are inaccessible. Whereas, the prevailing culture in Dhaka is to have access to roofs and use it as a community space. Moreover, not all the households in the building would be interested in investing in green roofs. Another problem might be about maintenance: who would be responsible for maintaining and watering these green roofs? Scarcity of water in Dhaka might also present problems. After considering these problems of green roof, in addition to the general disadvantages mentioned above, green roofs can thus be eliminated from the option of energy efficient design feature in the context of Dhaka.

Wong and Li (2007) examined the effect of introducing a special secondary roof to a 14 storied residential building in Singapore. The secondary roof slabs were made up of precast square or rectangular-shaped concrete slabs supported by concrete solid blocks (Fig. 5). All the gaps at the edges of the secondary slab layer were sealed with galvanized wire mesh bent into shape to prevent birds and foreign objects from entering. A thermal insulation effect was thus achieved by blocking direct sunlight with the top slab and by the airflow between the concrete roof and slab. Their study divulged that this kind of special secondary roof can reduce 11.59 % of the cooling load.

Construction of this sort of secondary roof proposed by Wong and Li in the residential buildings of Dhaka is not desirable because of the associated costs. Firstly, the creation of a second roof together with the concrete solid blocks would increase construction costs and secondly using concrete would further add to the construction cost because it is expensive building material in Dhaka.



Fig. 5. Secondary roof system construction.

Source: Wong, N.H. & Li, S. 2007.

Vijaykumar *et al.* (2007) demonstrates another new concept of special roof in which hollow clay tiles (HCT) are laid over reinforced cement concrete (RCC) instead of weathering course (WC). They studied the transient heat transmission across various types of roof structures for typical Indian climatic conditions. In order to analyse the performance of the proposed roof with the conventional roof, the following four roof structures as shown in Fig. 6 were investigated. The details are as follows:

Roof- 1 (RCC): Simple RCC roof (150 mm thickness).

Roof- 2 (WC): A 150 mm thick RCC roof covered with 75 mm thick weathering course.

Roof- 3 (HCT-AB): A 150 mm thick RCC roof covered with 75 mm thick hollow clay tiles, hollow passages (50 mm x 50 mm) are blocked at the ends and no airflow is permitted.

Roof- 4 (HCT-AF): Same as Roof-3 but the airflow through the hollow passage is permitted by opening the ends to the ambient.

The findings of the investigation indicate that Roof-4, i.e., reinforced cement concrete with hollow clay tile (open passage) combination is the preferred choice for tropical summer climates. The reduction in heat transmission of Roof -3 and Roof-4 when compared to Roof-2 is about 38% and 63% respectively. However, Vijaykumar *et al.* (2007) have not clarified how many storeys were present in the building on which the hollow clay tiles were laid.

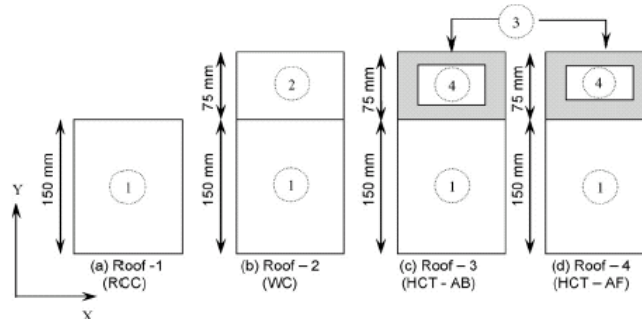


Fig. 6. Roof structures under investigation (uniform width of 75 mm) (material: 1-RCC, 2-WC, 3-HCT, 4-air)

Source: Vijaykumar, K.C.K., Srinivasan, P.S.S. & Dhandapani, S. (2007).

Vijaykumar and Srinivasan in Vijaykumar *et al.* (2007) have advised the use of hollow clay tiles (HCT) in place of weathering course for roofs. They have claimed that the use of such a system can save 18% - 30% of energy used in an air conditioned building. Application of hollow clay tiles as suggested by Vijaykumar and Srinivasan is easily feasible in the residential buildings of Dhaka as the cost of hollow clay tiles is not significantly higher compared to the cost of the weathering course.

3.4.5 Windows

3.4.5.1 Size

Openings are important design elements for admitting daylight, air flow, providing cross-ventilation and views. Gut and Ackerknecht (1993) recommend that windows should be large

and fully openable, with inlets of a similar size on opposite walls for proper cross-ventilation in tropical climates. However, windows in residential buildings of Dhaka are not fully openable and they do not function effectively in admitting airflow. Liping *et al.* (2007) claim that ventilation and indoor air quality can be improved by increasing the window to wall ratios (WWR), but it would also increase solar heat gain. There has always been a conflict with daylight provision and exclusion of solar penetration in designing windows. Liping *et al.* (2007) carried out an optimized and comprehensive evaluation using building simulation and indoor CFD (computational fluid dynamics) simulation for an accurate prediction of indoor thermal environment for naturally ventilated buildings in the hot-humid climate of Singapore. The window size in this coupled simulation was made to vary from WWR= 0.1 to WWR= 0.4 for all orientations. Their results show that the optimum window to wall ratio is equal to 0.24 and horizontal shading devices are needed for the four orientations, especially for large windows for further improvement in indoor thermal comfort.

It should also be noted that Mathur and Chand (2003) argue that that rooms in which identical windows are on opposite walls, the average indoor air speed increases rapidly with the increase of the width of window, up to about 2/3 of the wall width; beyond that, the increase in air speed is in much smaller proportion.

A study carried out by Ossen *et al.* (2005) to assess and compare the impact of horizontal shading devices in reducing unwanted solar heat gain and the amount of natural light penetration into the building will be discussed in the section on 'Shading device'.

3.4.5.2 Orientation

Gut and Ackerknecht (1993) note that openings in hot and humid regions should be placed according to the prevailing breeze so that air can flow through the internal space. However, this is difficult to achieve in multi-unit housing. Ahmed (1987) in her study on the effects of climate on the design and location of windows for buildings in Bangladesh states that the orientation of windows should aim at excluding solar penetration. She has also claimed that windows should be avoided on western walls as it is almost impossible to shade it in all seasons. Liping *et al.* (2007) also emphasize on avoiding east or west facing rooms for the purpose of thermal comfort and energy use. However, there are situations in Dhaka, where the orientation of building due to the site orientation is such that the west facade of a building is the front facing. In such cases, the architect and developer may not want to design a boring solid front facing wall. Rather, they go for big glazed surfaces only to make the building attractive. The solution might lie in having well-designed verandahs and roof overhangs. The surface that has the verandahs can have glass openings which are 2.1 metres in height, which serve both as window and door.

3.4.5.3 Shading device

Watson and Labs (1983) categorized shading devices into three categories namely solar transmittance of glazing materials, interior shading and exterior window shades. Solar transmittance is defined as the heat admitting or rejecting characteristic of the glazing materials.

Watson and Labs (1983) and Gut and Ackerknecht (1993) advice against heat absorbing, heat reflecting and tinted glazing. According to Watson and Labs (1983) heat absorbing clear and

tinted glazing reduces solar transmission by absorbing heat within the material itself. They state that the absorbed heat can be uncomfortable to occupants because it adds heat to the interior by conduction and thermal radiation. They also state that another disadvantage of heat absorbing and heat reflecting glazing types is that they block needed solar gain in winter and summer solar irradiation. Most of these glasses as Gut and Ackerknecht (1993) claim are limited in their effectiveness because their own temperature is raised, which increases the heat convected and re-radiated into the internal space, or they tend to reduce light rather than heat.

Glazing materials in residential buildings of Dhaka are clear and tinted without any solar transmittance properties. Special glasses such as heat reflecting and heat absorbing will not be considered for the context of Dhaka because they are not locally available. Heat absorbing and heat reflecting glasses could be used for air-conditioned buildings as proposed by Gut and Ackerknecht (1993). However, it would increase construction costs as the glasses would need to be imported.

In residential buildings of Dhaka, drapes and curtain is used for interior shading. Lam *et al* (2005) conducted a study to estimate cooling loads and energy use for conditioning due to the heat gain through building envelopes. They used a simulation program to investigate the likely impact of internal shading devices such as venetian blinds on cooling loads and electrical use. Their study shows that use of venetian blinds can bring about an energy reduction of 14%. Venetian blinds are usually not used in residential buildings of Dhaka. Furthermore, use of venetian blinds depends entirely on the choice of households. It is a decision that cannot be influenced by architects. Only the interior designers can influence the households to use venetian blinds.

Cheung *et al.* (2005) studied the effects of shading devices (overhangs and wing walls) along with five other passive design strategies on the cooling load for an apartment. The length of the overhang and wing wall were 1.5 metres each. Their results suggest that the longer the shading, the greater the reductions in both annual required cooling energy and peak cooling load (Figs. 8 and 9). They concluded that the use of such shadings, achieved savings of approximately 5% in annual required cooling energy. However, according to Mowla (1985), the length of shading devices depends on the orientations, width of the opening, height of the openings, horizontal shadow angle (characterises a vertical shading device) and vertical shadow angle (characterises a horizontal shading device). Hence, it is not reasonable to conclude that shading devices should have arbitrary lengths in general for all orientations.

Wong and Li (2007) used horizontal shading devices of lengths 0.3m, 0.6m and 0.9 m on both east and west facades of 14-storied building to study the effect on cooling load. Their results show that 3%, 7% and 10% energy can be saved by using 0.3 m, 0.6 m and 0.9 m respectively on east facades of the studied building. Similarly, 3%, 6% and 9% energy can be saved by using 0.3 m, 0.6 m and 0.9 m respectively on west facades of the studied building. This study by Wong and Li (2007) considers east and west orientations but does not consider other parameters such as width of the opening, height of the openings, horizontal shadow angle and vertical shadow angle.

Mowla (1985) has suggested using horizontal overhangs in the buildings of Dhaka for all facades except north; vertical fins for all facades except south and egg-crate (combination of horizontal and vertical) for east, west, south-east and south-west facades. However he claims that even

small projections over the windows on the southern facade are able to cut off direct summer sun because southern facades do not get any sun throughout the day. He suggests vertical fins for either side on the windows in north because except during early morning or late afternoon in summer, the sun does not shine directly on the northern facade. His study however, does not specify lengths for the shading devices and his study was not based on determination of energy savings by using shading devices.

Ossen *et al.* (2005) carried out a study using compute simulation to explore the effect of six different alternatives on incident solar radiation, transmitted solar heat gain, natural light penetration and energy use. Their main objective was to assess and compare the impact of horizontal shading devices in reducing the unwanted solar heat gain and the amount of natural light penetration into office buildings in Malaysia. The base-case model developed for the study was a single unit office room with dimensions of 6 metres for length and depth and a height of 2.8 metres (Fig. 7). The size of the window was taken to be 4.4 metres in length and 1.82 metres height (from sill to ceiling line). The window area was assumed to be 50% of the net external wall area. The corresponding window to floor area ratio was 22%.

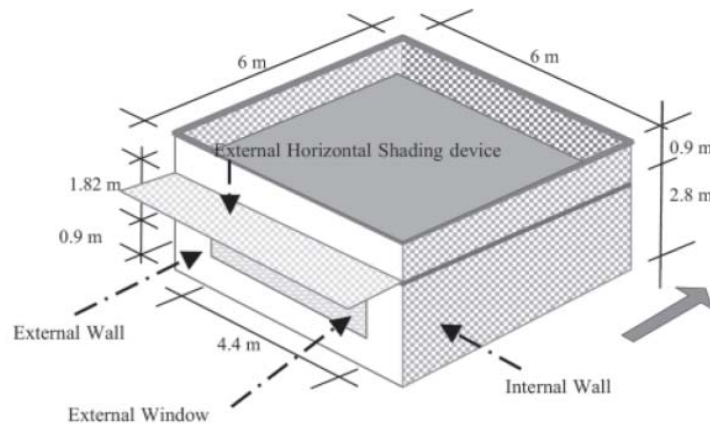


Fig. 7. Overhang design

Source: Ossen, D.R., Ahmad, M.H. & Madros, N.H. 2005

The depth of the overhang (external horizontal shading device) was the main variable in this study. A range of overhang depths were investigated to determine the optimum shading in terms of terminating maximum solar heat gain from form direct solar radiation. Table 4 outlines the various overhang depth studied and the relative overhang ratio (OHR).

Table 4. Description of Tested Cases for Independent Variable

OHR= D/H	Overhang Depth (Metres)
D= Overhang depth	
H= Fenestration height	
0.4	0.73
0.6	1.09
0.8	1.46
1	1.82

1.4	2.55
1.6	2.92

Source: Ossen, D.R., Ahmad, M.H. & Madros, N.H. 2005.

The findings from their study are summarized as follows:

1. Horizontal overhang ratios of 1.2, 1.6, 0.6 and 0.8 reduced direct solar radiation incident on the window pane by more than 80%.
2. Horizontal overhang ratio of 1.4 for both north and south reduced transmitted heat gain by 35.9% and 38% respectively. Similarly, horizontal overhang ratio of 1.4 for both east and west reduced transmitted heat gain by 48.9% and 45.4% respectively.
3. A work plane illuminance of 500 lux (SI unit of illuminance) was achieved by overhang ratios of 1, 1.3, 0.4 and 1 for east, west, north and south orientations respectively.
4. Increase of overhang ratios indicated energy saving for cooling. When cooling energy saving reached the optimum range, lighting energy use increased significantly.
5. Horizontal overhang ratios of 1.3, 1.2, 1 and 1 for east, west, north and south orientations respectively indicated optimum total energy savings of 14%, 11%, 6% and 8%.

Ossen *et al.* (2005) conclude that in hot and humid climates, external solar shading is the best option to optimize total energy use, considering the trade off between total heat gain and natural light penetration. This study, considered orientations and height of opening when determining the depth of the overhang hang. However, they did not consider horizontal shadow angles, vertical shadow angles and width of openings.

After considering all the studies on shading device, it is reasonable and logical to accept the proposal of Ossen *et al.* (2005) for the context of Dhaka because of the parameters they have considered in determining the length of shading device; and because they have also considered the trade off between total heat gain and natural light penetration when calculating total energy savings.

3.4.5.4 Natural ventilation

Ventilation is the movement of air. According to Watson & Labs (1983), ventilation has three useful functions in the building sector. It is used to:

1. satisfy the fresh air needs of the occupants
2. increase the rate of evaporative and sensible heat loss from the body
3. cool the building interior by an exchange of warm indoor air by cooler outdoor air.

Watson & Labs, 1983 explain that natural ventilation can be generated by the following two forces:

1. Temperature difference between the outdoors and the indoors (thermal force).
When a mass of air inside the room is heated, it expands and becomes less dense and rises. If openings are provided at different heights on the building's envelope, the indoor pressure is higher at the upper opening and lower at the lower opening. These pressure differences generate an inward flow at the lower opening and an outward flow at the

upper one. When thermal forces discharge air from a building, the action is termed as stack effect.

2. Wind flow against the building (wind pressure force).

As wind blows against a building, the air in front of the building is compressed and creates a pressure zone. The air next to the leeward wall and above the roof expands and the pressure is reduced, creating a suction zone. These pressure differences between any two points on the building's envelope determine the possibility for ventilation when openings are provided at these points (driving force) and if air can flow inside the building through openings with the higher pressure to openings exposed to a zone with lower pressure. Cross-ventilation is defined as the situation in which outdoor air can flow in through inlet openings, located in the pressure zone, and flow out via outlet openings located in the suction sections of the building

Wong and Huang (2004) made a comparative study on the indoor air quality of naturally ventilated and air-conditioned bedrooms of residential buildings in Singapore. They observed that CO₂ levels of bedrooms using air conditioners are consistently higher than those utilizing natural ventilation. Thermal comfort comparison of the air-conditioned bedrooms and naturally ventilated bedrooms indicate that the air-conditioned bedrooms are usually substantially overcooled, resulting in extremely high PPD (Percentage People Dissatisfied). Whereas, in natural ventilated bedrooms, the utilization of fans was sufficient to achieve the required thermal comfort. They also found that occupants utilizing air conditioners exhibited more SBS (sick building syndrome) symptoms than those utilizing natural ventilation. Liping *et al.* (2007) also conclude that natural ventilation is an attractive alternative to reduce the associated problems with air-conditioned buildings because natural ventilation has potential benefits such as reduced operation costs, improved indoor air quality and satisfactory thermal comfort.

Hirano *et al.* (2006) explored the possible effects that a porous building model may have on the natural ventilation performance and cooling load reductions in hot and humid regions (latitude 26° N and longitude 127° E). Two types of residential building models, namely a model with a void ratio of 0% and a “porous” model with a void ratio of 50%, were employed in the simulation (Figs. 8 and 9).

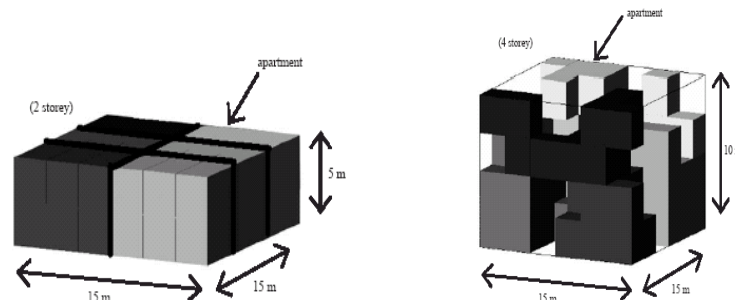


Fig. 8. (Left) Residential building model with a void ratio of 0% (with six apartments)

Fig. 9. (Right) Residential building model with a void ratio of 50 % (with six apartments).

Source: Hiranoa,T., Katoa,S., Murakamib, S., Ikagac, T. & Shiraishi, Y. 2006.

The model with a void ratio of 50% has 50% of its capacity occupied by voids, and the model with a void ratio of 0% is a simply shaped residential building without voids. Each model has 72 cubes (2.5 m each) and 12 cubes form an apartment. Each building model, therefore, consists of six apartments (Fig. 10).

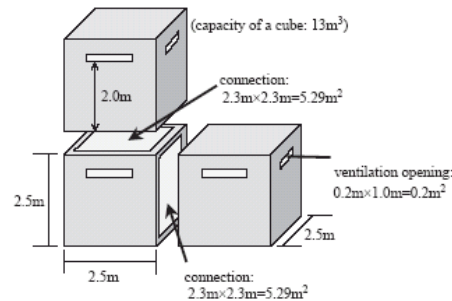


Fig. 10. Standard cube components of a residential building model.

Source: Hiranoa,T., Katoa,S., Murakamib, S., Ikagac, T. & Shiraishi, Y. 2006.

Each side of a cube has a ventilation opening dedicated to ventilation. This opening has dimensions 0.2 m by 1.0 m and is placed near the ceiling (0.5m –0.3m below the roof of the cube). The position of the opening is considered to be effective for a natural ventilation-aided cooling system. Owing to its shape, the model with a void ratio of 50% has more than three times as much opening area as the 0% model. CFD (computational fluid dynamics) analysis and thermal and airflow network analysis of the two models reveal that the model with a void ratio of 50% is more effective than the model with a void ratio of 0% in terms of air change rate (about four times larger) and average wind velocity at the openings (around 30% faster). The thermal and airflow network analysis shows that the sensible heat load for cooling is reduced by more than 20% by the effects of voids. This seems to be due to the improvement in the natural ventilation performance and particularly in the reduction of the internal load. The latent heat load also decreases by more than 10%, and the total heat load is reduced by around 20%. Accordingly, it can be concluded that the porous building model is effective in enhancing the natural ventilation (both cross-ventilation and ventilation due to thermal force) performance and, consequently, in reducing the cooling load in hot and humid regions.

Though the model with a void ratio of 0% is said to resemble the low storey housing in many of the cities in hot and humid regions, it is not quite true for Dhaka. Most of the residential housing in Dhaka is six storied and the buildings utilize every square inch of the land available. With Dhaka's enormous population and scarcity of land, such a model for Dhaka seems very unlikely because the voids would reduce the floor area and would incur higher construction costs.

Ahmed (2006) conducted a study in Dhaka to explore air change in still outdoor conditions in rooms with a single window. The study focuses on the design aspects of windows as a function of indoor airflow pattern generated by ceiling fans. Results from the full scale study and simulation studies using Computational Fluid Dynamic Software (CFD) showed that in rooms with single sided window-displacement, having two openings, one at sill level and the other above lintel level (2.14 m), displacement ventilation can be achieved with the aid of a commonly

used ceiling fan (Fig. 11). It can be stressed here that the electricity used by fans accounts for a small amount, less than 1% of the total household electricity use (Lam, 1996).

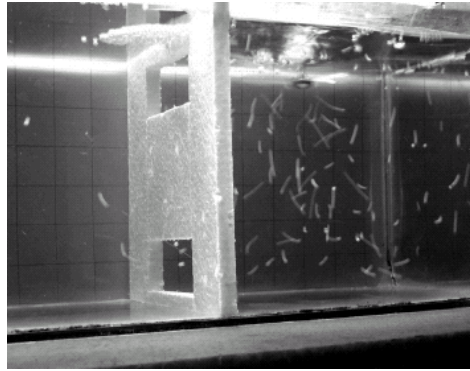


Fig. 11. Particle flowing out through the lower opening (indicated by motion blurs).

Source: Ahmed, K.A., Haq, A. & Moniruzzaman, M. 2006.

It has already been mentioned that not all rooms in multi-unit residential buildings of Dhaka have two exposed surfaces to ensure cross-ventilation. Furthermore, rooms that have single walls exposed to outdoors, have windbreaks because of the close proximity of the surrounding buildings. Furthermore, natural wind flow is not a continuous occurrence and there are still periods in different times of the day even in open areas. This study by Ahmed indicates that with two openings at different levels, the prospect of fan-induced ventilation is considerably increased. Mallick (1996) elaborated that in dense urban situations, where airflow is not always possible due to security grills and insect nets, ceiling fans are a reliable source of cooling if they are set at maximum or high speeds.

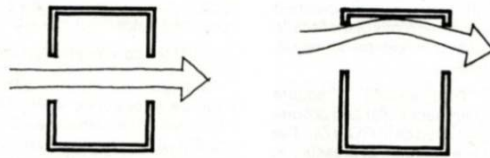
Another common natural ventilation and thus cooling technique is the use of atria and courtyards. A study of courtyards by Ali (2007) in Dhaka uses two typologies of six storied residential apartments, namely, the courtyard type and the non-courtyard type for comparison of thermal data. The results of this comparative analysis reveal that the buildings with courtyards are much more comfortable and thus desirable for the dwellers of Dhaka. However, due to constricted plot sizes, the dimensions of courtyards are such that they portray more as light well rather the true essence of courtyards. Furthermore, studies by Aldawoud and Clark (2008) and Safarzadeh and Bahadori (2005) show that courtyards can reduce the cooling energy needs of single-storey buildings by only a relatively small amount.

Guidelines for inducement of air motion for providing cross-ventilation as recommended by various authors are compiled as follows:

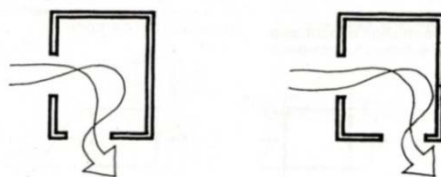
- There should be windows on opposite walls: one window should be on windward wall and the other on leeward wall (Mathur & Chand, 2003). However, as residential buildings in Dhaka are compact and not outward oriented, all rooms do not have windows in opposite walls. In such cases, two windows may be designed instead of a single window. Another possibility might include a door on the opposite facade of a

wall with the window to promote cross-ventilation. However, it would not be as effective as having two windows on opposite walls.

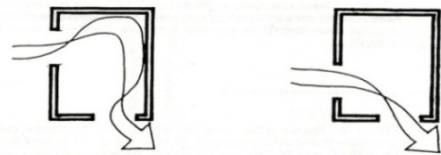
- Windows located diagonally opposite to each other (Fig. 12), with the windward window near the upstream corner, perform better than other window arrangements (Mathur & Chand, 2003). In typical residential buildings of Dhaka, not all rooms are provided with windows on opposite. Even if they are, as rooms are not very large (about 10 square metres) windows are placed in the centre of the facade because placement of furniture depends on window location.



Plans in which internal wind speed will be high but in which most of the space remains unaffected.



Relocating outlets to sidewall produces better wash of the interior.



Shifting intake window from centre of facade results in deflection of interior air current. Depending on location of outlet, this may improve or short-circuit the current with respect to its wash of the interior.

Fig. 12. Orientation of openings

Source: Watson, D. & Labs, K. 1983.

- Horizontal louvers like sunshades, over a window deflect the incident wind upward and cause a reduction in air motion in the zone of occupancy (Fig. 13). A horizontal slot between the wall and horizontal louver prevents upward deflection of air and ensures a downward flow (Mathur & Chand, 2003). Sunshades in the buildings of Dhaka totally ignore this design aspect.

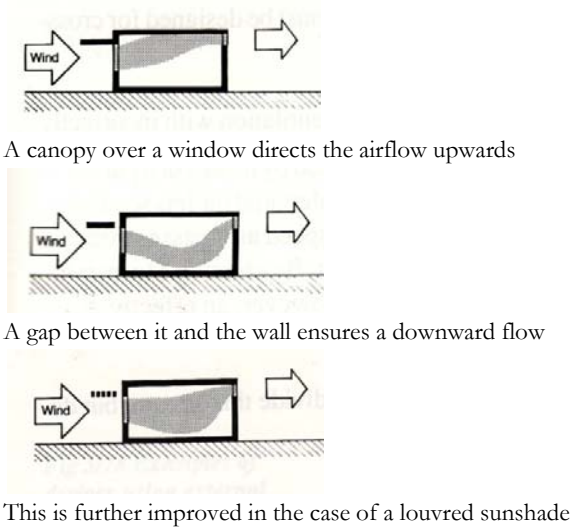


Fig. 13. Deflection by projecting slabs

Source: Gut, P. & Ackerknecht, D. 1993.

- Jalousie or louvered windows facilitate nearly unrestricted air movement. Louvered walls of wooden boards for example can also help facilitate airflow when used as interior partitions. A louvered door (Fig. 14) is ideal for porches, exterior rooms and spaces where openness is desirable without sacrificing security. Jalousie windows offer two advantages. One, it offers almost unrestricted openness in unbolted position (Fig. 15) and second, (Fig. 16) they restrict rain penetration (Watson & Labs, 1983). Louvered windows were used in traditional buildings of Dhaka. They are no longer used today because of the costs involved. Louvers can be made of opaque glass or aluminium to reduce costs. Louvers of aluminium frame or screen walls can be used on the part on the window that stretches to the beam in case of big windows that extend either from skirting to beam or sill to beam. The louvered openings below the beam can allow discharge of heated air by thermal force known as stack effect.

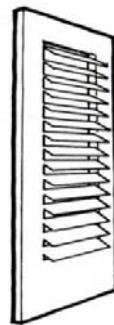


Fig. 14. Louvered door

Source: Watson, D. & Labs, K. 1983.

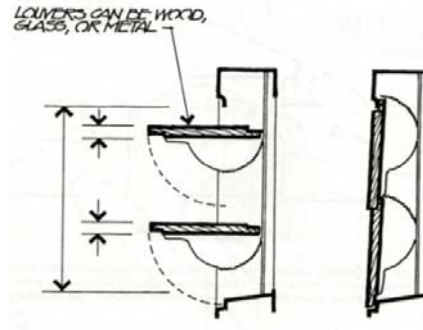


Fig. 15. Benefit of jalousie window: unrestricted openness in open position

Source: Watson, D. & Labs, K. 1983.

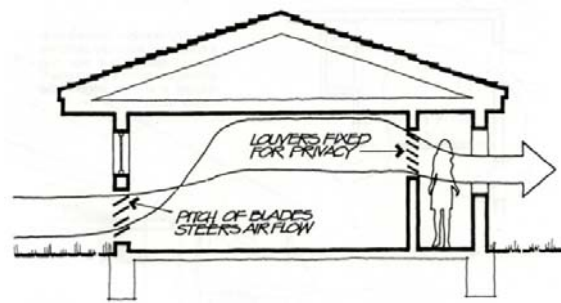


Fig. 16. Benefit of jalousie window: restrict rain penetration

Source: Watson, D. & Labs, K. 1983.

- Roof overhangs (Fig. 17) help air motion in the working zone inside buildings (Watson & Labs, 1983). However, this is only possible on the top most storey.

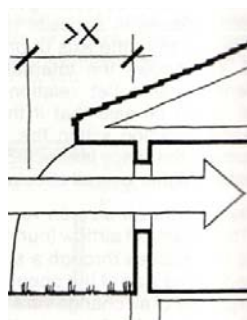


Fig. 17. Benefit of roof overhang

Source: Watson, D. & Labs, K. 1983.

- Wall projections such as fin (Fig. 18), wing wall can be used to direct wind flow into particular areas. (Watson & Labs, 1983). Compared to roof overhangs, fins seem to be more effective because they direct air flow in all floors. However, they might not always be easy to plan.



Fig. 18. Wing wall outside window

Source: Watson, D. & Labs, K. 1983.

- Parapets create greater ventilating-driving pressure by increasing air-damming action (Fig. 19). They may also be used to divert airflow in the living zone (Watson & Labs, 1983). This feature is effective only on the topmost floor, below the roof. Remaining floors in the building shall not be benefitted from this design feature.

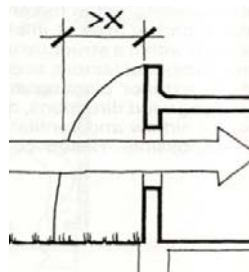


Fig. 19. Air-damming action of parapet

Source: Watson, D. & Labs, K. 1983.

- Balconies open on three sides is preferable as it can create an increase in air movement for most of the orientations of building with respect to the incident wind (Mathur & Chand, 2003). However, for the context of Dhaka, where air movement is necessary for comfort and shading is also needed to exclude solar heat, roofed balconies or verandahs are more appropriate.

3.4.5.5 Daylight

Krarti *et al.* (2005) conducted a simplified analysis method to evaluate the potential of day lighting to save energy associated with electric lighting use in commercial buildings. Performance of day lighting were investigated for several combinations of building geometry, window opening size, and glazing type for four geographical locations in the United States. Their simulation

results indicate that day lighting saves 31% of the total annual energy use from the artificial lighting system.

4 METHODOLOGY

4.1 Research Methodology

The study was extended to three main phases. The first and third phases consisted of desk studies that were conducted in Sweden. The second phase was a field research that was held in Dhaka.

The first phase defined the theoretical framework for this study. In addition, it identified the methodology of analysis and issues that were investigated in the case study. This phase, mainly a desk study, encompassed extensive literature reviews of books, journal papers, researches and documents to identify energy efficient design principles that could be used for the context of Dhaka.

The second phase involved a field trip to Dhaka for one month in the middle of January. The fieldwork consisted of visits to the instrumental case study with embedded units and interviews with the residents of the case study building. The case study is a multi-unit residential building that is representative of inefficient energy buildings in Dhaka city. Quantitative and qualitative data were collected from the case study building. All the information that was analyzed during this phase was intended to fulfil the structure outlined in theoretical framework formed in the first phase. As the fieldwork was done during winter, temperature readings inside the flats were not taken. Secondary sources such as articles in local newspapers or in the internet were also used to complement the information. The barriers for adopting energy-efficient solutions in residential buildings were investigated in this phase by interviewing developers, architects and other concerned people.

The third phase comprised of a desk study for the second time to analyze and evaluate the data from the first and second phase studies using quantitative and qualitative methods. The data on energy use of different flats/units in the building were analyzed quantitatively and the design features of the apartment were analyzed both quantitatively and qualitatively according to the basic design principles laid out in the theoretical framework.

Energy efficient principles that were identified through literature review were summarized and analyzed quantitatively to determine the energy savings of all the features that could be applied in the context of Dhaka. Calculations were then made to see how much energy the flats surveyed in the case study building could save, by adopting the energy efficient design principles.

4.2 Case study methodology

4.2.1 Research design

Yin (1994) defines case study research as an empirical enquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and the context are not evident. According to Yin, the method is the most important characteristic of a case study. Stake (1998) on the other hand argues that case study is not a methodological choice, but a choice of object to be studied. This object of study as Stake puts

it is a case. In accordance with Stake's definition, every study that has a case as the object of study is a case regardless of the methods used. Case study can be regarded as a research that incorporates several different methods for the collection of data and for the analysis and processing of findings.

Yin (1994) differentiates between two types of case studies: holistic and embedded. The holistic case study focuses on the case as a unit of analysis. On the other hand, embedded case study is one in which the case still functions as the unit of analysis; however, there are also subunits of analysis within the case. In this research, the three-unit residential apartment that houses upper middle-income groups is the primary case and the seven different households surveyed are the embedded units of analysis. The case study performed in this research is an embedded case study.

Yin (1994) also distinguishes between a single-case design and a multiple-case design. Single-case design uses only one case to deal with the research questions and in multiple-case design, two or more cases are studied. The research undertaken uses a single-case design with seven embedded units.

Stake (1998) makes a distinction between three types of case study: intrinsic, instrumental and collective. In an intrinsic case study, study is undertaken because one wants better understanding of that particular case (Stake, 1998). An instrumental case study is one in which a particular case is examined to provide insight into an issue or refinement of theory (Stake, 1998). A collective case study is an instrumental study that is extended to several cases (Stake, 1998). The case study in this research is instrumental in nature.

4.2.2 Selection of case study

In this research, the three-unit residential apartment that houses upper middle-income groups is the primary case and the seven different households surveyed are the embedded units of analysis. The selection of the case study building was based on the following criteria:

- It is representative of typical multi-unit residential building design in Dhaka
- The architectural drawings of the apartments were available
- It was accessible
- The households were cooperative.

4.2.3 Issues investigated/ units of analysis

Apart from the design aspects that were identified in the theoretical framework, the following issues in the case study apartment have also been investigated:

- energy use practices of households (appliances used, energy used by those appliances)
- energy use for cooling and lighting in typical multi-unit residential buildings of Dhaka
- general living pattern of the households
- role of architects, developers and interior designers in designing energy efficient buildings

- role of architects, developers, interior designers and clients (land owners) in creating barriers for designing energy efficient residential buildings
- common amenities provided by the developers in typical multi-unit residential buildings of Dhaka.

4.2.4 Data gathering strategies

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

- qualitative and quantitative physical survey of the case study building
- qualitative and quantitative semi-structured interviews that have open and closed questions
- quantitative calculation of energy use
- qualitative and quantitative architectural drawings of the case
- archival records of computerized quantitative statistics on the climate of Bangladesh
- quantitative statistics from newspaper clippings.
- photographs (qualitative and quantitative)

4.2.5 Evaluation and analysis of the data

The data gathered called for a number of different methods of analysis in order to find linkages between the research object and the outcomes with reference to the original research questions. Throughout the evaluation and analysis process, options were kept open to new opportunities and insights. Data has been categorized, tabulated, and recombined to address the initial purpose of the study. Facts and discrepancies in accounts have been crosschecked by using triangulation, as explained in the next section. Focused, short, repeated interviews were necessary to gather additional data to verify key observations or check a fact. Data was analyzed by placing information into array, creating tables, excel spreadsheets. Specific techniques include placing information into array, creating matrices of categories, creating pie charts, tables and excel spreadsheets.

4.2.6 Validation of results

The data obtained from the instrumental case study with seven embedded units have been validated by triangulation. Triangulation, as Johansson (2003) says, is the most important way of making the results of a case study valid. Stake (1998) defines triangulation as a process of using multiple perceptions to clarify meaning by identifying different ways in which the phenomenon is seen. According to Garson (2002), the case study method, with its use of multiple data collection methods and analysis techniques, provides researchers with opportunities to triangulate data in order to strengthen the research findings and conclusions.

According to Patton (1990), there are four different methods of triangulation in connection with qualitative methods:

- Data triangulation: several sources are used to collect data about the same phenomenon.
- Researcher triangulation: several researchers study the same phenomenon.

- Theory triangulation: the same data is analyzed using different principles.
- Method triangulation: several methods are used to gather data about the same phenomenon.

Among the different methods of triangulation described above, data triangulation, researcher triangulation and method triangulation were used in this study. Seven embedded units (the different households) in the case study building were used for data triangulation to investigate the issues or attributes of interest mentioned in Section 4.2.3. Data triangulation was also used to investigate the usage of air conditioners (different members in the family have been asked individually). Lighting conditions were crosschecked through method triangulation (interview, observation, photographs). Cross ventilation inside the rooms is triangulated by employing method triangulation (interview, observation).

4.2.7 Generalization

Flyvbjerg (2006) has addressed the misunderstanding that one cannot generalize based on an individual case and therefore the case study cannot contribute to scientific development. He has revised this misunderstanding, so that it now says:

'One can often generalize on the basis of a single case, and the case study may be central to scientific development via generalization as supplement or alternative to other methods. However, formal generalization is overvalued as a source of scientific development, whereas "the force of example" is underestimated.'

According to Svane (2005), architects customarily use a form of systematic generalization known as naturalistic generalization. Architects, based on their knowledge, professional training and experience are able to make systematic comparisons from similar examples; choose what is relevant to the specific context and design something unique. In naturalistic generalization, the reader or the user of the findings is confronted with uncontrollable generalizations, taking place in his or her mind. In this type of generalization, it is the reader who does the generalization by reflecting and relating to the results based on his or her experience or lack of it. It is thus left up to the reader or the user of the findings in this study to compare the examples and accept this study as one case in her or his compilation of related cases.

5 RESULTS: CASE STUDY FINDINGS AND DATA ANALYSIS

5.1 An overview of the case study building

The building is in Lalmatia residential area (Fig. 20), an upper-income neighbourhood, located at the heart of the city. Mohammadpur and Sher-e-Bangla Nagar to the north, Raja Bazar to the east and Dhanmondi and Rayerbazar to the south surround Lalmatia. Lalmatia is within walking distance of Bangladesh's National Assembly Building.



Fig. 20. Location of the case study building in Lalmatia, Dhaka

Source: Google Map



Fig. 21. The Case Study Building

The case study building (Fig. 21) is a typical six-storied multi-unit residential building with three flats on each floor and fifteen households. This type of multi-unit residential building is popular in Dhaka because of the increasing pressure on land and the dynamic changes in then urban lifestyle. Due to scarcity of land, old single-family houses are demolished and in its place residential buildings are built by developers. The process of constructing a building begins as the owner of a particular plot of land gives the land to the developer under a deal. In return of the land value, the owner usually gets 50%- 60 % of the flats that the developer would construct on that land. The developers sell the remaining 40 % to prospective clients. For reasons of profitability, both parties (developer and land owner) aim in constructing as many units /flats per floor as possible. In this case, the owners of the land (households of Unit B4 and household of another flat that was not surveyed) got seven flats out of 15. Thus the flats in this building are resided by both owners and tenants.

The three different flats/units in the building are: Type A, Type B and Type C (Fig.22). The sizes of flat Type A, B and C are 120, 122 and 120 square metres respectively. Type A is surrounded by a road on the southern side and by a residential building on the eastern side. Two roads, one on the western side and the other on the south, surround Type B. Type C is surrounded by a road on the west side and a residential apartment on the north.

Seven out of fifteen households were surveyed. These households are A2, A3, B2, B4, B5, C1 and C5. The residents of C1 are tenants; all other flats surveyed are owned by the households.

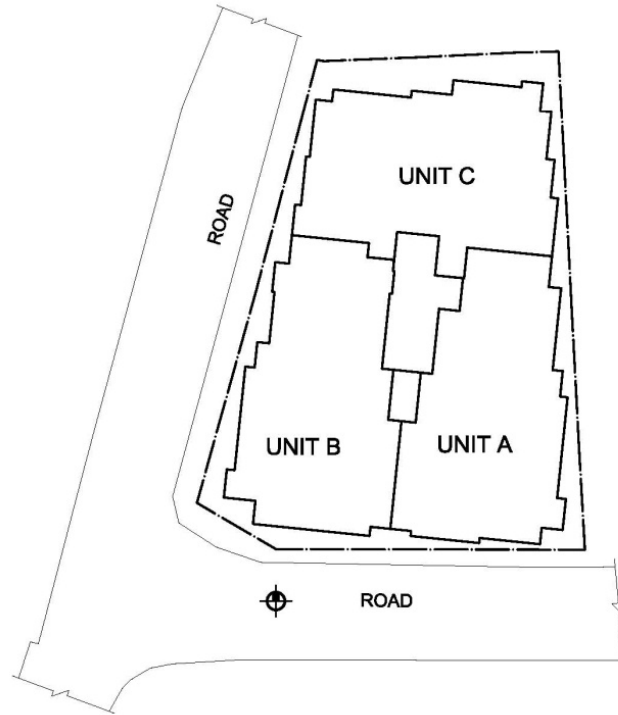


Fig. 22. Location of different units in the case study apartment

5.2 Design features of the case study building

5.2.1 Planning aspects of the case study building

5.2.1.1 *Site analysis:*

As buildings in Dhaka are densely packed, it is usually only the front that gets road side exposure. However, this case study building is sited on a corner plot and thus, it has two road facing exposures (Fig. 23). The building is interesting to study because of the strategic location of the flats: only one flat (south-western) has two road-side exposures, whereas the remaining two apartments have exposures only on one side. Two roads, 15 metres wide are flanked on the western and southern side of the plot (Figs. 23 and 24). Two other residential buildings surround the building: one on the north and the other on the east. The distance between the case study building and the two buildings on the north and east is 1.8 metres each (Figs. 25-30). The proximity of the surrounding buildings has both positive and negative effects. Negative, because they create windbreaks by impeding desirable breezes, block daylight from penetrating and disturb privacy; positive, because the surrounding buildings provide shade.



Fig. 23. Site plan of the case study building



Fig. 24. Two fifty feet width roads flanked on the western and southern side of the case study building



Figs. 25 and 26. The case study building and the building next to it on the eastern side



Figs. 27 and 28. Case study building and the building next o it on the northern side



Figs. 29 and 30. Narrow space between the case study building and the building next to it on the east

Building form:

The building has a compact shape (Figs. 31 and 32), unlike the form suggested by Gut and Ackerknecht (1993). They suggested buildings with spread-out forms for warm-humid climates. Givoni (1998) recommended a compact shape only if buildings are to be dependent on air conditioners. A discussion with the developers and architects of the building revealed the reality concerning the building form. The compactness of the form was not intended to support air conditioning. In fact, it had nothing to do with air conditioning. The compactness of the form was a result of maximum utilization of floor area.



Fig. 31 and 32. Compactness of the case study building

5.2.1.2 Building orientation

The long axis of the building runs north-south, i.e. the facades on the west and east are bigger than the north and south elevations (Fig. 33). The orientation of the case study building is contrary to the recommendation of Gut and Ackerknecht (1993) and Wong and Li (2007). They state that the best orientation for buildings in tropical climates is for the longer axis of the building to lie along east-west direction to avoid solar heat gain.

Protection from solar heat gain on the west and east were not the guiding factors while orienting the building. The outline of the building follows the layout of the site. It is all about using every square inch. The orientation for wind flow is a problem only on the northeast, northwest and southeast sides because of the phenomenon of windbreak. The surrounding buildings on the north and east are so close that they block the airflow.

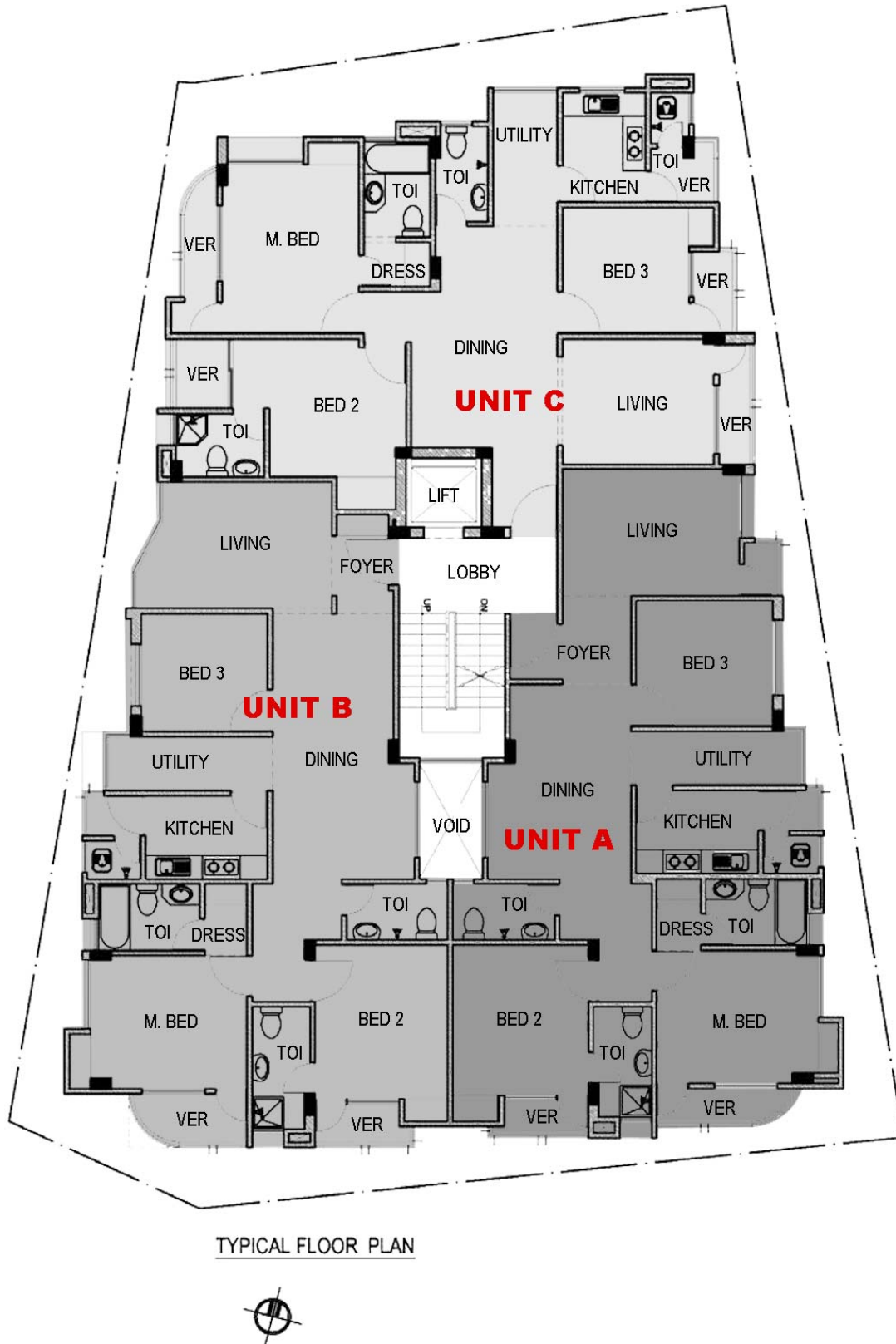


Fig. 33. Typical floor plan showing the longer axis oriented towards the north-south direction

5.2.1.3 Room arrangement

Gut and Ackerknecht (1993) have stated that the arrangement of rooms depends on their function and according to the time of the day they are in use. The households of the flats were interviewed about their occupancy pattern and the functions they perform in different rooms. Table 5 illustrates the number of residents in each flat, how many of those residents stay at home through out the day, their profession, the rooms they use the most and the location of television. Observation and interview demonstrate that dining spaces are the most frequently used rooms in all flats (Fig. 34). There is a culture of having a minimum of one housekeeper in the households of Dhaka. In addition, as it is the housewives aided by the housekeepers who do the cooking and household jobs, they prefer to use the dining space because it is easy for them to supervise the household tasks and cooking from the dining space. Another reason why the dining spaces are used the most among higher middle-income groups is because the family members catch up with each other and have meals together in the dining space. Households of Flat B5 do not use the dining room at all because both the households (husband and wife) work and return home late in the evenings. They do not cook their meals as they have meals with their parents who live in B4. They are the only family surveyed who do not have a housekeeper. However, even though, the dining space is the most frequently used room, it was given the lowest priority. It does not receive adequate daylight and is not well ventilated. This is a common scenario in almost all residential buildings in Dhaka.

Table 5. Occupancy pattern

Flat	No. of residents	Stays home throughout the day	Profession		Most occupied room	Location of TV
			Husband	Wife		
A2	5	1	Real estate developer	Doctor	Dining space, living room	Living and master bedroom
A3	5	2	Marketing manager	Housewife	Dining, Living room, master bedroom	Living
B2	4	3	Retired	Housewife	Dining space, living room, master bedroom	Living
B4	3	1	Civil Engineer	Teacher	Dining space, bedroom with TV	Dining & bedroom
B5	2	–	Officer, Resource management	Officer, Resource management	Study room & master bedroom	Study & master bedroom
C1	2	1	–	Executive officer	Dining space, master bedroom	Master bedroom
C5	6	5	Businessman	Housewife	Dining space and all bedrooms	Master bedroom & guest bed



Fig. 34. Dining space of Unit C5

The master bedroom was the second most used room followed by the living room. Both these rooms were used frequently because they had televisions (Figs. 35- 38). Watching television is the most common way of spending leisure time among upper middle-income households. Public spaces are so limited and have shrunk so much that people rely on watching television for relaxation and to pass time after they get home from offices.

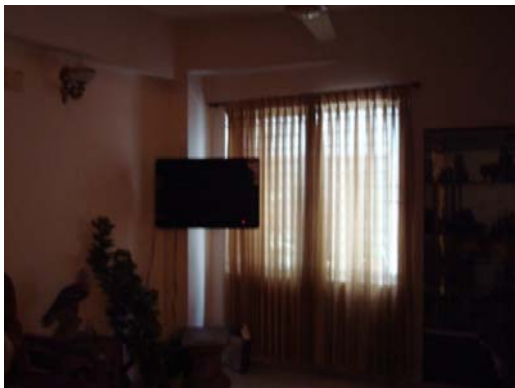


Fig. 35. TV in living room of Unit A3



Fig. 36. TV in living room of Unit A2



Fig. 37. TV in dining space of Unit B4



Fig. 38. TV in master bedroom of Unit B5

Among the flats surveyed, all A type and B type flats, flats B4, B5 and C5 have made changes in the internal layout of rooms. There were no changes in the internal layouts of flat C1 because the residents of this flat are tenants. In all the A type flats surveyed, the balcony in the living room has been made part of the indoor space of the room (Figs. 39 and 40). Neither the A nor the B type flats have the utility space beside the kitchen. It has been made part of the kitchen space.



These spaces, originally designed as verandahs, now form part of the interior space.

Figs. 39 and 40. Change in plans of unit A3 (left) and A2 (right)

Flat B4 does not have the bedroom beside the living room. Instead, the wall dividing the two rooms has been removed to form one big living room (Fig. 41).

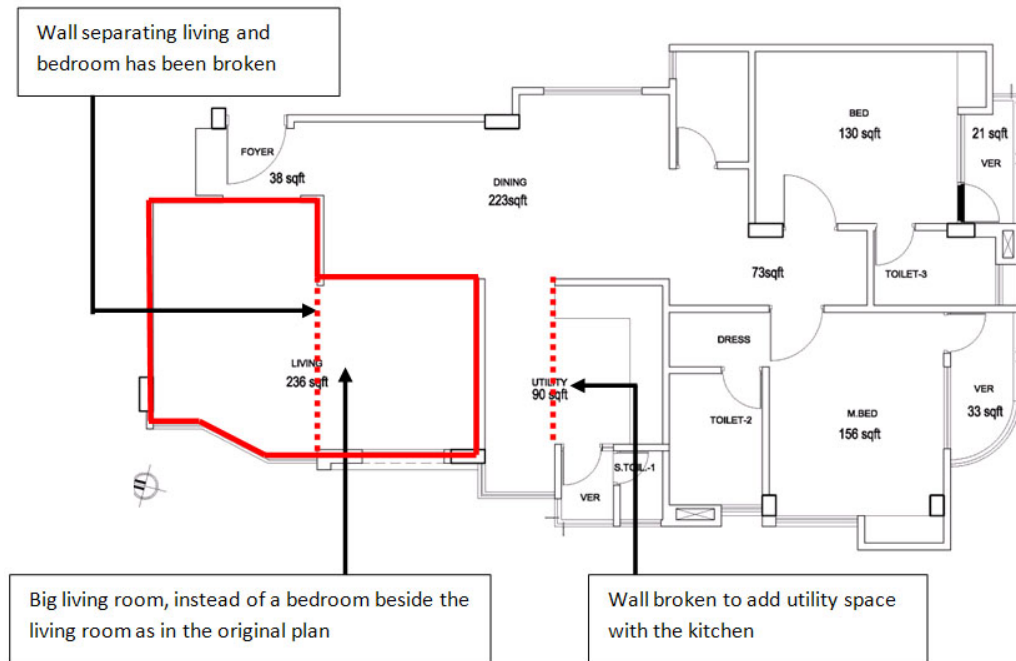


Fig. 41. Floor plan of Unit B4

Residents of flat B5 have reduced the size of the bedroom beside the living room, making it into a study room (Fig. 42).

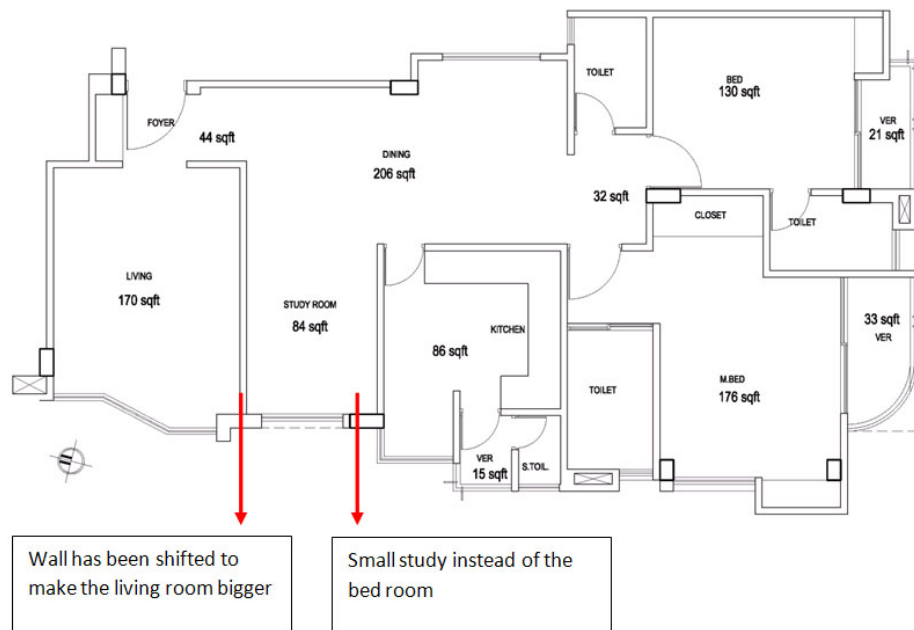


Fig. 42. Floor plan of Unit B5

Residents of flat C5 have broken the wall dividing the two verandahs on the western side, thereby, turning two verandahs into one.

Besides arranging rooms according to their function and time of the day they are in use, Gut and Ackerknecht (1993) also recommended detaching main rooms from rooms with internal heat load such as kitchens. The kitchen in all three units of the case study building is located beside a bedroom on one side and toilet on the other side. The internal heat gain from the kitchen is likely to get transmitted to the bedroom and raise the temperature of the bedroom. In addition, condensing units of split air conditioners in certain rooms of some units of the case study building are fixed on the exterior walls of the rooms that contain the split air conditioners. These condensing units not only raise the temperatures inside the rooms by transmitting heat, but also spoil the aesthetic quality of the building's external facade.

5.2.1.4 Room orientation

The orientation of each room in each individual flat surveyed will not be discussed as the planning of each type of flat is basically the same through out the building. Rather, the orientation of rooms in each type (A, B and C) of flat will be discussed. Table 6 shows the orientation rooms in all flat types (A, B and C).

Table 6. Orientation of rooms in all flat types (A, B and C)

	Living	Dining	Master bedroom	Bed room 2 (beside master bedroom)	Bedroom 3 (beside living room)	Kitchen
A type flats	East	Central	South, east	South	East	East
B type flats	West	Central	South, west	South	West	West
C type flats	East	Central	North, west	West	East	North, east

▪ Flat type A:

The orientation of bedrooms and living room in this type of flat is good because none of these rooms is located in the west. According to Gut and Ackerknecht (1993), stores and other auxiliary spaces should be located on the disadvantaged side, mainly facing west. Even though the kitchen and living room are located on the east, they do not get much heated during the day because of the shade provided by the building beside it. Only the dining space does not have a proper orientation in all flat types. Even though the kitchen is a source of internal heat load, it has not been separated from the bedroom beside it. Gut and Ackerknecht (1993) pointed out that bedrooms can be located on the east side because it is coolest in the evening. Accordingly, the bedroom beside the living room on the east does not present problems of excess heat.

▪ Flat type B:

The master bedroom, the bedroom beside the living room and the living room are located on the west and therefore heat up in the afternoon. The households in all B type flats have complained

of excessive heat gain in these rooms. The households of Unit B2 (Fig. 43) have put up curtains in two layers in the master bed and households of Unit B4 (Fig. 44) and Unit B5 (Fig. 45) have put up curtains in two layers for protection from solar heat gain in the living room. Households of B5 use bed sheets as the second layer of curtain in the master bed and study room (Figs 46 and 47). All the B type flats surveyed have air conditioners in their master bed, located on the west (Figs. 48- 50). The households of flat B5 is planning to buy an air conditioner for their study room on the west.



Fig. 43. Two layers of curtain and A.C in master bed (located on west) of Unit B2



Fig. 44. Two layers of curtain in living room of Unit B4



Fig. 45. Two layers of curtain in living room of Unit B5



Fig. 46. Bed sheet behind curtain in master bedroom of Unit B5



Fig. 47. Bed sheet behind curtain in study room of Unit B5



Fig. 48. A.C in master bedroom of Unit B5 (located on west)



Fig. 49. A.C in living room of Unit B5 (located on west)



Fig. 50. A.C in living room of Unit B4 (located on west)

– Flat type C:

Both the master bedroom and the bed beside the master bed have exposures on the west. The residents in this flat type too have complained about excess heat gain even though, the rooms on the two bedrooms on the west have a balcony. Even though the living room is located on the east, it does not get much daylight and heat during the day because of the shade provided by the building beside it. C type flats like flat A type, have one bedroom on the east and they too do not present problems related with heat gain.

5.2.1.5 Landscaping:

Even though Raeissi and Taheri (1999) recommended proper plantation of trees to save energy and provide many other benefits, the only landscaping is a few plants inside the boundary wall (Fig. 51), some potted plants on the roof (Fig. 52) and some on the ground floor outside the boundary wall (Figs. 53 and 54). The setback space between the building and the boundary wall of brick, however, is not adequate (1.25- 1.8 metres) to grow big trees. As this building was built in 2006, before the new rules of Dhaka City Building Construction Act were developed, the only space left open is the setback space. According to the new rules of Dhaka City Building Construction Act-2008, at least 32.5% open space is recommended to be left open as green space.



Fig. 51. Potted plants inside the boundary wall



Fig. 52. Potted plants on the roof



Figs. 53 and 54. Plants outside the boundary wall

5.2.2 Building envelope

5.2.2.1 External wall and building material

All external walls are of 125 mm solid brick. Wong and Li (2007) and Mallick (1996) however recommend thicker construction on east and west external walls. It was explained in the section on external walls in the theoretical framework that 280 mm brick walls including an air cavity of 50 mm can be used to reduce the heat gain from solar radiation and reduce cooling energy by 7%-10 %.

The owner of flat B4 was the owner of the land. She now regrets the limited thickness of external walls. During the interview, she complained that the heat gain on the western side of the building is profuse and unbearable. She claimed that the developers had suggested 125 mm wall thickness to reduce the construction costs of the building. She now feels that the heat gain on the western side would have been less if the external walls were 250 mm. She has admitted that the extra costs of using 250 mm wall thickness would have been worthwhile.

Both external and internal walls have a cement plaster over the brick and white wall finishes. Some exterior walls that face the roadside are clad with light coloured facing bricks (Fig. 55) for uplifting the front facade. According to Cheung *et al.* (2005) it is possible to save 12% on cooling energy by using white or light colour external wall finishes. Hence, this building is therefore successful in saving 12% on cooling energy because of the light colour external wall finishes.



Fig. 55. Facing brick on the front facade

5.2.2.2 Thermal Insulation

In general, residential buildings in Bangladesh do not have insulations because it is considered expensive and difficult to maintain. In the case study building, neither walls and windows nor roofs, have any type of insulation. Absence of insulation does not present problems because the findings from the literature review are not in favour of it for the context of Dhaka.

5.2.2.3 Roof

The roof is flat, about 100 mm thick. It is made of reinforced concrete slab with weathering course and neat cement finish. The roof has one big room that functions as a community room (Fig. 56). The roof is also used by the residents for hanging laundry and as a community space (Fig. 57).

The option of using hollow clay tiles in place of weathering course as proposed by Vijaykumar and Srinivasan in Vijaykumar *et al.* (2007) can be used in this roof to generate energy savings.



Fig. 56. Community room on roof



Fig. 57. Clothes hung on roof

5.2.2.4 Windows

- Size and location

The windows are sliding with aluminium frame (Fig. 58) and have 5 mm thickness tinted glass. The opening of these sliding windows is limited to 50% of the window size and so is not good for providing airflow in particular. The windows have fixed grills and sliding insect nets (Fig. 59). These insect nets provide hindrance to airflow. The general practice in Bangladesh is to have grills in windows for security reasons.



Figs. 58 and 59. Details of sliding window (50% openable with grill and insect net)

The window to floor area ratio (WFR) of each room in the different units (A, B and C) was calculated by dividing the area of the window by the area of the floor. Similarly, the window to wall area ratio in the different units was calculated by dividing the window area by floor area. The results are presented in Tables 7- 9. Analysis of the results for Unit A (Table 7) shows that the living room and the dining space have window to wall area ratios (WWR) of 0.22 and 0.18 respectively. The values are below the recommended value as suggested by Liping *et al.* (2007). Liping *et al.* (2007) recommend that the optimum window to wall ratio should be equal to 0.24. Even though the value of WWR in bedroom 3 is above the recommended value (0.27), this window does not admit adequate light because of the obstruction of the buildings on the east. The window in the dining space has a WWR not only below the recommended value (0.18), but is located against a central light well. In this Unit, only the master bedroom and bedroom 2 in the south have windows that extend from the skirting to the lintel level (2 metres).

Table 7. Window to floor area ratio (WFR) and window to wall area ratio (WWR) of rooms in Flat type A

Room	Window orientation	Floor area (In square metres)	Window size (In square metres)	Wall area (In square metres)	Window to floor area ratio (WFR)	Window to wall area ratio (WWR)
Master bedroom	East wall	12.87	2.1	8.75	0.16	0.24
Master bedroom	South wall	12.87	3	12	0.23	0.25
Bedroom 2	South wall	12.21	2.6	10	0.21	0.26
Bedroom 3	East wall	10.82	2.52	9.3	0.23	0.27
Living	East wall	14.1	2.1	9.5	0.15	0.22
Dining	Central void	13.63	2.52	14	0.18	0.18
Kitchen	East wall	5.8	1.5	6	0.26	0.25

Analysis of WWR in rooms of Unit B (Table 8) show that all rooms except the dining have values more than that recommended by Liping *et al.* (2007). In fact, the WWR of the living room (0.71) is more than double the recommended value. The windows in the living room and kitchen are located on the west and they stretch from the skirting to the lintel level (2 metres). The window in bedroom 3 too is located on the west wall and its height is also 2 metres. The WWR of the dining room is much less than the recommended (0.13). This window in the dining is also located against a central light well as in Unit A.

Table 8. Window to floor area ratio (WFR) and window to wall area ratio of rooms (WWR) in Flat type B

Room	Window orientation	Floor area (In square metres)	Window size (In square metres)	Wall area (In square metres)	Window to floor area ratio (WFR)	Window to wall area ratio (WWR)
Master bedroom	West wall	12.3	3.34	9.5	0.27	0.35
Master bedroom	South wall	12.3	3	13	0.24	0.23
Bedroom 2	South wall	12.22	2.61	9.8	0.21	0.27
Bedroom 3	West wall	9.41	3	8.75	0.32	0.34
Living	West wall	13.41	6.56	9.3	0.49	0.71
Dining	Central void	18.56	2.52	19.5	0.14	0.13
Kitchen	West wall	5.8	2.6	6	0.45	0.43

Bedroom 3 and the dining room in Unit C (Table 9) have a WWR which is less than the recommended value by Liping *et al.* (2007). Even though the value of WWR in the living room is above the recommended value (0.26), this window does not admit adequate light because of the obstruction of the buildings on the east. Here too, windows in the west are big (2 metres) and have higher corresponding values of WWR.

Table 9. Window to floor area ratio (WFR) and window to wall area ratio (WWR) of rooms in Unit type C

Room	Window orientation	Floor area (In square metres)	Window size (In square metres)	Wall area (In square metres)	Window to floor area ratio (WFR)	Window to wall area ratio (WWR)
Master bedroom	West wall	12.99	3.6	12.5	0.28	0.29
Master bedroom	North wall	12.99	2.31	9.68	0.18	0.24
Bedroom 2	West wall	11.16	3.4	10	0.30	0.34
Bedroom 3	East wall	10.76	1.53	9.3	0.14	0.16

Living	East wall	12	2.31	8.9	0.19	0.26
Dining	Indirect window on north	17.17	2.52	10.68	0.15	0.23
Kitchen	East wall	5.28	1.8	6	0.34	0.30

The general conclusion that can be drawn regarding the size of the windows is that in all units of this case study building, the rooms on the west have big windows (Figs. 60 and 61), stretching from the skirting to the lintel level (2 metres in height) and corresponding higher than recommended values for WWR. These big windows on the west should have been avoided to exclude solar penetration as recommended by Ahmed (1987) and Liping *et al.* (2007). Windows on the east and north should have been bigger because these facades do not have road-side exposures; rather, there are surrounded by buildings only 1.8 metres away.



Fig. 60. Windows on west facade



Fig. 61. Big windows from skirting to lintel on the west facade

- Natural lighting and ventilation

The windows on the north and east of flats C and windows on the east of flats A are not effective in allowing day light and airflow because of their sizes as discussed above and because of the close proximity of the buildings that surround this case study building on the north and east. As a result, the lights in these units need to be kept on through out the day. Figures 62-67 illustrate the poor natural lighting conditions in living and bed rooms of unit types A and C. These pictures were taken between 1 and 2 pm in the afternoon.

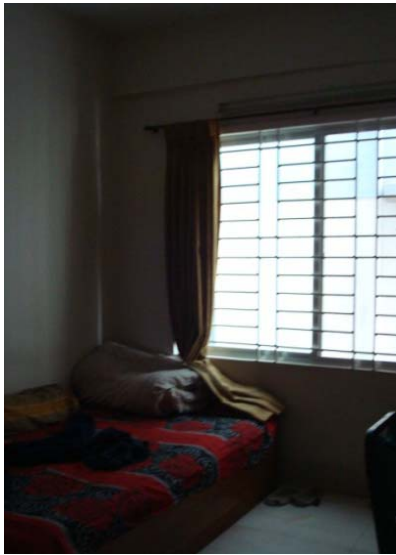


Fig. 62. Bedroom on east side of Unit A3



Fig. 63. Living room on east side of Unit A3

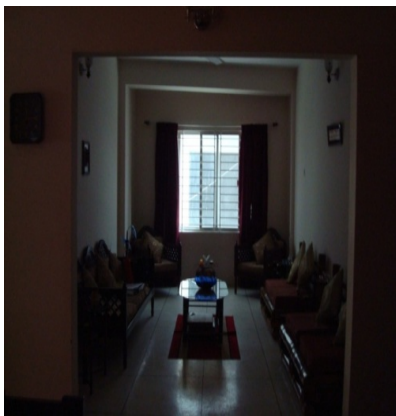


Fig. 64. Living room on east side of Unit C1

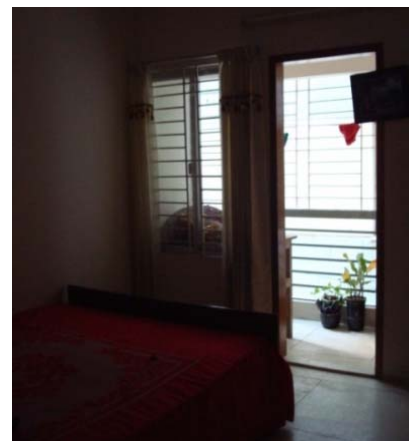


Fig. 65. Bedroom on east side of Unit C1



Fig. 66. Living room on east side of Unit C5



Fig. 67. Bedroom on east side of Unit C5

For proper cross ventilation, Mathur and Chand (1993) recommend windows located diagonally opposite to each other. However, only the master beds of all three flat types in this building have provision for cross-ventilation through two pairs of windows located on side walls (Figs. 68- 70). But, as the location of the outlet is very close to the inlet, most of the space inside the room is unaffected by the air current.



Fig. 68. Two windows in master bed of Unit C5

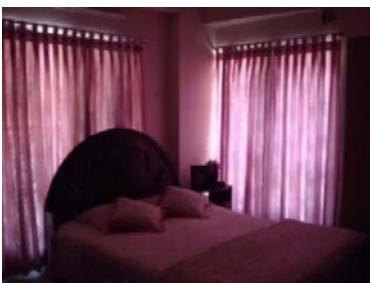


Fig. 69. Two windows in master bed of Unit C1



Fig. 70. Two windows in master bed of Unit C5

Flat type B gets airflow from the openings in southwest during summer. Flat types A and C are not benefitted from the orientation of openings in summer. In principle flat type A gets airflow from the southeast during the monsoon season. However, these winds are blocked because of the obstruction on the eastern side by another neighbouring building. Flat type C gets airflow from the northeast during the post-monsoon period and from the northwest during winter. Airflow to flat type C from the northeast is again blocked by the presence of the neighbouring building on the east. It can thus be concluded that because of the compactness of the form and the distribution of three different flat types, no flat types are well ventilated all year round. Overall, only the two bedrooms on the southern side of flat type A and B get airflow during the hottest period of the year.

Due to compact planning, ventilation and natural light facilities for inward rooms like dining have been attempted to be provided through openings in a central light well/open hollow shaft 4 square metres in area (Fig. 71 and 72). However, the dimensions of the shaft do not meet the requirements set by Dhaka City Building Construction Act (2008); the code recommends a minimum cross-sectional area of 5 square metres for these light well or shafts. The size of the shaft in the case study building is thus not adequate to provide natural light and ventilation through openings in the shaft.



Figs. 71 and 72. Central light well

As all the rooms except the master bedrooms in all three units of this case study building do not have windows on opposite walls for cross-ventilation, the solution would be to have two windows, side by side, on the same wall instead of one, as suggested by Mathur and Chand (2003). Another solution might involve having two windows, one at sill level and the other above lintel level as recommended by Ahmed *et al.* (2006). This concept would increase the prospect of fan-induced ventilation and stack ventilation.

▪ Shading devices

Shading devices are needed in Dhaka to ensure protection from the rain and solar heat gain; the shading devices of windows in the case building were analyzed using the method proposed by Ossen *et al.* (2005). The depth of the shading device for different orientations of windows in all rooms of the different unit types (A, B and C) were calculated using the overhang ratios of 1.3, 1.2, 1 and 1 for east, west, north and south orientations respectively, as proposed by Ossen *et al.* (2006).

The analysis of shading devices for windows (Tables 10- 12) demonstrate that shading devices are either absent or their sizes are much less than the recommended value. This analysis on shading devices represents the general scenario of shading devices in typical residential buildings of Dhaka

Table 10. Shading device analysis of Flat Type A using the method developed by Ossen *et al.* (2006).

Room	Window orientation	Window size (In metres)	Window to wall area ratio (WWR)	Recommended horizontal shading (In metres)	Actual horizontal shading (In metres)
Master bedroom	East wall	1.5 x 1.4	0.24	1.8	-
Master bedroom	South wall	1.5 x 2	0.24	2	0.78
Bedroom 2	South wall	1.3 x 2	0.27	2	0.78
Bedroom 3	East wall	1.8 x 1.4	0.28	1.8	-
Living	East wall	1.5 x 1.4	0.24	1.8	0.25
Dining	Central void	1.8 x 1.4	0.18		
Kitchen	East wall	1.1 x 1.4	0.18	1.8	-

Table 11. Shading device analysis of Flat Type B using the method developed by Ossen *et al.* (2006).

Room	Window orientation	Window size (In metres)	Window to wall area ratio (WWR)	Recommended horizontal shading (In metres)	Actual horizontal shading (In metres)
Master bed	West wall	1.67 x 2	0.38	2.4	-
Master bed	South wall	1.5 x 2	0.25	2	1.16
Bedroom 2	South wall	1.3 x 2	0.28	2	0.9
Bedroom 3	West wall	1.5 x 2	0.39	2.4	0.25
Living	West wall	3 x 2	0.70	2.4	-
Dining	Central void	1.8 x 1.4	0.13		

Kitchen	West wall	1.3 x 2	0.26	2.4	0.5
----------------	-----------	---------	------	-----	-----

Table 12. Shading device analysis of Flat Type C using the method developed by Oseen *et al.* (2006).

Room	Window orientation	Window size (In metres)	Window to wall area ratio (WWR)	Recommended horizontal shading (In metres)	Actual horizontal shading (In metres)
Master bed	West wall	1.8 x 2	0.31	2.4	0.78
Master bed	North wall	1.65x 1.4	0.24	1.4	0.5
Bedroom 2	West wall	1.7 x 2	0.27	2.4	1.4
Bedroom 3	East wall	1.09 x 1.4	0.28	1.8	0.9
Living	East wall	1.65 x 1.4	0.24	1.8	0.7
Dining	Indi t window	1.8 x 1.4	0.18		
Kitchen	North wall	1.3 x 1.4	0.18	1.4	-

5.2.3 Aspects provided by the developer

In general, the developers provide certain common amenities in the building. The developers do not appoint interior designers. Not all clients or owners can afford to hire interior designers. Upper middle-income and higher income group clients usually appoint interior designers. However, clients have freedom to choose internal layout and features at their own expenses. All the households studied have made changes in the internal layout. These changes were discussed under the section on room orientation and layout. Only households B4 and B5 had hired architects for interior designs. The interior architects were responsible for designing and choosing floor and wall tiles, designing wall cabinets, partition walls and lighting systems of the individual flats. One household surveyed had hired interior designers after the internal walls were completely built. As a result, the walls had to be broken at the expenses of the respective owners for any changes in design that the interior designers suggested.

5.3 Energy usage of the case study flats

5.3.1 Total energy usage

The energy use of the case study flats depend on the household size, occupancy pattern, appliances used, the power rating of the appliances and the duration for which they are used. The major electricity consuming appliances used by the households of the case study flats are illustrated in Table 13. The study does not take into account the energy efficiency of the different appliances and energy efficiency related to every day habits that cannot be influenced by design because the study focuses on the energy efficiency aspects that can be addressed through planning and design. The energy use of the households has been calculated for a typical summer

month, when the maximum temperature can be as high as 34° C, by first listing the number of major electricity consuming appliances and their respective energy ratings (in Watt). The estimated total load in kilo Watts for each appliance has been calculated by multiplying the appliances with their corresponding energy rating and dividing it by 1000 (to convert Watts to kilo Watts). This figure was multiplied with the hourly usage of the appliance to give the daily energy use during the used period in kWh. Finally, this figure was further multiplied with 30 to give the monthly energy use. A detailed calculation of the energy use for each flat is appended in Appendix 2.

Table 13. Appliances used by the different households

	Unit A2	Unit A3	Unit B2	Unit B4	Unit B5	Unit C1	Unit C5
Major Appliances							
AC	1.5 tonne (1)	1.5 tonne (1)	1 tonne (1)	1.5 tonne (1) 2 tonne (1)	1.5 tonne (1), 2 tonne (1)	None	1 tonne (1) 2 tonne (1)
Fan	8	7	7	7	7	6	7
Exhaust fan	2	2	2	4	4	1	1
Fluorescent light	12	12	11	11	12	10	9
Incandescent light	16	6	6	16	30	8	9
Energy saving light	2	16	16	7	3	None	7
Spot light	11	5	None	6	4	None	2
Fridge	1	1	1	1	1	1	1
Freezer	1	1	1	1	1	None	1
Micro oven	1	1	1	1	1	1	1
Washing machine	None	1	None	1	1	None	1
TV	2	2	1	1	2	1	2
DVD player	1	1	None	None	2	None	1
MP3 Player	1	1	None	None	None	None	None
Computer	None	1	None	None	1	None	None
Printer	None	1	None	None	None	None	None
Iron	1	1	1	1	1	1	1
Toaster	1	1	1	1	1	None	1
Blender	1	1	1	1	1	1	1

The monthly total energy use for a typical summer month for all the units studied is given in Table 14. A break up of the energy use pattern (in percentage) of the case study flats for a typical summer month has been outlined in Table 15. Analysis of energy use in Table 15 shows that the energy required for cooling and lighting takes up the largest share of the energy used by a flat. Unit C1 has very low energy use compared to the other units because the household size is small and it does not have excessive lighting and air conditioners for cooling. The average cooling and lighting energy used by all the units of the case study in a typical summer month has been calculated as 40% and 39% respectively.

Table 14. Monthly total energy use

	Unit A2 1 A.C	Unit A3 1 A.C	Unit B2 1 A.C	Unit B4 2 A.Cs	Unit B5 2 A.Cs	Unit C1 No AC	Unit C5 2 A.Cs
Monthly total energy use for a typical summer month (kWh)	1762	1401	900	1263	1356	450	1316

Table 15. Break-up of monthly total energy use

Energy used (%)	Unit A2	Unit A3	Unit B2	Unit B4	Unit B5	Unit C1	Unit C5
Cooling (A.C)	25.2 1 A.C	36 1 A.C	16.7 1 A.C	29 2 A.Cs	29.7 2 A.Cs	No AC	37.1 2 A.Cs
Cooling (Fan)	10.89	14.4	18.6	10.7	7.4	19.2	12.8
Lighting	46	30	40	41	42	56	29
Refrigeration	10.05	6.2	19.7	14.1	13.10	19.3	13.5
Other appliances	7.66	13.4	4.8	4.2	7.4	5.10	7.4
Ventilation in toilet & kitchen	0.18	0.22	0.2	0.34	0.05		0.1

5.3.2 Energy usage for cooling

It has already been stated that air conditioners contribute to the increase in electricity use by the residential sector during the summer months. Lam *et al.* (2005) clarified that air conditioners account for about 40% of the total residential sector electricity use of Hong Kong. Furthermore, Lam (2000) showed that the ownership of air conditioners in Hong Kong has risen from 50% in 1989 to 90% per household in 1993. It can be noted that the climate of Hong Kong is sub-tropical. Using the data in Table 16, the average cooling energy used by all the units of the case study has been calculated as 40 % and the average for air conditioners alone is 24%. This figure is less than the electricity use of air conditioners in the residential sector of Hong Kong because only 30% of the population in Dhaka belong to the Middle Middle and Upper Middle income group (Table 3 shows the different income groups in Dhaka City Corporation). The percentage of total cooling energy for Units A3 and C5 is 50% because they are more dependent on air

conditioners as compared to other units in the building; Unit A3 uses 36% of cooling energy for air conditioners and Unit C5 uses 37%. On the other hand, the percentage of total cooling for Unit C1 is extremely low when compared to other units because this household does not have air conditioners.

Table 16. Energy used for cooling

Energy used	Unit A2	Unit A3	Unit B2	Unit B4	Unit B5	Unit C1	Unit C5
Cooling (A.C) in kWh	444 1 A.C	499.5 1 A.C	150 1 A.C	366 2 A.Cs	402 2 A.Cs	- No AC	488.25 2 A.Cs
Cooling (A.C) in %	25.2	36	16.7	29	29.7	-	37.1
Cooling (Fan) in kWh	192	202	168	134.4	100.8	86	168
Cooling (Fan) in %	10.89	14.4	18.6	10.7	7.4	19.2	12.8
Total for cooling (kWh)	636	702	318	500	503	86	656
Total in kWh	1762	1401	900	1263	1356	450	1316
Total for cooling in %	36	50	35	40	37	19	50

The energy used by air conditioners depends on their capacity, type, power rating, usage and setpoint temperatures. Table 17 shows the energy use of air conditioners based on their capacity, type and power rating. According to Tham (1993), a rise of each degree Celsius in setpoint represents a saving of 6% in energy required for cooling. The households studied had split type air conditioners with a capacity of 1 tonne, 1.5 tonnes or 2 tonnes. Unit B4 and B5 have air conditioners with a capacity of 1.5 tonnes in the master bed and a capacity of 2 tonnes in the living room. Unit C5 has air conditioners with a capacity of 2 tonnes in the master bed and a capacity of 1.5 tonnes in the living room. This variation of different capacities depends on the volume of the room. The power ratings of 1 tonne, 1.5 tonnes and 2 tonnes capacity air conditioners are 1250, 1850 and 2400 Watts respectively.

Table 17. Energy use of air conditioners based on their capacity, type, usage and power rating

Units/ Flats	Air conditioner (A.C)	No.	Rating (W)	Estimated total load for appliance (kW)	Usage per day (h)	Daily energy use during used period (kWh)	Monthly energy usage of A.C (kWh)
A2	Split 1.5 ton	1	1850	1.85	8	14.8	444
A3	Split 1.5 ton	1	1850	1.85	9	16.65	499.5
B2	Split 1 ton	1	1250	1.25	4	5	150
B4	Split 1.5 ton	1	1850	1.85	4	7.4	222
	Split 2 ton	1	2400	2.4	2	4.8	144
B5	Split 1.5 ton	1	1850	1.85	4	7.4	222
	Split 2 ton	1	2400	2.4	2.5	6	180
C1	None						
C5	Split 1 ton	1	1250	1.25	1.5	1.875	56.25
	Split 2 ton	1	2400	2.4	6	14.4	432

Units A2, A3 and B2 have one air conditioner each and that alone is used for 8, 9 and 4 hours a day respectively. Units B4, B5 and C5 have two air conditioners each and both air conditioners in each unit is used for 6, 6.5 and 7.5 hours respectively. The preferred setpoint temperature and usage of the air conditioners of each household studied is outlined in Table 18.

Table 18. A.C usage pattern

	Unit A2	Unit A3	Unit B2	Unit B4	Unit B5	Unit C5
Timing	Master bedroom: 3:00- 6:00 pm & 11:00 -4:00 am	Master bedroom: 10:00 pm - 7:00 am	Master bedroom: 3:00 -4:00 pm & 10:00 pm- 1:00 am	Living room: 6:00-9:00 pm Master bedroom: 11:00pm-2:00 am	Master bedroom: 11:00 pm-2:30 am Living: 7:00 pm 10:00pm	Master bedroom: 10:00 pm-4:00am Child bed: 2:00pm-4:00pm
Total A.C usage (hours)	8	9	4	6	6.5	7.5
Preferred setpoint temperature for A.C	24°C	24°C	24°C	Master bed: 20°-23°C Living room: 18°C	Master bedroom: 23°C Living room: 18°C	24°-25°C

It can be observed that in flats, such as A3, B2 and C5 which are occupied by the households (excluding the housekeeper) throughout the day (Table 5) use air conditioners in the afternoon and at night. This can be interpreted as such that overheated periods that cause discomfort due to solar radiation on the building envelope extend from 10 am in the morning to 8 pm at night. Solar radiation incident on the building envelope raises the temperature of the exterior surface of the envelope, thereby creating a temperature gradient across the thickness of the envelope. As a result, heat is conducted through the inefficiently designed building envelope, causing a rise in the interior surface temperature. Ample ventilation is needed to dissipate this stored heat at night (Gut and Ackerknecht, 1993). As this stored heat cannot be dissipated outside due to inadequate cross-ventilation and placement of openings, it causes the occupants of the flats to swelter in poor ventilation.

Comparison of the energy use for flats with and without air conditioners (Table 14) shows that case study flats without air conditioners use much less energy. This highlights the necessity in paying attention to architectural characteristics and trends that can address the thermal comfort demands of the households without increasing the dependency of air conditioners. Although fans are also used for cooling, the energy used by them is not as significant as the energy use of air conditioners (Table 16). As already mentioned, Mallick (1996) elaborated the role of ceiling fans as a reliable source of cooling in dense urban conditions of Dhaka if they are set at maximum or high speeds.

It must be emphasized that the case study building is representative of upper middle-income households who have a minimum of one air conditioner. The value for the share of energy utilized for cooling by air conditioners would be much more for lower upper and upper upper-income groups who live in four bed roomed flats and have air conditioners in all their rooms.

5.3.3 Energy usage for lighting

There are substantial variations in energy used for lighting residential buildings. In the United States, lighting uses 12% of the energy used by a residential building (UNEP, 2007) and 9% of energy used in residential buildings of India contributes to lighting (UNEP, 2007). Residential buildings of Taiwan, on the other hand use 40% of the total residential sector electricity use for lighting (Yang and Hwang, 1993). Using the data in Table 19, the average lighting energy used by all the units of the case study has been calculated as 39%.

Table 19. Different types of lights and energy used for lighting

Type of lighting	Unit A2	Unit A3	Unit B2	Unit B4	Unit B5	Unit C1	Unit C5
Incandescent	16	6	6	16	30	8	9
Fluorescent	12	12	11	11	12	10	9
Energy saving	2	16	16	7	3	None	7
Spot	11	5	None	6	4	None	2
Total number of artificial lights	41	39	33	40	49	18	27
Total energy for lighting (kWh)	810.6	422.4	360	518.25	574.35	252	382.8
Energy used for lighting (%)	46	30	40	41	42	56	29

The energy use for lighting in the households is seen to vary with type of lighting, the number of lights, power rating and the usage of lights. Table 19 shows the different types of lights, the total number of lights and the share of energy use for lighting in both in kilo Watt hours and in percentages for the case study building. Analysis of the different types of lights and the energy use of each type of light is depicted in Table 20. The analysis illustrates that incandescent lights use more energy than fluorescent lights. The analysis also shows that energy saving lights use less energy. Nagarajan (2006) states that compact fluorescent light (CFL) or energy saving light as it is commonly called is energy efficient and consumes 80% less electricity when compared to incandescent light.

Table 20. Energy use of lights based on their type, usage and power rating

Unit	Appliances	No.	Rating (W)	Estimated total load for appliance (kW)	Usage per day (h)	Daily energy use during used period (kWh)	Monthly energy usage (kWh)
A2	Fluorescent light	12	60	0.72	10	7.2	216
	Incandescent light	16	100	1.6	10	16	480
	Energy saving light	2	15	0.03	10	0.3	9
A3	Spot light	11	40	0.44	8	3.52	105.6
	Fluorescent light	12	60	0.72	8	5.76	172.8
	Incandescent light	6	100	0.6	8	4.8	144
	Energy saving light	16	15	0.24	8	1.92	57.6
	Spot light	5	40	0.2	8	1.6	48
B2	Fluorescent light	11	60	0.66	8	5.28	158.4
	Incandescent light	6	100	0.6	8	4.8	144
	Energy saving light	16	15	0.24	8	1.92	57.6
	Spot light						
B4	Fluorescent light	11	60	0.66	7	4.62	138.6
	Incandescent light	16	100	1.6	7	11.2	336
	Energy saving light	7	15	0.105	7	0.735	22.05
	Spot light	6	40	0.24	3	0.72	21.6
B5	Fluorescent light	12	60	0.72	5	3.6	108
	Incandescent light	30	100	3	5	15	450
	Energy saving light	3	15	0.045	5	0.225	6.75
	Spot light	4	40	0.16	2	0.32	9.6
C1	Fluorescent light	10	60	0.6	6	3.6	108
	Incandescent light	8	100	0.8	6	4.8	144
	Energy saving light						
	Spot light						
C5	Fluorescent light	9	60	0.54	8	4.32	129.6
	Incandescent light	9	100	0.9	8	7.2	216
	Energy saving light	7	15	0.105	8	0.84	25.2
	Spot light	2	40	0.08	5	0.4	12

Developers in Bangladesh generally provide a minimum of two average quality wall mountable lighting fixtures, but not the lights. The households studied in this building did not use the

lighting fixtures provided by the developers. Instead, they purchased a multitude of lighting fixtures and lights of their own choice or as suggested by the interior designers who were responsible for the interior design of the flats. The number of lights in all flats except unit C1 and C5 are much more than what is needed for strictly practical reasons (Fig. 73). A schedule of the number of lights in each room of the households studied is appended in Appendix 3. Units C1 and C5 are good examples to show that use of excessive lights are not a necessity. It is possible to use fewer lights and have good indoor artificial lighting conditions. The superfluous lights in the remaining households are for aesthetic purposes and to some extent, to signify the status of the households (Fig. 74). Gut and Ackerknecht (1993) have advised against the use of unnecessary lighting as it adds up to internal heat gain.



Fig. 73. Four out of six lights indicated by arrows in the dining space of Unit B4

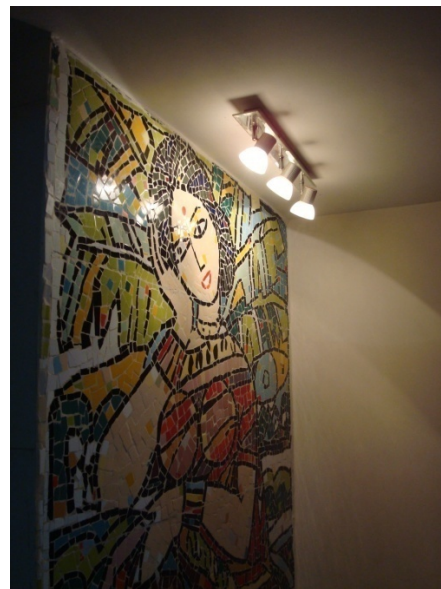


Fig. 74. Spot lights to highlight a mural in the foyer space of Unit A3

Even though Unit C1 has the least number of lights compared to the other units, energy used for lighting in unit C1 is more than 50% because this household does not use air conditioners and other major energy consuming appliances. Lighting alone contributes to more than 50% of the share of energy used by this household. It is thus seen that percentages are not relevant on their own, but only in relation to a total.

6 DISCUSSION

6.1 Energy efficient design features

The theoretical framework in this study contains a list of basic principles in energy efficient building design. Out of the numerous energy efficient design features that were discussed in the theoretical framework, only those features have been chosen that can meet the purpose of this study and can be applied in the context of Dhaka. The features that have been selected pertain only to the building envelope, reduce heat gain by the buildings, and they mainly reduce the energy use for cooling. It needs to be strictly emphasized that the chosen features reduce only the cooling energy; the features do not influence the energy used for electrical appliances. It must also be stressed that as this study focuses on possible energy savings by adopting energy efficient design features, only those energy efficient design features have been selected that quantify the energy savings.

It can be recalled that the use of thicker construction on east and west walls reduced cooling energy and is adaptive for the context of Dhaka. Use of hollow clay tiles for the roof reduced cooling energy and can also be applied for Dhaka's context. Appropriate shading devices on all four orientations also indicated energy savings and are suited for residential buildings in Dhaka.

The research front has thus been summarized to formulate the adoption of the following energy efficient features in Dhaka (Table 28):

1. Cooling load can be reduced by 7%- 10% by doubling the thickness of external walls with 280 mm brick walls including an air cavity of 50 mm on east and west facades instead of 125 mm brick external walls as is the general practice.
2. The use of hollow clay tiles (HCT) in place of weathering course for roofs can save 18% - 30% of cooling energy (Vijaykumar and Srinivasan in Vijaykumar *et al.*, 2007).
3. Optimum total energy savings of 14 %, 11%, 6% and 8% can be obtained by using horizontal overhang ratio of 1.3 for east orientations, 1.2 for west orientations, 1 for north orientations and 1 for south orientations respectively. The energy savings for all the orientations together sum up to 39%. (Ossen *et al.*, 2005).

Table 21. Energy efficient design features

Feature	Application	Reduction/Saving	Reference
External wall	Doubling the thickness of external walls with 280 mm brick walls including an air cavity of 50 mm on east and west facades.	7% - 10%	Modified by the author
Roof	The use of hollow clay tiles (HCT) in place of weathering course for roofs	18% - 30%	Vijaykumar and Srinivasan in Vijaykumar <i>et al.</i> (2007)
Shading device	Horizontal overhang ratios of 1.3 for east	14 %	Ossen <i>et al.</i> (2005)
	Horizontal overhang ratios of 1.2 for west	11 %	Ossen <i>et al.</i> (2005)

Horizontal overhang ratios of 1 for north	6 %	Ossen <i>et al.</i> (2005)
Horizontal overhang ratios of 1.3 for south	8 %	Ossen <i>et al.</i> (2005)

Assuming that the energy savings estimated by the authors above are roughly correct, then addition of the lower range energy saving values of all the features above gives a total energy savings of 64% (7% + 18% + 39%) for cooling. Given the concrete features of the case study building, the energy efficient design features listed above can be recommended for the context of Dhaka and lies within the field of influence of the architect.

6.2 Energy use of the flats in the case study on adoption of the energy efficient features

The energy use of each flat in the case study building has been delineated in section 4.3. Out of all the energy use that the households use, only the cooling energy of each flat has been reduced because the design measures are not connected to energy use for lighting and other appliances. It should be highlighted again that the design measures are related only to reduction of the cooling energy. If the building were to adopt the energy efficient features discussed above, then the cooling energy use of the surveyed flats in the case study building would be reduced by 64%. As explained above, the 64% reduction is a summation of the lower range energy saving values of all the energy efficient features.

Table 22. Reduced energy use of the flats

Energy use		Unit A2	Unit A3	Unit B2	Unit B4	Unit B5	Unit C1	Unit C5
Energy use (kWh)	Cooling	636	702	318	500	503	86	656
	Electrical appliances	1126	700	582	753	853	364	660
	Total Energy	1762	1402	900	1253	1356	450	1316
Net energy use after adopting design features. (kWh)	64 % reduction on cooling energy	229	253	114	180	181	31	236
	Electrical appliances	1126	700	582	753	853	364	660
	Total energy	1355	953	696	933	1034	395	896
Percentage reduction in total energy use		23%	32%	23%	26%	24%	12%	32%

Table 22 above illustrates total energy used by the flats before and after adopting the energy efficient features. The first row in Table 22 shows the total energy use of all the flats surveyed. The total energy use is broken up as energy used for cooling and energy use for electrical appliances. The second row in Table 22 first shows the reduction of 64% on the cooling energy that was outlined in the first row of the table. Since the design features reduce the cooling load, 64% was deducted from the cooling energy of each unit or flat. During the calculation for the reduced energy of the flats, the energy used by electrical appliances has been left unchanged as shown by the values in the second row of the table. The total energy after a reduction of 64% is shown in the second row. For example, the cooling energy of Unit A2 was 636 kWh before the reduction and it is 229 kWh after a reduction of 64%. The total energy used by Unit A2 was 1762 kWh before the reduction on the cooling energy. After the cooling energy of Unit A2 is

reduced to 229 kWh and the consequent reduction in total energy use of Unit A2 is 1355 kWh as compared to the initial value of 1762 kWh. This is a reduction of 23% in the total energy use of Unit A2 as shown in the last row of the table. The percentage reduction was calculated by subtracting the difference in energy use before and after reduction of 64% and then dividing this value by the total energy use before the reduction. For example, by subtracting the total energy use for Unit A2 before (1762 kWh) and after the reduction on cooling energy (1355 kWh), the result is 407 kWh. Dividing this value by the original total energy (1762 kWh) and multiplying the result by 100 gives the result in percentage.

In a similar way, the percentage reduction on the total energy use of Units A2, A3, B2, B4, B5, C1 and C5 is calculated as 23%, 32%, 23%, 26%, 24%, 12% and 32% respectively. This is an average reduction of 26% on the total energy use of the building. This average reduction was found by adding the total energy use of all the units before (8439 kWh) and after the reduction of 64% in cooling energy (6262 kWh). The difference of these two values (2177 kWh) is divided by the total energy use before the reduction of 64% (8439 kWh) and then multiplied by 100 to give the average percentage reduction of 26% on the total energy use of the units surveyed.

The percentage reduction in cooling energy is seen to be more in Units A3 and C5 because these units use 50% of the total energy in cooling (shown earlier in Section 5.3.2). Whereas, the percentage reduction in cooling energy of Unit C1 is only 12% as it uses only 19% of the total energy for cooling. It was shown in Section 5.3.2 that units A3 and C5 are more dependent on air conditioners as compared to other units in the building and Unit C1 does not use air conditioners. The unit without air conditioners (Unit C1) is not as benefitted as those that have air conditioners because the reduction in energy use was directed at those who have air conditioners and are very much dependent on them. Nevertheless, households of Unit C1 would have a better indoor climate with lower energy use for cooling by fans and lower costs.

It can thus be concluded that a 64% reduction in cooling energy literally implies that more than half of the devices that were used for cooling are no longer used. Households would use the fans for a lesser period of time or to enhance cross ventilation or when there is no air flow. It would also mean that those who are dependent on air conditioners might use it for a lesser period of time or probably do not need air conditioners.

Further reduction in total energy use is possible if the energy required for lighting is reduced by using energy efficient lights. However, discussions on reducing energy use for lighting are outside the scope of this study as mentioned in Section 1.3.2.

6.3 Barriers in adopting energy efficiency in residential buildings

6.3.1 Barriers related to designing energy efficient buildings

Energy efficient building features have been identified in this study through literature review. The study also shows the proficiency of these energy efficient features. Despite the effectiveness of these features, there are barriers that may impede the construction of energy efficient buildings. Based on the experience of the real estate market and on the way architects, developers and interior designers work and how the clients behave, the roles of these actors

involved in the process of designing energy efficient building are scrutinized below to identify the barriers.

6.3.1.1 Role of architect

Architects are not fully aware of the energy situation of the country. They have little knowledge about the possibilities, techniques and potentials of energy efficiency design solutions. They need more information and technical skills to design energy efficient buildings. Even if the architects are well-informed about energy efficient design features, they might still not be able to use all the energy efficient design features mentioned in Section 6.1, because the architect is not the only actor in the design process who can bring changes. Architects are appointed or hired as consultants by the developers and the architects are under constant pressure from the developers and the clients to maximize space utilization with minimum construction costs. Unless the developers and the clients (land owners) are very keen in including energy efficient features, architects cannot take the entire responsibility of designing energy efficient residential buildings.

6.3.1.2 Role of developer

Like architects, developers too are not fully aware of the urgency of the energy crisis in Bangladesh. Neither are they aware that the residential building sector in Dhaka uses almost 45% of the electricity generated. They lack information and technical skills to construct energy efficient buildings.

Developers are primarily interested in maximizing the net saleable area and in the speedy completion of the building. Future operating costs, which are borne by prospective occupants of the building, are not key considerations because the developers do not take long term responsibilities; their role is limited to the moment the flat is handed over to the client.

From previous experience of the real estate market and from interviews with developers and architects, it can be said that buildings are generally designed without the much needed proper shading devices that are very energy efficient because the developers want to save costs. Even though cavity walls and walls of increased thickness are known to be energy efficient, such features are unlikely to be adopted by developers because of their increased construction costs and reduced room sizes. Hollow clay tiles on the roof have been found to reduce the cooling load and it is the developer who would decide whether he/she would incur the small extra costs to have an energy efficient building. Typical residential buildings constructed by most developers represent matchboxes with some sort of ornamentation on the front facade. Buildings are designed without open spaces and voids because apartments are charged per square footage and every given up space would incur a loss in price.

6.3.1.3 Role of interior designer

The interior designers are hired by the owners of the flats and they work in alliance with the owners, without any sort of collaboration with the architects who designed the building. They too are unaware of the necessity and potentials of energy efficient design solutions. As the interior designers were not involved in the design stage and came in later, they are not aware of

the energy efficient design features that the architect may have designed. Owners of the flats usually want a grand interior with lots of decorative lights to symbolize their status and lifestyle. Use of fancy lights for interiors has become a symbolic culture and practise. As the interior designers are appointed by the owners, they are under the obligation to listen to the requirements put forth by the owners; otherwise they would lose their job. Hence, the interior designers put in plenty of lights with different shades to create the symbolic and dramatic effect as desired by the owners of the flats. The interiors designers may also change the orientation and size of openings on all walls except the front facade as the developers do not allow a change in design on the front facade.

6.3.1.4 Role of clients (land owner) and residents

Clients too are unaware of the role they can play in mitigating the energy crisis of Bangladesh. They need to be explained about the necessity of energy efficient buildings. Like developers, land owners or clients are also interested in maximum profits through lower construction costs and maximum utilization of land. The different energy efficient features can only be implemented if the clients are prepared to pay the extra costs and compromise with reduced floor area. Barriers in the form of behavioural characteristics of residents, their lifestyle and split incentives can also hamper the energy efficiency of residential buildings and are discussed as follows:

- Behavioural characteristics of residents

Even if a building is designed with energy efficient features, behavioural characteristics of individuals are in fact a great hindrance to achieving energy efficiency in residential buildings. Kanyama and Linden (2006) have asserted that energy use in the home may be reduced by 20% through changes in behaviour. However, it should also be noted that their results are from a different cultural setting. Small, but easy practices such as switching off the lights when leaving a room are often ignored. Using higher setpoint temperatures for air conditioners instead of lower temperatures like 24°C, can also achieve energy efficiency (Tham, 1993). According to Tham (1993), each degree Celsius rise in setpoint temperature represents a saving of approximately 6% in both cooling energy and total energy use.

- Lifestyle of residents

The lifestyle of the higher income groups contradicts with the notion of energy efficiency. In such cases, a well-designed energy efficient building can fall short of its endeavour. For example, using air conditioners in each and every room, latest and biggest appliances irrespective of their energy use and plenty of trendy lights such as spotlights, chandeliers in an interior decorated house is a matter of status symbol for the upper income groups.

- Split incentives

Split incentives occur when costs and benefits of investing in energy efficiency improvements are split between two parties (Williams, 2008). Flat owners do not always reside in the flats they buy. They rent the flats to tenants. The owners are therefore not interested in energy efficient design features as they are not the end users and would not bear the energy costs.

6.3.2 Recommendations for overcoming barriers

Different roles of developers, architects, interior designers and owners that act as barriers in achieving energy efficiency in residential buildings have been discussed above. These barriers can be overcome by the following changes in design practice.

Architects and developers need to learn about the importance and problems of achieving energy efficiency in residential buildings and the opportunities of addressing them. The architects can learn about these issues at the university or through journals. The Institute of Architects and the regulations in Dhaka City Building Construction Act can pressurize the architects and developers to learn about the issues related to energy efficient residential buildings and then based on that knowledge, they can act differently.

The architects first need to brief the developers and clients on the urgency of energy efficiency in residential buildings. Both developers and clients need to be explained that the energy efficient design features listed in Section 6.1 (doubling external wall on east and west facades, use of appropriate shading devices and use of hollow clay tiles on roof) reduce the cooling energy by 64%. Only if the developers and clients are convinced and agree to compromise with floor area and construction costs, the energy efficient features can be adopted. Clients should be made to understand that though energy efficient features may appear costly at the initial stage, they can bring back returns and are profitable in the end. Developers should take more responsibility and should not be concerned with maximum utilization of land and profitability. Instead, they should focus on providing open space and greenery. They should understand that the provision of such aspects not only adds value to a land but also has a role in energy efficiency.

It was seen in Section 6.3.1.3 that interior designers do not have any collaboration with the architect and can unknowingly end up in changing the interior in such a way that the flat is no longer energy efficient. Collaboration between architect, interior designer, developer and the client can help in achieving the overall target of designing energy efficient residential buildings. Once the building has reached a stage where interior designers are hired by the clients, all the actors involved need to sit together. The architect can then explain the energy efficient features used and can also recommend the interior designers and clients to use energy efficient lights and less trendy lights for the interiors. Once influenced by the architect, the interior designer can continue to explain the importance of energy efficiency to clients and motivate them into using less trendy lights and more energy efficient lights. Another option can be that developers integrate interior design of the flats as a part of the building design process. The developers can recruit interior designers or they can also have the interiors done by the architect who designed the building.

7 CONCLUSION AND RECOMMENDATION

This study has identified the following energy efficient building features for the context of Dhaka:

- Doubling the thickness of external walls with 280 mm brick walls including an air cavity of 50 mm on east and west.
- The use of hollow clay tiles (HCT) in place of weathering course for roofs.
- Horizontal overhang ratio of 1.3 for east orientations, 1.2 for west orientations, 1 for north orientations and 1 for south orientations respectively.

All the features that were analysed in this study for adoption in the case study building reduce the energy use for cooling. The study shows that it is possible to reduce the cooling load of the flats studied by 64% and hence reduce the total energy use of the flats surveyed by 26%. It should also be stressed that the theoretical framework has outlined many other options that reduce the cooling load and also improve natural ventilation. However, only those features were selected that can quantify the energy savings and can be adopted in the context of Dhaka.

Once the design features are identified and the energy savings are demonstrated, the next emerging questions are: 'Who is going to bring a change in the design practice? Who is responsible for the design of energy efficient residential buildings?' As evident from the section on barriers in adopting energy efficiency in residential buildings, the process of designing energy efficient residential buildings is not a 'one-man's show'. It is just not the architect who is responsible for designing energy efficient residential buildings and changing the design practice. Developers, interior designers and the clients are the other actors who can bring a change in the design practice. All the actors are closely intertwined. The architect, with increased knowledge and awareness can be the initiator of designing energy efficient buildings and the change in design practice. The architect should influence the developer, interior designer and the client. Once influenced by the architect, the interior designer should further motivate the client. Finally, it depends on the client and the developer. If the client and developer can compromise with construction cost, change their concept of making most of the floor area and if the client can change her/ his culture of using more and more air conditioners and flashy lights, it would be possible to design energy efficient residential buildings in Dhaka.

In addition to overcoming the barriers in energy efficiency, building codes need to be developed by The Dhaka City Building Construction Act to promote and influence energy efficiency in buildings. The Dhaka City Building Construction Act can formulate building regulations for energy efficient residential buildings. These regulations or building codes would pressurize the developers, the architects and the land owners or the clients to overcome the barriers and implement the energy efficient design features in the residential buildings of Dhaka. The focus of the codes should be to incorporate energy efficient design features right from the design stage.

Considering the significant amount of energy used by the residential buildings in general and the prevailing energy crisis in Dhaka, it is important to overcome the barriers and adopt the reasonably simple energy efficient design features highlighted in this study that reduce the total energy use of the flats in the case study building by a factor of one third and also provide

reduced comfort to the households. In addition to the benefits of energy savings from the use of this energy efficient design features, improving the energy efficiency of the residential buildings in Dhaka can also result in reduced energy costs to users, improved supply of electric energy as a result of the decreased use of energy by the residential building sector and finally it can also play a role in lowering green house gas emissions.

APPENDICES

Appendix 1. Benefits of green roofs

Teemusk & Mander (2009) claim that research confirm that green roofs:

- protect the base roof membrane against solar radiation, lowering its temperature and minimize temperature fluctuations.
- lowers cooling costs trough the insulation of the soil
- have the ability to reduce urban storm water run off problems.
- have the ability to reduce the pollution of urban rain water run off by absorbing and filtering pollutants.
- can help to keep buildings cool in summer and also to reduce a building's energy use by direct shading, evaporative cooling and additional insulation
- can improve air quality by catching a number of polluting air particles and gases, including smog.
- improve the microclimate by the evaporation and oxygen producing effect of vegetated roofs.
- can provide habitats for many kinds of plants and birds and opportunities for urban food production.
- can mitigate noise pollution.
- green roofs can create space for people to rest and interact with friends in dense urban areas, where access to green space is negligible
- have the ability to provide psychological benefits because of their differing appearance from ordinary roofs.

Appendix 2. Total energy use of all the flats

2.1. Total energy use of Unit A2

Appliances	No.	Rating (W)	Estimated total load for appliance (kW) Number of appliance x corresponding rating	Usage per day (h)	Daily energy use during used period (kWh) Estimated total load fro appliance x usage per day	Monthly energy use (kWh) Daily energy use x 30
AC (1.5 ton)	1	1850	1.85	8	14.8	444
Fan	8	80	0.64	10	6.4	192
Exhaust fan	2	35	0.07	1.5	0.105	3.15
Fluorescent light	12	60	0.72	10	7.2	216
Incandescent light	16	100	1.6	10	16	480
Energy saving light	2	15	0.03	10	0.3	9
Spot light	11	40	0.44	8	3.52	105.6
Fridge	1	145	0.145	20	2.9	87
Freezer	1	150	0.15	20	3	90
Micro oven	1	1800	1.8	1	1.8	54
Washing machine						0
TV	2	138	0.276	6	1.656	49.68
DVD	1	35	0.035	2	0.07	2.1
MP3 Player	1	35	0.035	2	0.07	2.1
Computer						0
Printer						0
Iron	1	1200	1.2	0.5	0.6	18
Toaster	1	800	0.8	0.25	0.2	6
Blender	1	400	0.4	0.25	0.1	3
						1761.63

2.2. Total energy use of Unit A3

Appliances	No.	Rating (W)	Estimated total load for appliance (kW) Number of appliance x corresponding rating	Usage per day (h)	Daily energy use during used period (kWh) Estimated total load fro appliance x usage per day	Monthly energy use (kWh) Daily energy use x 30
AC (1.5 ton)	1	1850	1.85	9	16.65	499.5
Fan	7	80	0.56	12	6.72	202
Exhaust fan	2	35	0.07	1.5	0.105	3.15
Fluorescent light	12	60	0.72	8	5.76	172.8
Incandescent light	6	100	0.6	8	4.8	144
Energy saving light	16	15	0.24	8	1.92	57.6
Spot light	5	40	0.2	8	1.6	48
Fridge	1	145	0.145	20	2.9	87

Microoven	1	1800	1.8	1	1.8	54
Washing machine	1	410	0.41	0.5	0.205	6.15
TV	2	138	0.276	8	2.208	66.24
DVD	1	35	0.035	2	0.07	2.1
MP3 Player	1	35	0.035	2	0.07	2.1
Computer	1	200	0.2	5	1	30
Printer	1	100	0.1	0.08	0.008	0.48
Iron	1	1200	1.2	0.5	0.6	18
Toaster	1	800	0.8	0.25	0.2	6
Blender	1	400	0.4	0.25	0.1	3
						1401.72

2.3. Total energy use of Unit B2

Appliances	No.	Rating (W)	Estimated total load for appliance (kW) Number of appliance x corresponding rating	Usage per day (h)	Daily energy use during used period (kWh) Estimated total load from appliance x usage per day	Monthly energy use (kWh) Daily energy use x 30
AC (1 ton)	1	1250	1.25	4	5	150
Fan	7	80	0.56	10	5.6	168
Exhaust fan	2	35	0.07	1	0.07	2.1
Fluorescent light	11	60	0.66	8	5.28	158.4
Incandescent light	6	100	0.6	8	4.8	144
Energy saving light	16	15	0.24	8	1.92	57.6
Spot light						
Fridge	1	145	0.145	20	2.9	87
Freezer	1	150	0.15	20	3	90
Micro oven	1	1800	1.8	0.25	0.45	13.5
Washing machine						
TV	1	138	0.138	6	0.828	24.84
DVD						
MP3 Player						
Computer						
Printer						
Iron	1	1200	1.2	0.07	0.084	2.52
Toaster	1	800	0.8	0.05	0.04	1.2
Blender	1	400	0.4	0.095	0.038	1.14
Sandwich maker						
						900.3

2.4. Total energy use of Unit B4

Appliances	No	Rating (W)	Estimated total load for appliance (kW) Number of appliance x corresponding rating	Usage per day (h)	Daily energy use during used period (kWh) Estimated total load fro appliance x usage per day	Monthly energy use (kWh) Daily energy use x 30
AC (1.5 ton)	1	1850	1.85	4	7.4	222
AC (2 ton)	1	2400	2.4	2	4.8	144
Fan	7	80	0.56	8	4.48	134.4
Exhaust fan	4	35	0.14	1	0.14	4.2
Fluorescent light	11	60	0.66	7	4.62	138.6
Incandescent light	16	100	1.6	7	11.2	336
Energy saving light	7	15	0.105	7	0.735	22.05
Spot light	6	40	0.24	3	0.72	21.6
Fridge	1	145	0.145	20	2.9	87
Freezer	1	150	0.15	20	3	90
Microoven	1	1800	1.8	0.25	0.45	13.5
Washing machine	1	410	0.41	0.2857	0.117137	3.5
TV	1	138	0.138	6	0.828	24.84
DVD						
MP3 Player						
Computer						
Printer						
Iron	1	1200	1.2	0.25	0.3	9
Toaster	1	800	0.8	0.05	0.04	1.2
Blender	1	400	0.4	0.095	0.038	1.14
						1253.03

2.5. Total energy use of Unit B5

Appliances	No.	Rating (W)	Estimated total load for appliance (kW) Number of appliance x corresponding rating	Usage per day (h)	Daily energy use during used period (kWh) Estimated total load fro appliance x usage per day	Monthly energy use (kWh) Daily energy use x 30
AC (1.5 ton)	1	1850	1.85	4	7.4	222
AC (2 ton)	1	2400	2.4	2.5	6	180
Fan	7	80	0.56	6	3.36	100.8
Exhaust fan	4	35	0.14	0.15	0.021	0.63
Fluorescent light	12	60	0.72	5	3.6	108
Incandescent light	30	100	3	5	15	450
Energy saving light	3	15	0.045	5	0.225	6.75
Spot light	4	40	0.16	2	0.32	9.6
Fridge	1	145	0.145	20	2.9	87
Freezer	1	150	0.15	20	3	90

Microoven	1	1800	1.8	0.1667	0.3	9
Washing machine	1	410	0.41	0.2857	0.117137	3.5
TV	2	138	0.276	5	1.38	41.4
DVD	2	35	0.07	2	0.14	4.2
MP3 Player						
Computer	1	200	0.2	4	0.8	24
Printer						
Sound system						
Iron	1	1200	1.2	0.5	0.6	18
Toaster	1	800	0.8	0.025	0.02	0.6
Blender	1	400	0.4	0.02	0.008	0.24
						1355.72

2.6. Total energy use of Unit C1

Appliances	No	Rating (W)	Estimated total load for appliance (kW) Number of appliance x corresponding rating	Usage per day (h)	Daily energy use during used period (kWh) Estimated total load fro appliance x usage per day	Monthly energy use (kWh) Daily energy use x 30
AC (1 ton)						
AC (2 ton)						
Fan	6	80	0.48	6	2.88	86
Exhaust fan	1	35	0.035	1.5	0.0525	1.575
Fluorescent light	10	60	0.6	6	3.6	108
Incandescent light	8	100	0.8	6	4.8	144
Energy saving light						
Spot light						
Fridge	1	145	0.145	20	2.9	87
Freezer						
Microoven	1	1800	1.8	0.0238	0.4284	1.2852
Washing machine						
TV	1	138	0.138	5	0.69	20.7
DVD						
MP3 Player						
Computer						
Printer						
Sound system						
Iron	1	1200	1.2	0.0238	0.02856	0.8568
Toaster						
Blender	1	400	0.4	0.0238	0.00952	0.2856
						450.1026

2.7. Total energy use of Unit C5

Appliances	No	Rating (W)	Estimated total load for appliance (kW) Number of appliance x corresponding rating	Usage per day (h)	Daily energy use during used period (kWh) Estimated total load fro appliance x usage per day	Monthly energy use (kWh) Daily energy use x 30
AC (1 ton)	1	1250	1.25	1.5	1.875	56.25
AC (2 ton)	1	2400	2.4	6	14.4	432
Fan	7	80	0.56	10	5.6	168
Exhaust fan	1	35	0.035	1.5	0.0525	1.575
Fluorescent light	9	60	0.54	8	4.32	129.6
Incandescent light	9	100	0.9	8	7.2	216
Energy saving light	7	15	0.105	8	0.84	25.2
Spot light	2	40	0.08	5	0.4	12
Fridge	1	145	0.145	20	2.9	87
Freezer	1	150	0.15	20	3	90
Microoven	1	1800	1.8	0.25	0.45	13.5
Washing machine	1	410	0.41	0.4286	0.175726	5.27
TV	2	138	0.276	7	1.932	57.96
DVD	1	35	0.035	2	0.07	2.1
MP3 Player						
Computer						
Printer						
Sound system						
Iron	1	1200	1.2	0.25	0.3	9
Toaster	1	800	0.8	0.125	0.1	0.3
Blender	1	400	0.4	0.02	0.008	0.24
						9.54
						1315.535

Appendix 3. Number of lights in all the Units of the case study building

3.1. Number of lights in each room of Unit A2

Unit A2	Incandescent	Fluorescent	Energy saving	Spot	Special
Foyer				4	
Living	4	2			
Dining	2	2	2		
Kitchen		2		4	
Master bed	2	2			
Child bed	2	2			
Guest bed	1	1			
Changing room				1	
Common toilet	1			1	
Toilet (master bed)	1	1			
Toilet 2					
Housekeeper's toilet	1				
Kitchen balcony					
Balcony 1	1				
Balcony 2	1				
Foyer to beds				1	

3.2. Number of lights in each room of Unit A3

Unit A2	Incandescent	Fluorescent	Energy saving	Spot	Special
Foyer				1	Table lamp (incandescent light)
Living			4	2	Stand lamp (incandescent light)
Dining	1		2	2	
Kitchen		1			
Master bed		1	2		
Child bed		1	2		
Guest bed		1	2		
Changing room					
Common toilet	2	1			
Toilet (master bed)		2	2		
Toilet 2		2			
Housekeeper's toilet	1				
Kitchen balcony		1			
Balcony 1		1			
Balcony 2		1			
Foyer to beds			2		

3.3. Number of lights in each room of Unit B2

Unit B2	Incandescent	Fluorescent	Energy saving	Spot	Special
Foyer			1		
Living		1	2		
Dining	1		2		
Kitchen		1	1		
Master bed		1	2		
Child bed		1	2		
Guest bed	1		2		
Changing room	1				
Common toilet		1	1		
Toilet (master bed)	1	1	1		
Toilet 2	1	1	1		
Housekeeper's toilet	1				
Kitchen balcony		1			
Balcony 1		1			
Balcony 2		1			
Foyer to beds			1		

3.4. Number of lights in each room of Unit B4

Unit B4	Incandescent	Fluorescent	Energy saving	Spot	Special
Foyer				2	
Living	6	1		1	Stand lamp (incandescent light)
Dining	1	1	2		Stand lamp 2 (incandescent light)
Kitchen	1	1		2	
Master bed	2	1			
Child bed	2	1			
Changing room				1	
Common toilet		1	1		
Toilet (master bed)		1	2		
Toilet 2		1	2		
Housekeeper's toilet	1				
Kitchen balcony		1			
Balcony 1		1			
Balcony 2		1			
Foyer to beds					

3.5. Number of lights in each room of Unit B5

Unit B5	Incandescent	Fluorescent	Energy saving	Spot	Special
Foyer				2	Table lamp (incandescent light)
Living	8				2 Stand lamp (incandescent light)
Dining	4	1	3	2	
Kitchen	1	1			
Master bed	2	2			Table lamp (incandescent light)
Child bed	2	1			
Study room	1	1			Table lamp (incandescent light)
Changing room					
Common toilet	2	1			
Toilet (master bed)	2	1			
Toilet 2	2	1			
Housekeeper's toilet	1				
Kitchen balcony		1			
Balcony 1		1			
Balcony 2		1			
Foyer to beds					

3.6. Number of lights in each room of Unit C1

Unit C1	Incandescent	Fluorescent	Energy saving	Spot	Special
Foyer	1				
Living	2	1			
Dining	2	1			
Kitchen		1			
Master bed	1	1			
Child bed		1			
Guest bed		1			
Changing room					
Common toilet		1			
Toilet (master bed)		1			
Toilet 2		1			
Housekeeper's toilet	1				
Kitchen balcony					
Balcony 1		1			
Balcony 2					
Foyer to beds	1				

3.7. Number of lights in each room of Unit C5

Unit C5	Incandescent	Fluorescent	Energy saving	Spot	Special
Foyer					1 (Incandescent light)
Living		2			
Dining	1	1	2		
Kitchen		1	1		
Master bed		1			
Child bed		2			
Guest bed		1			
Changing room					
Common toilet	2		1		
Toilet (master bed)	2		2		
Toilet 2	2				
Housekeeper's toilet	1				
Kitchen balcony		1			
Balcony 1				1	
Balcony 2					
Foyer to beds					

REFERENCES

- Ahmed, K.A., Haq, A. & Moniruzzaman, M. 2006. Potentials of Window Design in Inducing Air Change in Still Air Condition. *Proceedings of the 23rd Conference on Passive and Low Energy Architecture*. Geneva, Switzerland.
- Ahmed, Z.N. 1987. *The Effects of Climate on the Design and Location of Windows in Bangladesh*. Ph.D. thesis. Department of Building Science, Sheffield University.
- Alam, M.S., Kabir, E., Rahman, M.M. & Chowdhury, M.A.K.. 2004. Power Sector Reform in Bangladesh: Electricity Distribution System. *Energy*, 29 (11): 1773-1783.
- Aldawoud, A. & Clark, R. 2008. Comparative Analysis of Energy Performance Between Courtyard and Atrium in Buildings. *Energy and Buildings*, 40 (3): 209-214.
- Ali, Z.F. 2007. Comfort with Courtyards in Dhaka Apartments. *BRAC University Journal*, IV (2): 1- 6.
- Alvarado, J.L., Martí'nez E. 2008. Passive Cooling of Cement-Based Roofs in Tropical Climates. *Energy and Building*, 40 (3): 358-364.
- BBS. 2008. Statistical Pocket Book of Bangladesh 2007. Bangladesh Bureau of Statistics Planning Division: Ministry of Planning.
- Bolatturk, A. 2008. Optimum Insulation Thicknesses for Building Walls with Respect to Cooling and Heating Degree-Hours in the Warmest Zone Of Turkey. *Building and Environment*, 43 (6): 1055–1064.
- Cheung, C.K., Fuller, R.J. & Luther, M.B. 2005. Energy-Efficient Envelope Design for High-Rise Apartments. *Energy and Buildings*, 37 (1): 37-48.
- Chowdhury, A.A., Rasul, M.G. & Khan, M.M.K. 2006. Towards Energy Efficient Building Assets. A Review on Sub-Tropical Climate. Fifteenth Symposium On Improving Building Systems in Hot and Humid Climate . [Online]. Available: <http://repository.tamu.edu/bitstream/handle/1969.1/4541/ESL-HH-06-07-30.pdf?sequence=1>. [accessed 22 December, 2008].
- Clarke J.A. & Maver, T.W. 1991. Advanced Design Tools for Energy Conscious Building Design: Development and Dissemination. *Building and Environment*, 26(1): 25-34.
- Development and Land Use Policy Manual. 2000. Energy Efficient Building Design. [Online]. Available: http://www.fremantle.wa.gov.au/council/resource/DBH12_Energy_Efficient.pdf. [accessed 28 December , 2008].
- Dhaka City Building Construction Act. 2008.
- Dhaka Mirror.2009. Sufferings of City Dwellers Mount Due to Severe Power Crisis. [Online]. Available: <http://www.dhakamirror.com/?p=3428>. [accessed 10 March, 2009].

- Flyvbjerg, B. 2006. Five Misunderstandings about Case-Study Research. *Qualitative Enquiry*, 12(2): 219-245.
- Garde, F., Adelard, L., Boyer, H. & Rat, C. 2004. Implementations and Experimental Survey of Passive Design Specifications Used in New Low-Cost Housing Under Tropical Climates. *Energy and Buildings*, 36 (4): 353–366.
- Garson, G.D. 2002. *Guide to Writing Empirical Papers, Theses and Dissertations*. New York: Marcel Dekker, Inc.
- Givoni, B. 1998. *Climate Considerations in Building and Urban Design*. New York: Van Nostrand Reinhold.
- Gut, P. & Ackerknecht, D. 1993. *Climate Responsive Building: Appropriate Building Construction in Tropical and Subtropical Regions*. Switzerland: SKAT.
- Hancock, J.M. 2006. *Dhaka Electric Supply Company Hosts Final USEA/USAID Utility Partnership Exchange Program With U.S. Distribution Utilities*. Retrieved 15 December, 2008, from http://www.usea.org/Programs/EPP/EPP_News/DESCO_12_2006.pdf.
- Henning, H.M. 2007. Solar Assisted Air Conditioning of Buildings – An Overview. *Applied Thermal Engineering*, 27 (10): 1734-1749.
- Hiranoa, T., Katoa, S., Murakamib, S., Ikagac, T. & Shiraishi, Y. 2006. A Study on a Porous Residential Building Model in Hot and Humid Regions: Part 1-The Natural Ventilation Performance and the Cooling Load Reduction Effect of the Building Model. *Building and Environment*, 41 (1): 21-32.
- Islam, N. & Shafi, S.A. 2008. *A proposal for a Housing Development Programme in Dhaka City*. Dhaka: Centre for Urban Studies.
- Janssen, R. 2004. *Towards Energy Efficient Buildings in Europe*. London: The European Alliance of Companies for Energy Efficiency in Buildings.
- Johansson, R. 2003. *Case study methodologies* (Lecture III B). Stockholm: Royal Institute of Technology, Built Environment Analysis.
- Jones, D.L. 1998. *Architecture and the Environment: Bioclimatic Building Design*. UK. London: Laurence King.
- Kanyama, A.C & Lindén, A.L. 2007. Energy Efficiency in Residences- Challenges for Women And Men in the North. *Energy Policy*, 35 (4): 2163-2172.
- Khan, S.I., Mahfuz, M.U., Aziz, T. & Zobair, N. M. 2002. Prospect of Hybrid Wind System in Bangladesh. *Second International Conference on Electrical and Computer Engineering ICECE 2002*: 212-215.
- Krarti, M., Erickson, P.M. & Hillman, T.C. 2005. A Simplified Method to Estimate Energy Savings of Artificial Lighting Use from Day Lighting. *Building and Environment*, 40 (6): 747-754.

- Lam, J. C. 1996. An Analysis of Residential Sector Energy Use in Hong Kong. *Energy*, 21(1):1-8.
- Lam, J. C. 2000. Residential Sector Air-conditioning Loads and Electricity Use in Hong Kong. *Energy Conversion and Management* 41(16):757- 1768.
- Lam, J.C., Tsang, C.L., Li,D.H.W. & Cheung, S.O. 2005. Residential Building Envelope Heat Gain and Cooling Energy Requirements. *Energy*, 30 (7): 933–951.
- Levinson, R.,Berdahl,P.,Berhe, A. & Akbari, H. 2005. Effects of Soiling and Cleaning on the Reflectance and Solar Heat Gain of a Light-Coloured Roofing Membrane. *Atmospheric Environment*, 39 (40): 7807–7824.
- Liping, W. & Hien,W.N. 2007. The Impacts of Ventilation Strategies and Facade on Indoor Thermal Environment for Naturally Ventilated Residential Buildings in Singapore. *Building and Environment*, 42 (12): 4006-4015.
- Liping, W., Hien,W.N & Shuo, L. 2007. Facade Design Optimization for Naturally Ventilated Residential Buildings in Singapore. *Energy and Buildings*, 39 (8): 954-961.
- Lippiatt, B. C. & Boyles, A. S. (2001). Using BEES to Select Cost-Effective Green Products. *International Journal of LCA*, 6(2):76-80.
- Mallick, F.H. 1996. Thermal Comfort and Building Design in the Tropical Climates. *Energy and Buildings*, 23 (1996): 161-167.
- Mathur,V. K. & Chand, I. 2003. Climatic Design for Energy Efficiency in Buildings. *IE (I) Journal-AR*, 84 (2003): 33-39.
- Mozumder,P. & Marathe, A. 2007.Viewpoint: Causality Relationship Between Electricity Use and GDP in Bangladesh. *Energy Policy*, 35 (1): 395-402.
- Mowla, Q.A. 1985. *An Analytical Study of Sun-Building Interaction*. Roorkee. Master's thesis. Department of Architecture and Planning.University of Roorkee.
- Nagarajan, N. 2006. Energy Efficiency Improvement in Buildings. *Proceedings of the India-IEA Joint Workshop on Energy Efficiency in Buildings and Building Codes*. New Delhi, India.
- Ossen, D.R., Ahmad, M.H. & Madros, N.H. 2005. Optimum Overhang Geometry for Building Energy Saving in Tropical Climates. *Journal of Asian Architecture and Building Engineering*, 4(2): 563-570.
- Patton, M.Q. 1990. *Qualitative Evaluation and Research Methods*. 2nd Edition. Newbury Park, California: Sage.
- People's Report 2004-2005.2006. Bangladesh Environment. Dhaka: Unnayan Shamannay
- Racissi,S. & Taheri, M. 1999. Energy Saving by Proper Tree Plantation. *Building and Environment*, 34(1999): 565-570.

- Rahman, A. & Mallick, D.L. n.d. Climate Change Impacts on Cities of Developing Countries: A Case Study on Dhaka. *Bangladesh Centre for Advanced Studies*. [Online]. Available: http://www.c40tokyo.jp/en/pdf/keynoteLecture_symposium/dl_mallick.pdf. [accessed 20 December, 2008].
- Reza, S.I. 2008. Housing Crisis. *The Financial Express, Dhaka*. [Online]. Available: http://www.thefinancialexpress-bd.info/search_index.php?page=detail_news&news_id=41131. [accessed 20 December, 2008].
- Safarzadeh, H. & Bahadori, M.N. 2005. Passive Cooling Effects of Courtyards. *Building and Environment*, 40 (1): 89-104.
- Saleque, A.K. 2008. *Bangladesh Energy Security – Entering Red Zone*. [Online]. Available: <http://energybangla.com/index.php?mod=article&cat=SomethingtoSay&article=105> [accessed 17 December, 2008]
- Saleque, A.K. 2008. *Energy Security of Bangladesh – Issues and Options*. Retrieved 18 December, 2008, from <http://energybangla.com/index.php?mod=article&cat=SomethingtoSay&article=1173>
- Simpson, J.R. & McPherson, E.G. 1996. Potential of Tree Shade for Reducing Residential Energy Use in California. *Journal of Arboriculture*, 22 (1): 23-31.
- Stake, R. E. (1995). *The Art of Case Study Research*. Thousand Oaks, California: Sage.
- Svane, Ö. 2005. *Useful Concepts or Eternal Truths? Reflections on Case Study Generalization* in Vestbro D U, Hürol Y & Wilkinsson N (eds): *Methodologies in Housing Research*. Great Britain The Urban International Press.
- Suehrcke, H., Peterson, E.L. & Selby, N. 2008. Effect of Roof Solar Reflectance on the Building Heat Gain in a Hot Climate. *Energy and Buildings*, 40 (12): 2224-2235.
- Tang, R. & Etzion, Y. 2004. On Thermal Performance of an Improved Roof Pond for Cooling Buildings. *Building and Environment*, 39 (2): 201-209.
- Teemusk, A. & Mander, U. 2009. Green Roof Potential to Reduce Temperature Fluctuations of a Roof Membrane: A Case Study from Estonia. *Building and Environment*, 44 (3): 643-650.
- Tham, K.W. 1993. Conserving Energy without Sacrificing Thermal Comfort. *Building and Environment*, 28 (3): 287-299.
- The Daily Star. 2009. 4 Hours Outage a Day in Dhaka. [Online]. Available: <http://www.thedailystar.net/newDesign/news-details.php?nid=79210>. [accessed 12 March, 2009]
- Tuhin, F. 2008. *Revisiting the Energy Scenario in Bangladesh*. [Online]. Available: <http://energybangla.com/index.php?mod=article&cat=SomethingtoSay&article=1055>. [accessed 17 December, 2008].

- United Nations. 1991. *Energy Efficient Design: A Guide to Energy Efficiency and Solar Applications in Building Design*. ECE Energy Series No. 9. New York: United Nations.
- United Nations. 1999. *World Urbanization Prospects: The 1999 Revision*. New York: United Nations.
- UNECE. 2008. *Climate Change and Rising Oil Prices: Why Energy Efficiency in Housing is Crucial?* [Online]. Available: http://www.unece.org/press/pr2008/08env_p13e.htm. . [accessed 20 December, 2008].
- UNEP. 2006. *Eco-housing Guidelines for Tropical Regions*. Bangkok: United Nations Environment Programme Regional Resource Centre for Asia and the Pacific.
- UNEP. 2007. *Buildings and Climate Change: Status, Challenges and Opportunities*. United Nations Environment Programme.
- USAID. 2007. *South Asia Regional Initiative for Energy*. [Online]. Available: http://www.sari-energy.org/PageFiles/Countries/Bangladesh_Energy_Overview.asp. [accessed 3 April, 2009].
- Vangtook, P. & Chirarattananon, S. 2007. Application of Radiant Cooling as a Passive Cooling Option in Hot Humid Climate. *Building and Environment*, 42 (2): 543-556.
- Vijaykumar, K.C.K., Srinivasan, P.S.S. & Dhandapani, S. (2007). A Performance of Hollow Clay Tile (HCT) Laid Reinforced Cement Concrete (RCC) Roof for Tropical Summer Climates. *Energy and Buildings*, 39 (8): 886-892.
- Watson, D. & Labs, K. 1983. *Climatic Building Design: Energy-Efficient Building Principles and Practice*. New York: McGraw-Hill.
- Williams, B.E. 2008. *Overcoming Barriers to Energy Efficiency for Rental Housing*. Master's thesis. Department of Urban studies and Planning, Massachusetts Institute of Technology.
- Wong, N. H., Tay, S. F., Wong, R., Ong, C.L. & Sia. A.(2003). Life Cycle Cost Analysis of Rooftop Gardens in Singapore. *Building and Environment*, 38 (3): 499- 509.
- Wong, N.K. & Huang, B. 2004. Comparative Study of the Indoor Air Quality of Naturally Ventilated and Air-Conditioned Bedrooms of Residential Buildings in Singapore. *Building and Environment*, 39 (9): 1115-1123.
- Wong, N.H. & Li, S. 2007. A Study of the Effectiveness of Passive Climate Control in Naturally Ventilated Residential Buildings in Singapore. *Building and Environment*, 42 (3): 1395-1405.
- Yang, K. H. & Hwang, R. L. 1993. The Analysis of Design Strategies on Building Energy Conservation in Taiwan. *Building and Environment*, 28(4): 429-438.
- Yin, R.K. 1994. *Case Study Research: Design and methods*. Second Edition. Thousand Oaks, California: Sage.
- Yu, J., Yang, C. & Tian, L. 2008. Low-Energy Envelope Design of Residential Building in Hot Summer and Cold Winter Zone in China. *Energy and Buildings*, 40 (8): 1536-1546.

Zain, Z.M., Taib, M.N. & Baki, S.M.S. 2007. Hot and Humid Climate: Prospect for Thermal Comfort in Residential Building. *Desalination*, 209(1-3): 261-268.