Effect of Orientation and Building Geometry on Thermal Comfort and Energy Efficiency of Planned Residential Buildings of Tropical City Dhaka

Fariha Seraj*[1]

[1] Dhaka University of Engineering & Technology, Gazipur, Bangladesh
fariha.seraj@duet.ac.bd

Abstract. In tropics, a significant amount of energy is used for ensuring thermal comfort in buildings. The geometry of a building is a major factor in the early design stage, affecting not only the thermal comfort of occupants but also energy consumption and construction costs. The majority of studies on thermal comfort and energy efficiency in residential buildings focus primarily on the design of the building envelope and fenestration. Studies related to building geometry are focused on either thermal comfort or energy efficiency. This research aims to examine the effect of orientation and building geometry on indoor thermal comfort and energy efficiency of planned residential buildings of tropical city Dhaka. The performance of seven different building geometries (Existing shape, Rectangular shape, L, U, T, H, and O shapes) for four orientations was evaluated. Thermal comfort and energy efficiency of the studied options were calculated using Mean Radiant Temperature (T_{mrt}) and Energy Use Intensity (EUI) respectively. Thermal comfort and energy simulations were carried out using Rhinoceros, Grasshopper and ClimateStudio. The results indicate that L-shape building form provides higher thermal comfort and lower energy consumption in all four orientations. Highest thermal comfort and lowest energy consumption was observed in north facing L-shape and east facing T-shape buildings respectively. It is also found that T_{mrt} and EUI can be reduced up to 11% and 8% respectively by combining appropriate building geometry and orientation. The findings of this study can assist architects in making design choices during the initial phase of residential building projects.

Keywords: Orientation, Building geometry, Thermal comfort, Energy efficiency, Residential building**.**

1 Introduction

Buildings contribute substantially to global energy demand, with the residential sector accounting for approximately 21% of the total worldwide energy consumption [1]. The energy scenario of Bangladesh is more aggravated. Among the consumers of Dhaka Electric Supply Company Limited (DESCO), 90.6% are residential and they consume 55% of the total electricity consumption [2]. Due to growing demand and shortage of

Md.K. Miah et al. (eds.), *Proceedings of the 1st International Conference on Recent Innovation in Civil Engineering and Architecture for Sustainable Development (IICASD 2024)*, Advances in Engineering Research 260,
https://doi.org/10.2991/978-94-6463-672-7_9

power supply, load shedding has increased especially during the hot- humid summer months as the hot discomfort leads many people to rely on air conditioners. In Dhaka, 77% of urban households consume between 100 and 400 kWh of energy per month, with cooling accounting for 42% of this usage [3].

In tropical countries where solar radiation is intense, achieving thermal comfort inside buildings is challenging due to global warming and poor design of buildings. In Dhaka, thermally comfortable, non-compact building designs with courtyards have disappeared due to land scarcity and the pressures of a growing population. Compact apartment building became popular as it suits the contemporary trend of living [4]. Thermal performance of these compact building forms is not suitable for the occupants as the external walls facing the narrow alley between buildings cannot flush out the heat gain from solar radiation, people and equipment. As a result, achieving thermal comfort in these buildings is challenging without relying on mechanical cooling systems. Alike other tropical cities, Dhaka is characterized by lack of access to energy, energy security and energy poverty where use of air conditioning system to achieve thermal comfort means higher energy consumption. Passive building design can be an effective way to ensure energy efficiency as well as thermal comfort of the occupants. Several parameters of building design have been identified in previous studies to ensure energy efficiency and thermal comfort in buildings. The parameters are: building geometry, orientation, building envelope, materials etc. [5].

One of the important consideration at the early design stage of building that affects the thermal performance and energy consumption is building geometry. Building geometry can influence the efficiency of passive cooling strategies (solar protection, day and night time ventilation etc.). Numerous studies have explored how building geometry parameters, such as shape, orientation, and compactness, affect thermal comfort and energy consumption. In a study on the commercial building of Indonesia, two important parameters in the building geometry are identified- building shape and its orientation [6]. Based on the geographical location of building, the study indicated that a compact building shape with a proper orientation might save energy usage for heating and cooling systems by as much as 81%. A study [7] investigated the effect of the zoning scheme (building height, floor area ratio, and density) on the thermal performance of naturally ventilated residential buildings in Dhaka. Another study examined the impact of building shape on energy demand by analyzing two factors: the building shape factor and relative compactness [8]. The study suggested that shape factor (surface-to-volume ratio) of building is particularly significant in hot climates. Researchers [9] analyzed the correlation between building shape and heating energy usage by using the shape coefficient (C) that external surface to volume ratio. They studied different shape configurations for the same volume and found that, in case of cold climate, the heating energy usage is inversely proportional to compactness. The effect of building geometric shape and orientation was studied [6] by using two co- efficient: building's external surface to volume ratio and width to length ratio. The study showed that combination of appropriate orientation and building geometry can reduce heating and cooling energy load, depending on the geographical location of the building. Most of the studies are confined to either thermal comfort or energy consumption of commercial buildings rather than residential. At this point effect of building geometry and orientation need to be studied for tropical residential buildings.

Densification changes the compactness and shape of Dhaka's building geometry from the traditional building features that were more appropriate for passive cooling [7]. To control building density Dhaka Metropolitan Building Construction Act (DMDC)-2008 was legislated by limiting maximum buildable area and floor area ratio (FAR) [10]. This law specified a maximum buildable area and FAR for a lot which ensures a mandatory open area must be preserved in the lot. This study is focused on the Dhanmondi residential area of Dhaka city where lots are limited to 1/3 acre and maximum buildable area and FAR for this lot size is 50% and 5.25 for a 9m wide front road [10]. After implementation of the law building forms changed in Dhaka and several types of building geometry is identified by a study conducted in 2014 on Dhanmondi residential area, among which rectangular shape with narrow void for daylight and ventilation is largest in number [7]. At this point, thermal comfort and energy consumption of other possible shapes permitted by the DMDC, 2008 need to be investigated.

This research aims to investigate the effect of two building geometry parameters- building shape and orientation, on both thermal comfort and energy efficiency of naturally ventilated planned residential buildings of tropical city Dhaka. To achieve the objective, building characteristics and shapes are identified in the first part. Then thermal and energy simulations are performed using Rhinoceros [11], Grasshopper [12] and ClimateStudio [13] to investigate the effect of the identified parameters. Finally, results from the simulation studies are analyzed and design guidelines are provided.

2 Methodology

2.1 Local Climate Data

The latitudes and longitudes of Dhaka are 23°40'to 23°55' north and 90°20'to 90°30' east, respectively. Bangladesh experiences three distinct seasons in its composite monsoon climate, as classified by Koenigsberger's classification of tropical climate: a hot humid summer (March to June); a humid warm rainy monsoon season (June to October); and a cool dry winter (October to March). In Dhaka, maximum summer temperatures range from 30°C to 40°C during the hot and humid season, with April being the hottest month of this period [14]. In this study, hourly weather data (BGD_ Dhaka.419230_SWERA) obtained from the website of EnergyPlus [15] is used.

2.2 Selection of Case Space

The Among the planned residential areas of Dhaka, Dhanmondi residential area is found to be most appropriate as the typical plot size is 1/3 acre and variations of building shapes are observed in this location. After conducting a visual survey in the selected area, a number of building geometry and characteristics are observed. Based on the survey, the following selection criteria are developed to select a case residential building:

1. The case building must be located in the planned residential area of Dhaka city.
2. The building should be constructed according to the Dhaka Metropolitan Building Construction Rules 2008 [10].
3. Only the front side of the case building should be open to the road and other three sides should be surrounded by buildings.

Based on the above criteria, a north oriented 13- storied apartment building (see Fig. 1) is selected as case space for simulation analysis. The physical characteristics of the building, occupancy and energy demand related information and material properties are described in Table 1.

Fig. 1. (a) Site plan, (b) Floor plan, (c) Images of the 13- storied case apartment building.

2.3 Selection of Design Variables

To study the effect of building geometry on thermal comfort and energy efficiency, some building geometry parameters are fixed i.e. area of each floor, FAR, total volume of the form, height of the building, total number of floors. Other construction (window size, width of the shading device, construction material) and occupancy (total no of unit per floor, people density, equipment and lighting power density) related parameters also remain fixed.

There are two independent design variables (see Fig. 2) for the building geometry: building shape and orientation. Six different building shapes are selected: Rectangular, L, U, T, H and O- shape. In order to present the effect of building shape on thermal comfort and energy efficiency, shape parameter must be selected. In this study 'shape co- efficient, C' is used to define a shape and defined as following [9]:

$$C = S/V \quad (1)$$

Here, S is the envelope surface area of the building and V is the inner volume of the building. Different shapes of building are compared for same volume (V) as the maximum ground coverage (MGC) and height remained same as the existing condition. Another independent variable is orientation. Four orientations are considered: North (0°), East (90°), South (180°) and West (270°). Multiple design options are created by changing these two variables. The independent design variables and their values are listed in Table 2.

Table 1 Physical characteristics, Occupancy and energy consumption and material properties of the case apartment building.

Physical Characteristics	
Orientation	North
Plot Size	1146.4 m^2 (0.3 acre)
Front Road width	9m
Floor Area Ratio (FAR)	5.25
Maximum Ground Coverage (M.G.C)	539.1 m^2 (43.75%)
Number of floors	13 (Ground+ 12)
Total envelope surface area (S_e)	487.8 m^2
Volume of the building (V)	21,024.9 m^3
No of unit per floor	3
Occupancy and energy consumption	
People Density	0.05 p/ m^2
Average equipment power density	14.5 W/ m^2
Average lighting power density	5.4 W/ m^2
Material Properties	
Roof	0.2 m Concrete, U-Value: 2.273 W/ m^2K
Facade	0.25 m Plastered Brick, U-Value: 2.907 W/ m^2K
Partition Wall	0.159 m Plastered Brick , U-Value: 2.241 W/ m^2K
Window	0.006m Single glazing with aluminium frame, U-Value: 5.8 W/ m^2K

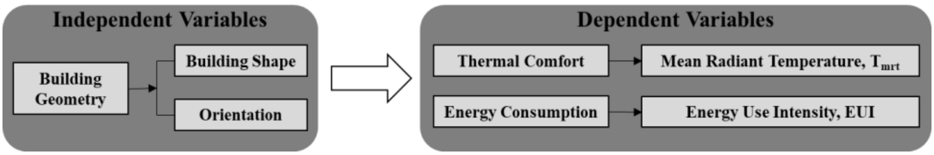
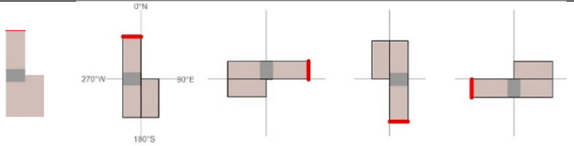
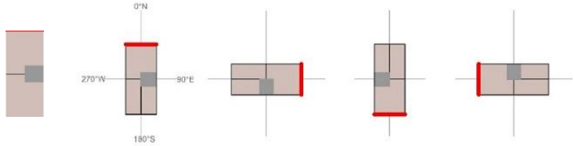
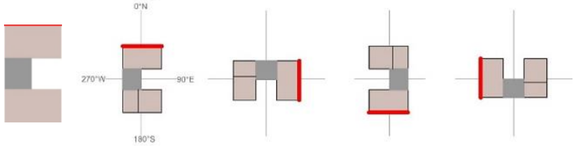
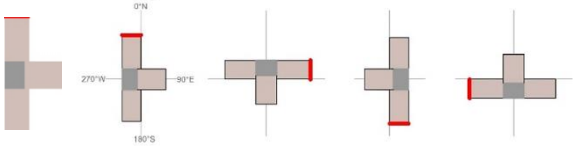
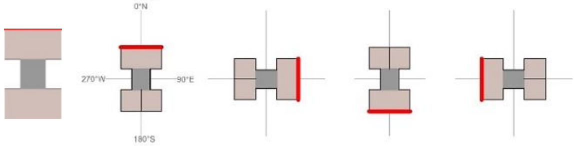
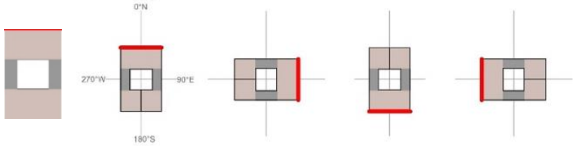
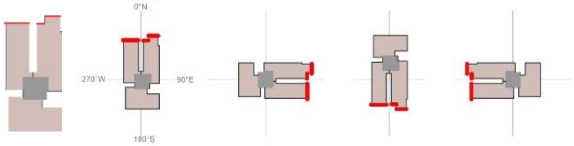


Fig. 2. Design Variables for the simulation study.

Table 2. Details of the independent design variables.

Shapes	Shape Co-efficient	Plan	Orientation

L-Shape	0.014	
Rectangular-Shape	0.014	
U-Shape	0.018	
T-Shape	0.019	
H-Shape	0.02	
O-Shape	0.021	
Existing Shape	0.023	

Front Facade **Dwelling Units** **Vertical Core**

2.4 Simulation Tools and Method

The multi zone energy model of the case apartment building and the other six studied options for building shapes with the existing surrounding buildings are created using Rhinoceros 7 and Grasshopper. Then the model is connected to the thermal and energy simulation workflow templates in Climate Studio [13] (Fig. 3). Both thermal and energy simulation workflows of Climate Studio run via algorithmic modelling environment of Grasshopper [12]. For thermal simulation Spatial Thermal Comfort workflow template is used to calculate the Mean Radiant Temperature (T_{mrt}) across the floor area of the multi zone energy model. Energy simulation is done using the Shoebox model for multi zone energy models with uses the Energy Plus [15] to calculate the Energy

Use Intensity (EUI). Simulation parameters i.e. people density, equipment and lighting power density, material and construction properties are set according to the data found from the field survey (Table 1). Window to wall ratio and illuminance target is set to 20% and 150 lux (with continuous dimming) respectively according to the Bangladesh National Building Code (BNBC) [10].

Spatial thermal comfort simulations are done for the month of April as highest temperatures were observed in this month (Section 2.1). From the simulation results, average T_{mrt} for April is calculated from the hourly temperature simulation data and analyzed for seven different building shapes and four orientations using the Neutral Temperature index proposed by Humphreys [16] as it found to be most suitable thermal comfort index identified by a previous study on thermal comfort in Dhaka [17]. Energy simulations are done for the whole year for the seven building shapes and four orientations and expressed as EUI in kWh/m^2/year.

.

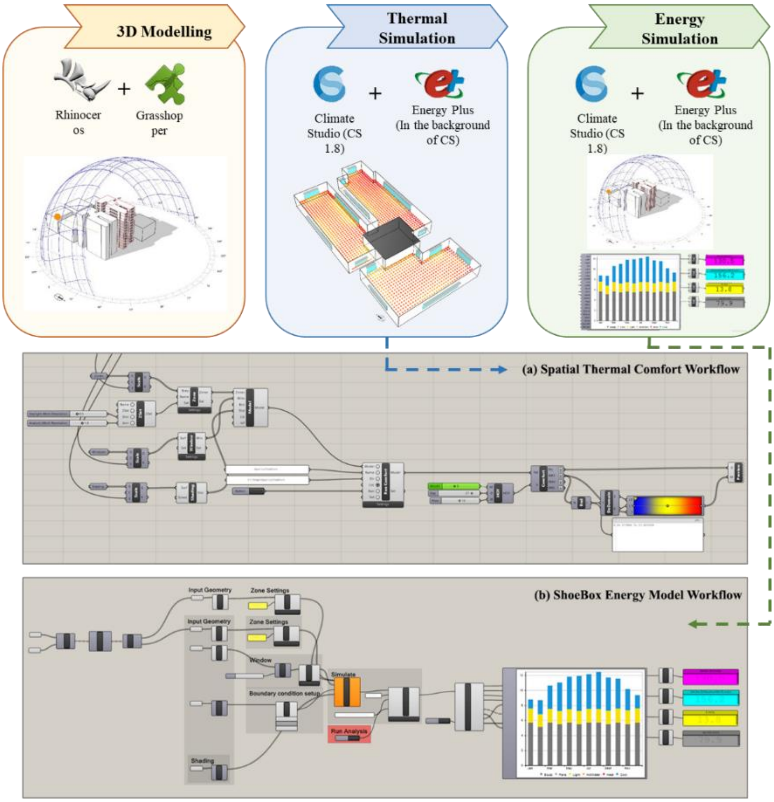


Fig. 3. Details of the simulation method with software prototypes and thermal and energy workflow in Grasshopper.

3 Results

The effect of building geometry and orientation on thermal comfort and energy efficiency are discussed separately in Section 3.1 and 3.2. Finally, the optimized solutions considering the lowest T_{mrt} and lowest EUI are identified by considering each building geometry parameter and discussed.

3.1 Effect of Building Geometry on Thermal Comfort and Energy Efficiency

The effect of building geometry on thermal comfort and energy efficiency are shown in Fig. 4. Parameters other than geometry is not considered here to identify the effect of building geometry on thermal comfort and energy efficiency solely. The lowest T_{mrt} and EUI values are observed in L-shape building. In addition to this, only L-shape building provide the T_{mrt} within the comfort range. The highest value of T_{mrt} and EUI are observed in T- shape and existing building shape respectively. The building geometries are arranged in the chart from lower value of shape co- efficient to the higher value. It is found that both T_{mrt} and EUI do not decrease with increased shape co- efficient (C) value. In tropical climate, building envelope (roof and walls) absorb solar heat gain during the day and consequently the indoor temperature increases in the non-compact building (higher value of C). This increases the cooling energy demand. On the other hand, during night these non- compact buildings cannot dissipate the unwanted heat to the outdoor through the narrow alley between buildings in case of Dhaka. U, H and O- shaped buildings perform better than the rectangular, T and existing building shape. Besides the higher shape co- efficient value, positioning of the open space plays an important role here. U, H and O shaped buildings have recessed open spaces that provide more shade on the envelope during the day comparing the rest three types. This not only reduce the solar heat gain during daytime but also maximize night flush cooling and ventilation.

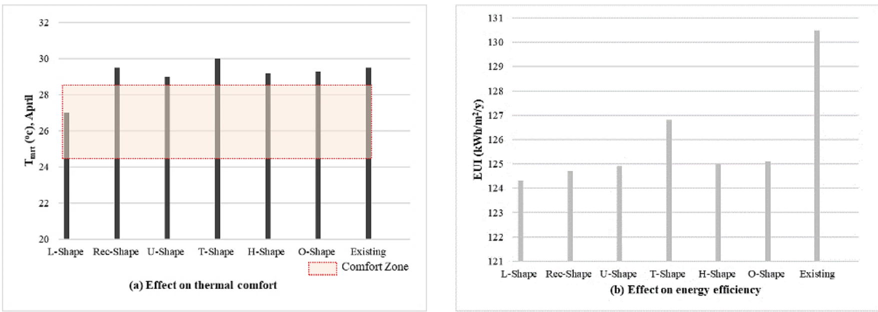


Fig. 4. Summary of performance of the studied building geometry on (a) thermal comfort and (b) energy efficiency.

3.2 Effect of orientation on thermal comfort and energy efficiency

The effect of orientation on thermal comfort and energy efficiency are shown in Fig.5. The lowest T_{mrt} that is within the comfort range is found in 0° North by L- shape building. Its thermal performance in other three directions are almost similar to the other building shapes. On the other hand, highest T_{mrt} is observed in T- shaped building in 0° North. The thermal performance of U, H, O and existing shape is similar as they are almost identical to their longitudinal axis and contain recessed open spaces within their form as described in the previous Section 3.1. Highest value of EUI is observed on 0° North by existing building shape and also it shows the worst energy performance in all four orientations comparing to the other shapes. Performance of O and H- shape buildings are similar to all directions. Best configuration of building shape in four orientations for maximum thermal comfort and lowest energy efficiency are given in Table 3.

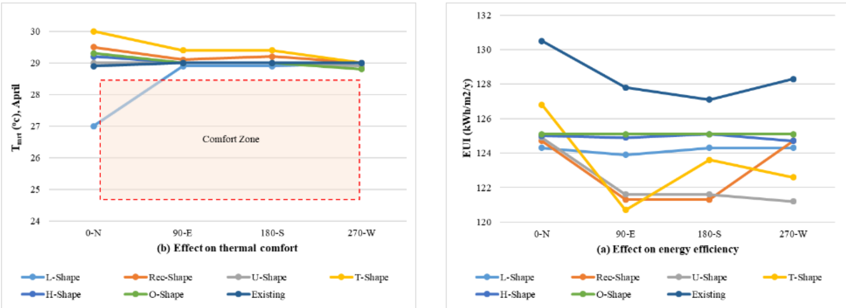


Fig.5. Summary of performance of the studied four orientations on (a) thermal comfort and (b) energy efficiency

To compare the combined thermal and energy performance of different geometric shape of buildings, their average performance on all four orientations are calculated and plotted in a single graph. From Fig. 6, it can be concluded that thermal and energy performance of L and U shaped buildings on all four orientations are better than the other studied options.

Table 3. Best configuration of building shape in four orientations considering maximum thermal comfort and lowest energy consumption.

Parameters	0° N	90° E	180° S	270° W
T_{mrt}	L- Shape	L-Shape	L-Shape	O-Shape
EUI	L- Shape	T- Shape	Rectangular- Shape	U- Shape

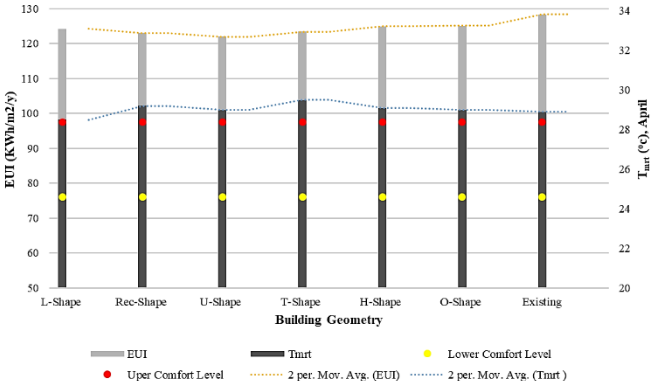


Fig. 6. Average thermal and energy performance on all four orientations of the studied building geometries.

4 Conclusion

Building geometry and orientation has an effect on its thermal and energy consumption. Conventional practice of using shape co-efficient as an indicator of building's thermal and energy performance is proven insufficient in case of Dhaka due to its urban and building planning regulations. To provide better solar protection during daytime and night flush cooling during night, positioning of the open space is important. L- shape buildings provide better thermal comfort in almost all orientations. In case of energy performance, U- shape building perform better than other configurations. These two geometry contained open spaces that act like courtyard which was proven to be effective for this particular context. However, highest thermal comfort and lowest energy consumption was observed in north facing L-shape and east facing T-shape buildings respectively. The existing shape does not provide this type space within its geometry. Best configuration of building shape in four orientations for maximum thermal comfort and lowest energy consumption are provided in this paper which can guide architects and planners not only to design buildings but also to formulate zoning regulations. Besides thermal and energy performance, daylight performance is also significant in case of passive building design. However, size and position of windows, shading device is also important. The effect of those components ae beyond the scope of this paper because of time and other constraints. It is expected that this research can act as a foundation for further research to study the effect of other parameters described above.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

References

1. IEA World Energy Outlook, https://www.iea.org/events/world-energy-outlook-2024, last accessed 2024/10/01

2. DESCO Annual Report 2021, https://www.desco.org.bd/uploads/attachments/annual_report_2021.pdf, last accessed 2024/10/01
3. Ahsan, T, Svane, O.: Energy Efficient Design Features for Residential Buildings in Tropical Climates: The Context of Dhaka, Bangladesh. In: Lehmann, S., AlWaer, H., AlQawasmi, J. (eds.) Sustainable Architecture and Urban Development (SUAD) 2010, CSAAR PRESS, vol. **4**, pp. 183–202. University of Jordan, Amman (2010)
4. Kamruzzaman, M., Ogura, N.: Apartment Housing in Dhaka City: Past, Present and Characteristic Outlook. In: Fukao, S. (eds.) Building Stock Activation 2007, pp. 81–88. Tokyo Metropolitan University, Japan (2007)
5. Pathirana, S., Rodrigo, A., Halwatura, R.: Effect of building shape, orientation, window to wall ratios and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate. International Journal of Energy and Environmental Engineering **2**(5), 107–120 (2019)
6. Lapisa, R.: The effect of building geometric shape and orientation on its energy performance in various climate regions. GEOMATE Journal **16**(53), 113–119 (2019)
7. Ahsanullah, S.I., Van Zandt, S.: Article title. Journal of Housing and the Built Environment **19**(4), 677–697 (2014)
8. Catalina, T., Virgone, J., Iordache, V.: Study on the impact of the building form on the energy consumption. In: Editor, F., Editor, S. (eds.) 12th Conference of International Building Performance Simulation Association 2011, BS Conference Proceedings vol. **12**, pp. 1726–1729. IBPSA, Sydney (2011)
9. Depecker, P., Menezo, C., Virgone, J., Lepers. S.: Design of buildings shape and energetic consumption. Building and Environment **36**(5), 627–635 (2001)
10. MHPW: Bangladesh National Building Code. Ministry of Housing and Public Works (MHPW), Peoples Republic of Bangladesh, Dhaka (2020)
11. Rhinoceros 3D, https://www.rhino3d.com/, last accessed 2023/11/23
12. Grasshopper 3D, https://www.grasshopper3d.com/, last accessed 2024/02/18
13. Solemma LLC, https://www.solemma.com/climatestudio/, last accessed 2023/11/05
14. BMD Homepage, https://live7.bmd.gov.bd/, last accessed 2024/12/19
15. EnergyPlus, https://energyplus.net/, last accessed 2024/08/18
16. Humphreys, M.: Field studies of thermal comfort compared and applied. Building services engineer 44, 5–27 (1976)
17. Ahmed, Z.N., Howarth, A.T., Zunde, J.M.: Thermal comfort studies and applications for Dhaka. Building Services Engineering Research and Technology **11**(3), 105–108 (1990)