The Pennsylvania State University

The Graduate School

DAYLIGHTING IN DENSITY: A PARAMETRIC STUDY OF HIGH-RISE RESIDENTIAL BUILDINGS AND URBAN STREET CANYON CONFIGURATIONS IN DHAKA, BANGLADESH

A Thesis in

Architecture

by

Sumaiya Mehjabeen

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2020

The thesis of Sumaiya Mehjabeen was reviewed and approved by the following:

Ute Poerschke
Stuckeman Professor of Advanced Design Studies
Thesis Co-Advisor

Lisa Domenica Iulo
Associate Professor of Architecture
Director of Hamer Center for Community Design
Thesis Co-Advisor

Benay Gürsoy Toykoç
Assistant Professor of Architecture

Richard Mistrick
Associate Professor of Architectural Engineering

Mehrdad Hadighi
Professor, Stuckeman Chair of Integrative Design
Head of the Department of Architecture

Abstract

Daylighting has gained significant attention in the contemporary building industry to support a sustainable living environment. Access to daylight in design is a challenge in the ever-increasing density of urban contexts, especially in developing countries. Empirical research shows that daylighting needs to be incorporated to ensure a sustainable living condition in regularly occupied spaces, including residential buildings for occupant well-being. Surprisingly, residential buildings are designed largely ignoring daylighting necessity in compact urban contexts in developing countries. It is imperative to ensure enough daylighting ingress in residential buildings for positive health outcomes and comfort conditions. Daylighting in high-rise residential buildings in a dense urban context is still a less explored field in empirical research.

This research presents an analysis of daylighting ingress relating to urban street canyon configurations of high-rise residential buildings in the dense urban context of Dhaka, Bangladesh. A computational workflow is used to investigate the impact of building and street canyon geometry on daylight autonomy in high-rise residential buildings. First, an analysis of a case example in Dhaka, Bangladesh, shows the challenges of daylighting in deep spaces in high-rise building conditions. Then, several identified residential building typologies in Dhaka, Bangladesh, are analyzed concerning how varied geometry of these typologies and width of urban street canyons impact daylight ingress. The key aspects to analyze daylight autonomy in this study are building geometry, surrounding obstructions, orientation, and urban street configurations. These are computationally analyzed and visualized utilizing software packages, Rhinoceros, Grasshopper, and the environmental plugins Honeybee and Ladybug. Comparing daylight autonomy levels that result from varying these aspects mentioned above in the simulation helps understand the impact each aspect makes in high-rise residential buildings in the dense urban context of Dhaka. Finally, recommendations for new configurations of residential buildings related to the adjacent urban canyon are given as daylighting design strategies based on the parametric investigation of the impact and efficacy of a residential block geometry.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to thank my thesis advisors Ute Poerschke and Lisa Iulo, for their continuous support and guidance throughout the research. I am grateful to Professor Richard Mistrick for his valuable feedback and advice to outline the workflow of my parametric exploration. I am also thankful to Benay Gürsoy Toykoç for her critical feedback on my research.

I am indebted to the Department of Architecture, Professor Mehrdad Hadighi, the head of the department for helping me support my graduate education.

I would like to acknowledge Sarith Subramaniam, Mike Barber, and Shannon Kaplan for their expert input on my research. I appreciate the help and support of my colleagues at Stuckeman School throughout my graduate studies.

I am immensely grateful to my super supportive family. A special thanks to my dear husband, Arif Rokoni, for the tremendous support and the words of encouragement whenever I needed it.

Chapter 1

Introduction

1.1 Background

Urbanization is a global phenomenon. Urban densification is an inevitable global trend, and it is happening even faster in developing countries ("Urbanization | United Nations Population Division" n.d.). The justification for density extends to urban-scale sustainability, economic growth, and many more (Owen 2009). Nonetheless, this worldwide trend of urban densification is changing the landscape of human settlements, with momentous implications on our living conditions, well-being, and the physical environment, particularly in developing countries where limited land and housing crisis is already persistent. Consequently, our built environment is changing to tackle these crises while prioritizing densification over factors that affect our living conditions. For a healthy and sustainable living environment and our well-being, access to natural resources such as daylight and fresh air is crucial.

Daylighting is as old as architecture itself and has a significant influence on building design. Before artificial lighting replaced natural light, the provision of daylight in every space was a necessity. Throughout history, daylight has influenced the building forms in numerous ways (Nancy et al. 2000). The interaction between building design and daylighting depends on the importance of daylight availability in the building. The typology of a building defines the required level of illuminance quantity and quality. Building form determines the possibilities of daylight utilization and illuminance distribution patterns. The factors related to building forms that influence daylighting design are the ratio between exterior façade area and total floor area, building height, floor depth, floor-to-floor height, interior walls, and other obstructions (Compagnon 2004; Hachem, Athienitis, and Fazio 2011b; Mayhoub and Carter 2010). Moreover, designing for daylight in a dense urban context asks for external urban factors, such as external obstructions, height, and width of urban canyons, and other geometric aspects of the buildings, such as façade window-to-wall ratios, orientation, size, and location of windows (Cheng et al. 2006; Compagnon 2004; Hachem, Athienitis, and Fazio 2011a; Shishegar 2013).

Evaluation of daylighting as a building performance strategy is a complicated task. A universally acceptable level of daylight in a specific space is still a question yet to be answered by researchers. One of the reasons for this difficulty to pinpoint good daylighting could be that building professionals focus on various aspects of it, such as the visual aspect, energy consumption, cost-efficiency (Reinhart 2014, 27). Appropriate lighting level criteria should be established based on the functions and requirements of the various living spaces to arrive at a daylighting strategy in a compact urban form. Then, building exterior and interior factors need to be considered.

Consequently, some potential solutions can be proposed, experimented, and validated using parametric models. There are many conventional daylighting systems and strategies, such as traditional windows with wide awnings, courtyards with verandas/corridors that no longer deliver the intended illuminance levels due to the gap between rapid urbanization and planning regulations (Edmonds and Greenup 2002). Today, innovative daylighting systems, such as lightwells, daylight guides, light shelves, etc. are developed and incorporated in the design of buildings, which influence the built form (Kotani et al. 2003).

1.2 Problem Statement

The development of high-rise buildings is a consequence of urban densification, expanding urban populace, and economic growth. This is an ongoing issue, particularly countries in Southeast Asia. The tendency to grow vertically continues to increase day by day because of land limitations to accommodate these growing urban populations. In many Southeast Asian cities, such as Dhaka, Mumbai, Hong Kong, Kuala Lumpur, high-rise residential buildings are abundant (Farea et al. 2012). Bangladesh is one of the fastest-growing developing countries in Asia (CIA 2015). Dhaka, the capital of Bangladesh, is the 9th most densely populated city in the world (UN 2016). According to Ahsan et al. (2016), the number of high-rise buildings has increased by three times between 2010 and 2016, whereas in Bangkok and Kuala Lumpur, the number has doubled over the same time (Ahsan 2016). 30% of these high-rise buildings in Dhaka are of the residential type, and this number is increasing (Ahsan et al. 2014). The current number of high-rise housing may be much higher.

It is a matter of concern that, due to lack of proper enforcement, a majority of these buildings are largely not compliant with the Floor Area Ratio (FAR) and Maximum Ground Coverage (MGC) rules set by the Dhaka Building Construction Rules 2008 and *Rajdhani Unnayan Kartripakkha* -the Capital Development Authority of the Government of Bangladesh (RAJUK) (Mahmud 2007). The relevant rules are discussed briefly in chapter 3, section 3.3. This tendency to build barely following existing building codes has adverse effects on occupants' psycho-physical well-being, comfort, and overall urban environment (Ahsan 2016). These high-rise buildings take advantage of the setback rules, the rules restricting the buildings to have a minimum distance from the site-lines, which was set 10 years ago for low and mid-rise buildings (6-10 stories). As a result, the short distance between the adjacent buildings creates narrow canyons and obstructs admission of daylight and natural airflow into the buildings, thus forcing the occupants to rely on artificial and mechanical means of lighting and ventilation (Ahsan et al. 2014). This creates the problem of very dark interior living spaces in these buildings and the increased use of artificial lighting (Ahsan et al. 2014). That poses the following research questions:

- What are the specific parameters at the neighborhood scale that impact daylight availability within building interior spaces in the dense residential urban context of Dhaka, Bangladesh?
- How do specific building geometries perform regarding daylight availability?
- How do urban parameters such as street canyon width and geometric configurations impact daylight availability in overshadowed urban areas?

1.3 Significance of the Issue

Natural light has been proven to be a significant factor contributing to human health and well-being (Boubekri 2014; Brandi 2006; Baker and Steemers 2000). Our body synchronizes with the natural changes of daylight, which affects our day-to-day activities and our subjective, physiological responses (Hraska 2015). Indoor illumination using artificial lighting poses many problems from a sustainability standpoint - including its adverse effect on human health and well-being (Ellis et al. 2013). For positive health outcomes and comfort conditions, it is imperative to daylight regularly occupied indoor spaces.

Globally, with limited land, buildings are getting taller to accommodate the needs of the growing urban population. According to the United Nations, 55% of the world population today lives in urban areas, and the projected percentage of the urban population will be 68% by 2050 (UN 2018). In the world's most densely populated cities, i.e., Dhaka, Hong Kong, etc., high-rise residential buildings are abundant. Daylighting design in these buildings is a challenge, and thus, artificial lighting in indoor spaces is frequently used, even in the daytime. Moreover, buildings cast shadows on each other, making indoor daylighting even more challenging. Possible solutions to this problem can be identified by looking into the geometry of the high-rise residential buildings and street canyons. According to Nicholson, an urban street canyon is a relatively narrow street created by continuously lined up tall buildings along both sides (Nicholson 1975).

The introduction of daylighting within residential buildings as a daytime source of illumination is addressed in many sustainable building design guidelines, including LEED, WELL, NGBS, WBDG. The Architecture 2030 Palette has multiple 'swatches' for daylighting for buildings. The Living Building Challenge – Health & Happiness Petal also gives imperatives for admission of Daylight in every regularly occupied space. What these guidelines recommend for daylighting will be discussed in a later chapter in this thesis. On the other hand, daylighting in residential buildings is still a less explored field in empirical research (Dogan et al. 2017). There is a gap in knowledge and scope for conducting research concerning strategies for daylighting in high-rise residential buildings in dense urban cores (Strømann-Andersen and Sattrup, 2011).

1.4 Research Aims

This research aims to investigate the persisting challenges of daylighting in residential building design in the dense urban context of Dhaka, Bangladesh. From this investigation, it is to be determined which geometric aspects of buildings and urban street canyons affect daylighting ingress in heavily obstructed high-rise residential buildings and whether a parametric exploration of present challenges can help designers understand how daylighting ingress in new constructions can be addressed. This investigation primarily examines the relationship between daylighting and specific geometric aspects, such as building and urban street canyon configurations, external obstructions, and orientation of the building and streets. The research relies on a computational method for this analysis. Consequently, this study aims to develop a computational framework for simulation analysis based on existing literature and tools used in this field. This framework is then applied to a two-phase parametric study. First, a simulation analysis is done on a case study to help the readers understand the extremities and challenges of the research context. Second, a parametric study for daylight availability concerning building form typologies at two levels, building and urban levels, delves into geometric aspects that play a crucial role in daylighting in such a context. Finally, this research seeks to give recommendations that might benefit planners and designers to incorporate daylighting strategies in new high-rise residential construction in Dhaka.

1.5 Research Overview

Following is a summary of this thesis structure.

The following chapter (chapter 2) presents a review of existing scientific literature regarding daylighting. This chapter reviews the importance of daylighting and the history of daylighting, existing scientific research on daylighting and human well-being, sustainable guidelines and daylight recommendations, and previous research done on the parametric exploration of daylighting, methods and tools adopted by researchers. This chapter establishes a background for the computational methodology, tools, and simulation workflow of this parametric daylighting study.

The third chapter discusses the research context of Dhaka, Bangladesh. The author puts forward the primary factors considered for daylighting in a dense city. Then, the research context, a brief historical background of residential buildings in Dhaka, typologies of building form, and the case study are introduced.

In the fourth chapter, the author describes the computational framework designed for this research. First, the factors considered for the computational study, such as climate, sun angles, weather data, and various parameters, are discussed. Then, the author gives a detailed description of the workflow and the simulation process. The assumptions made for this study are also discussed in this chapter.

The following two chapters, the fifth and sixth chapter, discuss a computational analysis to explore the challenges of daylighting through the analysis of a case study in Dhaka (Chapter 5) and a parametric framework for the geometric building typology study (Chapter 6) within the scope of the computational workflow. First, the author investigates the changing effect of floor levels on daylight autonomy through a series of simulations of the case study. Then, a parametric typology study at the building and urban levels is presented. As stated before, in the case study chapter, the author talks about the specific geometric features of one building in the case study site and its surrounding context. The typology study explores the effects of geometry, orientation, and urban canyons. Annual daylight availability simulations provide a basis for understanding the impact of the abovementioned factors on daylight ingress within the spaces.

Finally, the seventh chapter encompasses a discussion on the research conclusions and recommendations concerning the knowledge derived from these parametric studies regarding daylighting design for new high-rise residential construction in Dhaka.

Chapter 2

Review of Scientific Literature on Daylighting

This chapter presents a review of literature on the significance, history, human dimensions of daylighting, and the daylighting recommendations of various sustainable design guidelines. Additionally, a literature review on parametric daylighting research presents contemporary research methods, daylighting metrics used, tools utilized, and parameters studied to build a body of existing knowledge about daylighting analysis and evaluation.

2.1 Significance of Daylighting

> "Architects in planning rooms today have forgotten their faith in natural light. Depending on the touch of a finger to a switch, they are satisfied with static light and forget the endlessly changing qualities of natural light, in which a room is a different room every second of the day."
>
> — Louis I Kahn (Samalavicius 2011, 22)

Daylight, being the primary source of life and energy on earth, greatly influences our subjective responses to the surrounding environment. These responses to buildings, spaces, and objects are the result of the visual information received by our vision and have a significant effect on our activities and general health and well-being (Wong 2017). Reinhart (2014) defines daylight as the combination of direct sunlight and diffuse skylight (Reinhart 2014, 23). It is a significant factor in creating a healthy living environment. From a designer's perspective, daylighting can be defined as the controlled use of natural light within and around built environments (Reinhart 2014, 9). According to Reinhart (2014), daylighting is "a process by which direct sunlight and diffuse daylight are reflected, scattered, admitted, and/or blocked to achieve the desired lighting effect" (Reinhart 2014, 9).

Daylighting has its benefits as well as problems. Proper daylighting can reduce energy consumption for electric lighting and resultant cooling and help create a healthy living environment, outdoor views, and enhance spatial quality (Reinhart, Mardaljevic, and Rogers 2006). On the other hand, excessive daylight into space can result in overheating, glare, and privacy issues (Reinhart 2014, 25). A balanced daylighting design is critical to ensure a healthy living environment.

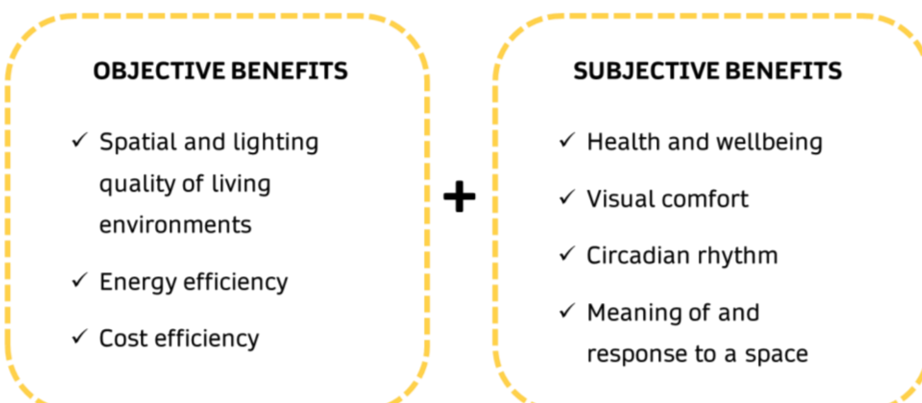


Figure 1: Rationale for Daylighting Design.

The rationale for the daylighting design of buildings can be explored from both subjective and objective perspectives (DeKay 2010, 36). The objective reasons are enhancing the spatial and lighting quality of living environments, energy, and cost-efficiency (Dekay 2010, Reinhart 2014, Tregenza and Wilson 2013). The subjective reasons are equally compelling to support daylighting design. Daylight is not a mere revealer of form, shape, and colors, it is also a fundamental source of life. Daylight affects our circadian rhythms and psychophysical processes (Zielinska-Dabkowska 2018, 274). Daylighting design of architectural spaces guide our perception of connections to the outside, influence the interpretation of the space, along with our subjective responses (Brown 1985). The diurnal cycle, the intensity of the sunlight, sky coverage, and seasonal patterns are the most significant natural presence in our lives (Brandi 2006).

2.2 A Brief Timeline of Daylighting Design

The notion of daylighting is not new. It has been relevant since the conception of architecture. This section talks about the historical background of daylighting in design over the past couple of centuries.

The “Rights to Light” in the UK goes back to the early eighteenth century. A right to light is an easement in English law. It gives the owner of a building with windows having received natural light for over 20 years the right to maintain the level of illumination for the benefit of buildings (Francis 2008). During the mid-18th century, with rapid industrialization, Western Europe experienced a housing crisis that resulted in densely built housing along narrow streets with little or no access to daylight and deplorable living conditions. To address this situation, planners in the 19th century launched a movement to introduce fresh air and natural light into housing for public health and welfare that led to the enactment of the Prescription Act 1832 and later the Public Health Act 1848 in Great Britain (Boubekri 2008). The design community started to advocate for maximizing natural lighting in buildings around the mid-19th century. The New York City Zoning Regulation (1916) introduced requirements for light and air ingress for residential buildings (Power 2018).

As civilization advanced towards newer technologies, new ways of building design came into being, long spans with large openings replaced dark masonry structures with small windows. The modern movements, such as Bauhaus in Germany and De Stijl in the Netherlands, gained popularity in the building design community, intending to maximize natural light and fresh air in building design.

However, parallel to these building design movements, different forms of artificial lighting were introduced, such as the electric incandescent and fluorescent lamps of the late 19th century that evolved in today's daylight simulating lamps, LEDs, daylight sensors, etc. With the emergence of artificial lighting and mechanical ventilation, tall buildings with deeper floor plans and comparatively low floor-to-ceiling heights came into being, and thus, provisions for daylight and fresh air were not prioritized. We have seen experimentations with 'windowless classrooms' during the late 1960s when looking out the window was considered a distraction. During the oil crisis of the 1970s, a renewed attention to daylighting encouraged researchers, designers as well as public policy entities to promote more efficient use of energy to replace artificial lighting with natural lighting. During these two decades (the 1960s-70s), a lot of experimentation and explorations in passive solar, energy efficiency, and other environmental design concepts were explored.

Throughout history, architects and designers designed buildings to be of shallow depth to allow for daylight ingress and cross ventilation in all the living spaces. Today, built environments are planned and designed deeper and higher as there are innovative technologies for artificial lighting and mechanical ventilation. These buildings account for roughly one-third of global energy consumption and almost 40% of Carbon-dioxide emissions. This problem calls forth our attention to design sensitively utilizing renewable energy sources. Over the last two decades, growing awareness of green building technologies was observed and, various high-performance building standards and rating systems were introduced. Among these, LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Methodology), DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen), WELL Building Standard and LBC (Living Building Challenge) are well known for making recommendations for daylight as part of their assessment schemes. These will be discussed in detail later in this chapter in section 2.4.1. Although daylighting in building design is included in these sustainable design schemes, it is still not an integrated scheme in building design practice apart from some of the energy-conscious developments.

Table 2.1: Timeline of daylighting in buildings.

1800			1900			2000	
Early	Mid	Late	Early	Mid	Late	Present	Future
➢ Prescription Act 1832 (UK) – **Rights to light**	➢ Rapid industrialization ➢ Housing Crisis – densely built housing with narrow streets ➢ Deplorable living conditions ➢ **Public health act (1848) – access to natural light and air**		➢ **Widespread use of artificial lighting** ➢ Daylight became dispensable ➢ **New York City Zoning Regulation 1916 – Setback guidelines**	➢ experimentations ➢ 1960 windowless classrooms ➢ 1970 – oil crisis ➢ **Renewed attention to daylight** ➢ New York City Zoning Regulation 1961	➢ Explorations of energy efficient and various environmental design concepts ➢ **Green building guidelines -LEED, BREEAM**	➢ Guidelines & recommendations for daylighting design ➢ **New tools** ➢ **Introduction of dynamic daylight metrics** ➢ Rapid technological advancement	**?**

Table 2.1 shows the fundamental shifts that occurred in daylighting over the past centuries, redefining the relevance of daylighting design. Daylighting design is getting an increased amount of attention among researchers, architects, planners, and designers not only for energy efficiency but also to inform the various aspects of building design, for example, building form, glazing ratio. Additionally, the impact of daylighting on occupant's well-being reinforces the importance of daylighting in our built environment. There is a plethora of research and knowledge regarding daylighting in building design. Nevertheless, it is still surprising that we develop our cities focusing on density and forgetting the factors of our overall well-being, such as daylight ingress into the buildings. This situation

is even worse in compact urban contexts, particularly in dense cities of developing countries such as the city of Dhaka in Bangladesh. This issue is critical because the existing building codes mandate no specific regulation for daylighting in Dhaka.

2.3 Human Dimensions of Daylighting in Architecture

> "We are born of light. The seasons are felt through light. We only know the world as it is evoked by light."
>
> — Louis Kahn (Bainbridge and Haggard 2011, 136)

Daylight plays a crucial role in our consciousness. Earth's systems are profoundly influenced by the sun's seasonal and diurnal positions transcribing cyclical rhythms of days, months, seasons, and years. The sense of varying times is perhaps the most significant phenomenon resulting from the apparent movement of the sun. These movements have their cadence and qualities depending on the geographic location. Daylight is an essential means of maintaining and supporting our circadian rhythms and connection to the rhythms of nature. The experience of daylight vividly marks important diurnal events such as the time of day, sunrise, and sunset. These luminous events help us orient ourselves in time. Apart from the ordering of time, the color, angle, and intensity of daylight are also important factors that facilitate our perception of color, texture, material, and other experiences. The experience of time is about the place, nature, and many psycho-physical experiences (Guzowsky 2000).

Human health and well-being primarily relate to the physical and psychological conditions of the body and mind. Additionally, our senses are affected by the quality of the natural and built environments (Capra, 2009, 244). Daylight is one of many crucial environmental health factors (Guzowsky 2000, 291).

How does daylight relate to our built environment? Our awareness and knowledge of time through daylight influence our built environment. Architecture connects sunlight with us through meaningful interplay among structure, form, and light. The position of the sun, the length, and effect of a shadow, or the pattern created by daylight projected from an opening, are all unique to a specific geographic location. Daylight reveals a story about time and place. For this very reason, daylight is used as a central element of the design concept by many renowned architects (Guzowsky 2000). Occupants response and decision making are directly related to the lighting conditions, where excitement, alertness, and dominance are linked to proper lighting, and dullness, boredom, and submissiveness are connected to poor lighting conditions. There is a notion that human beings respond better to natural light than electric lighting (McColl and Veitch 2001).

The dynamic nature of natural light acts as a trigger for our psychological processes, eventually affecting our psychological well-being. Daylight affects our mood by altering the subjective response towards space. The feeling of a space such as warmth or coldness, relaxation, or tension, healthy or unhealthy, spaciousness or intimacy, is considerably dependent on the light levels of that space, both natural and artificial. However, how we respond to that space is subjective. Therefore, the required amount of daylight is also subjective and may substantially differ from person to person, from place to place. The orientation of a space and related openings, windows, forms, configurations, materiality, and detailing can be shaped to achieve specific luminous effects within a space utilizing the dynamic characteristics of daylight (Guzowsky 2000). The necessity of visual comfort in indoor and outdoor environments stems from the human psychological and physiological needs. According to Santamouris, psychological needs for visual comfort are fulfilled if the lighting condition is such that it provides us with (Santamouris 2013):

- Visual cues for our movements and orientation in a space.
- The visual connection to the surrounding environment.
- Reinforcement for circadian rhythms.
- Information about space and objects.
- A feeling of intimacy or spaciousness withing spaces.
- Visual association with psychological responses such as tension in very bright spaces or relaxation in dimly lit spaces.

Visual comfort has received much attention as the use of display devices proliferated along with other visual tasks (Gardner and Hannaford 1993). Two related aspects of visual comfort are the quality and quantity of light (Guzowsky 2000, 313). The quality of lighting directly correlates to vision-related problems of occupants (Burge et al. 1987). Glare from sunlight, flicker, and uneven lighting within a space adversely affect occupants' health and well-being. These issues also influence our feelings and reactions in a space (Guzowsky 2000, 308). Hence, our buildings need a luminous environment that supports human activities and well-being. On the other hand, the quantity of light refers to existing recommendations by building guidelines. These recommendations will be discussed later in this chapter.

Buildings should also have a relationship to the environment – its place, microclimate, and surroundings. Our built environment should support, maintain, and enhance the site and nature. The façade windows and openings of the building are the means that establish this relationship. These provide access to daylight and view to the outside and the sky. The quality and quantity of illumination, including daylighting, considerably improve the quality of lives and activities of the occupants. The building design and relevant urban street canyons should be carefully considered to sustain a healthy living environment through daylighting design.

2.4 Daylighting and Sustainability

In a discussion about what types of issues are included in the theme of sustainable design, the American Institute of Architects (AIA) (www.aia.org) and the International Union of Architects (IUA) define the scope as the following -

> "…Sustainable design integrates considerations of resource and energy efficiency, healthy buildings and materials, ecologically and socially sensitive land-use, and an aesthetic sensitivity that inspires, affirms, and ennobles…"
>
> (Guzowsky 2000, XXV)

In other words, sustainability is not all about energy and resource efficiency; the other non-quantifiable and human factors are also important. While daylighting design is a small part of a larger whole, it represents an intersection point of the triad of a sustainable design approach given by Guzowsky - the environmental, architectonic, and human factors (Guzowsky 2000).

In this research, the author investigates the architectonic factors such as building shape, geometry, and related urban canyon configurations specific to residential high-rises concerning daylight availability. To address the problem of daylighting in high-rise residential architecture, first, we need to know about existing daylighting strategies and recommendations and how architects and planners incorporate these in designing high-rise residential buildings.

2.4.1 Daylighting recommendations in building design guidelines

Surprisingly, there are minimal codes and requirements for daylighting in existing building regulations and standards that are mandated as codes or laws in any country, with a few exceptions, such as New York City Zoning regulations. However, there are some green building guidelines and assessment systems that give recommendations for daylighting in buildings. Several independent authorities also published guidelines and set criteria for best practices for daylighting.

Table 2.2 provides an overview of how different guidelines approach daylighting. LEED (Leadership in Energy and Environmental Design) gives credit points for achieving a certain percentage of Spatial Daylight autonomy, a dynamic daylighting metric, and offers recommendations for the view to the outside, reinforce occupants' circadian rhythms, and limit the use of artificial lighting by introducing daylight into interior spaces. WELL Building Standard features daylight to support circadian rhythm and psychological health by setting thresholds for indoor daylight exposure. This standard also talks about the "right to light" (see section 2.2) and providing operable windows in regularly occupied spaces. The Living Building Challenge also has similar intent related to daylighting, focusing on the health and well-being of the occupants. The LBC emphasizes providing windows in residential buildings for 100% of its occupants.

The BREEAM (Building Research Establishment Environmental Assessment Method) of the UK, DGNB (German Sustainable Building Council) of Germany, and The European Committee for Standardization (CEN) give recommendations for the daylight factor in specific spaces in a building.

Apart from these green building guidelines, some other guidelines talk about daylighting requirements. In 2012, as a lighting authority, the Illuminating Engineering Society (IES), USA published a standard on approved methods using annual daylight availability metrics - Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for existing buildings and new designs (IES LM-83-12). The Chartered Institution of Building Services Engineers (CIBSE), UK, also published its Lighting Guides on Daylighting and window design. The Zoning Regulations of New York City has legal requirements for light and air ingress for residential buildings. According to the regulation, every “living room,” which is any habitable space other than a service (kitchen, dinette, bathroom) or circulation space (foyer, hallway), must have a ‘legal window’ that provides required light and air to space. Per Zoning Resolution Section 23-861, these legal windows need to open directly onto a street or setback area facing the street or an open yard space having at least 30 feet (9 meters) open between the legal window and opposite wall or rear or side lot line. This distance should be measured perpendicular to and at the sill level of such a window.

From this discussion, it is evident that daylighting is getting increased attention in building codes and standards and guidelines. Many rules and guidelines promote daylighting as a daytime lighting strategy in buildings and recognize windows as sources of illumination and daylighting ingress in buildings for healthy indoor environments and reduction of electricity use for lighting the spaces. Three key points can be identified from analyzing these standards and guidelines –

1. Daylight as a primary source of illumination during the daytime,
2. Dynamic daylighting metrics – the metrics typically used to quantify daylighting in a space are- daylight autonomy and daylight factor. Typically, a required minimum illuminance level ranges from 300-500 lux depending on the type of space and building.
3. Windows are considered as a primary source of daylight in building design. Some guidelines provide requirements for windows and their glazing area concerning wall area or room area (window-to-wall ratios). Windows are essential for a view to the outside, including sky view, which provides the occupants with important information about orientation and diurnal and annual changes outside. However, it is necessary to mention that the guidelines that talk about a minimum ratio for windows do not correctly translate to an actual quantity of daylight within the space or building since

they do not consider factors such as, outside obstructions and shadings, glazing material transmittance, window configurations.

2.4.2 Rationale for recommendations

Daylighting recommendations in leading sustainable building guidelines have evolved to meet specific criteria depending on the use and functionality of buildings. There are many metrics in the literature to assess daylight availability and performance that are either illuminance based or luminance based metrics (Costanzo, Evola, and Marletta 2017). Recently, for the most part, researchers primarily use the illuminance-based metrics of daylight availability – Daylight Factor and Daylight Autonomy. The various major green building guidelines recommend thresholds for these daylighting metrics.

This research extracts specific daylighting criteria from the recommendations and guidelines from the design guidelines provided by LEED v4, WELL Building Standard, and IES recommendations. LEED V4 specifies dynamic daylighting metrics such as daylight autonomy as a standard evaluation metric. This research utilized the spatial daylight autonomy ($sDA_{[300lux]\ [50\%]}$) option 1 of 55% given by LEED v4, also referred to in the WELL and IES standard for daylight evaluation. Although extensively used and specified in BREEAM and DGNB, the Daylight Factor metric has its limitations as it does not consider dynamic sky conditions, and it is a static parameter that does not describe how illuminance levels vary with time (Costanzo, Evola, and Marletta 2017).

This research also extracts other parameters for simulation analysis specified in these guidelines. LEED v4 specifies a minimum simulation grid size of 2’. WELL Building Standard and Living Building Challenge recommends the minimum window-to-wall ratio to be 0.2 or 20%. These recommended minimum criteria are considered for parametric exploration and evaluation in this research.

The following Table 2.2 gives an overview of existing daylighting recommendations in sustainable building guidelines and IES guidelines:

Table 2.2: Daylighting guidelines.

	LEED V4 LEED BD+C: New Construction	WELL V2(Q4 2019)	LBC	BREEAM	IES (2013)	DGNB
Intent	IEQ -Daylight Credit; 3 points; Connection to the outdoors, reinforcement of circadian rhythms, and reduction of the use of electrical lighting by introducing daylight into the space.	Feature 62- P1 To support circadian and psychological health by setting thresholds for indoor sunlight exposure.	Health + Happiness Petal Fostering Environments that Optimize Physical and Psychological Health and Well Being	Health and Wellbeing - Daylighting - Visual comfort		Criteria 4- Sociocultural and functional quality -Visual comfort (SOC1.4)
Daylight Metrics	Daylight Autonomy (DA) [Annual]	Daylight Autonomy (DA) [Annual]	---	Daylight Factor (DF) [Availability]	Daylight Autonomy (DA) [Annual]	Daylight Factor (DF) [Availability]
Spatial Daylight Autonomy	55%- 2 points. 75% - 3 points	55%	---		55%	

$sDA_{[300lux][50\%]}$						
Annual Sunlight Exposure $ASE_{1000,250}$	No more than 10%	No more than 10%	---			
Simulation Criteria	Grid size ≤ 2'(600mm). Work plane height – 30" (760 mm) AFF		---			
Daylight factor (DF)	LEED V2 (older version) – 2%		---	1. 80% of the floor area in occupied spaces has an average daylight factor of 2% or more 2. Domestic Buildings- Kitchens - a minimum 2%; living rooms, dining rooms, and studies - minimum 1.5%		50% of the usable area throughout a building has a DF > 3% very good, > 2% medium, > 1% slight, < 1% none

Windows and Views	IEQ - Quality views. Possible 1 point 75% of all regularly occupied floor area must have at least 2 of the four kinds of views stated.	<u>Feature 61 – P1:</u> Right to Light - 75% of the area of all regularly occupied spaces is within 7.5 m [25 ft] of view windows. <u>Feature 19-P1:</u> Operable windows to provide access to daylight	<u>Imperative 9:</u> - Provide views outside and daylight for 75% of occupants. <u>Imperative 10:</u> - 95% of occupants access to views and daylight. - Residential projects must provide operable windows for 100% of the occupants.		Visual contact with the outside.
Window-to-wall Ratio (WWR)		<u>Feature 63 – P4:</u> Daylighting fenestration - Window Sizes for Living Spaces	The window/opening must be ≥ 20% of the surrounding wall area.		

		a. 30-60% - Living rooms b. 20-40% - bedrooms		
Other			- 80% of the working plane in each new space, receive direct light from the sky. - Vertical Sky Component (VSC) - Uniformity Ratio - Average Daylit Illuminance	Durations of exposure to daylight

2.5 Literature Review on Parametric Research on Daylighting

Parametric methods have been utilized in many research and design projects that intend to solve the complex problem of daylighting design utilizing available data and taking advantage of the flexibility of user manipulation (Eltaweel and Su 2017). Daylighting design is dependent on many divergent criteria such as the latitude, longitude, sun-path, sun angles during solstice and equinox days, dynamic sky conditions, solar irradiations, which makes the task notoriously complex and challenging. The parametric method can provide the utility of processing and connecting all the relevant data using specific software, which can make the process of analysis and decision making easier. For this reason, numerous pieces of research have been undertaken to evaluate daylight ingress using parametric methods over the past couple of decades.

Compagnon (2004) proposed a computational method to quantify daylighting by looking at the irradiance values on building roofs and facades in the urban fabric of Fribourg, Switzerland (Compagnon 2004). At the core of this method is obtaining solar illuminance and irradiation values through simulations. The author used the Radiance lighting simulation software using a ray-tracing method. Through this method, the author computed the annual irradiation per floor area and the sky view factor. The author claims that this method is a useful tool to analyze and evaluate solar and daylight availability in dense urban areas with further refinement. However, this method has limitations as it does not consider the fact that daylight ingress is dependent on the depth of the building.

In PLEA 2006, Cheng et al. (2006) introduced another parametric approach to investigate daylight availability by looking into the façade daylight factor and average sky view factor, concerning urban built form and density in the context of Sao Paulo, Brazil (Cheng et al. 2006). This study presented the potential of daylighting simulations for the planning of high-density solar cities. However, this approach is applied thus far to a limited set of urban models generated by the random number function in the software. The authors investigated the daylight factor, which is a static daylight metric measured at a single point in time.

In another research by Strømann-Andersen and Sattrup (2011), building depth and related urban canyons were analyzed in the urban context of Copenhagen (Strømann-Andersen and Sattrup 2011). Their correlational study investigated building scale, urban density, and passive energy factors and established a relation between urban canyon geometry, building operational energy, and daylight availability in office and housing building units, assuming a homogeneous urban setting. The authors used Ecotect and Radiance based Daysim engine for simulations to analyze annual illuminance in street canyons. The main parameters in this study are street width and aspect ratios of urban canyons.

Many researchers used the daylighting metric of Daylight Factor to assess daylight performance (Calcagni and Paroncini 2004; Ibarra and Reinhart, 2009; Lau et al. 2006; Ng 2001). However, in recent years, climate-based daylighting metrics based on annual hourly indoor illuminance data are repeatedly investigated, promoted, and validated by researchers (Mardaljevic, Heschong, and Lee 2009; Reinhart, Mardaljevic, and Rogers 2006). The Illuminating Engineering Society (IES) introduced Lighting Measurement protocol LM-83 that provides recommendations for using spatial daylight autonomy metric (sDA) to evaluate daylight availability in buildings. According to the IES recommendation, a point in the work plane of an interior space is considered 'daylit,' if it receives daylight above 300lux at least 50% of the occupied time ($sDA_{[300lux][50\%]}$) ("Illuminating Engineering Society – The Lighting Authority" n.d.). According to LEED V4, the recommended sDA level for an interior living space is at least 55% of a regularly occupied floor area ("LEED Green Building Certification | USGBC," n.d.). The WELL building standard also adopted this metric of daylight availability ("Light | WELL Standard," n.d.).

Erlendsson (2014) investigated Daylight Autonomy as a metric to assess the daylight performance of atria in large scale buildings in Stockholm, Sweden (Erlendsson, 2014). The author simulated various hypothetical side-lighting and top-lighting designs to compare the results for daylight autonomy. The main parameters were geometric shapes and the width of atria, floor-to-ceiling heights, window-to-wall area ratio (WWR), atrium roof glazing, and orientation of the glazing. Predictably, high WWR and fully glazed atrium roof performed better than other scenarios. Three design guidelines - LEED, BREEAM, and Swedish rating system *Miljöbyggnad* were considered as the daylighting criteria. Additionally, this research presented a comparative analysis of various available tools such as Honeybee for Grasshopper, DIVA for Rhinoceros and Grasshopper, RadianceIES (IESVE), Velux Daylight Visualizer, Daysim, and Autodesk Ecotect. Another research in 2018 presented a comparative analysis of four daylight analysis tools (Anderson and Ghobad 2018). This research compared DesignBuilder, DIVA for Rhinoceros, Honeybee for Grasshopper, and Insight 360 for Revit. Both studies show that Honeybee and DIVA provide highly accurate results for estimation and simulation of daylight impact. Although Honeybee simulates slower than DIVA, it has a cleaner workflow and provides more user flexibility (Anderson and Ghobad 2018). Honeybee's default workflow is based on 'boundary representations' (breps), and it lets the user manipulate the parameters (Anderson and Ghobad 2018). Therefore, Honeybee plug-in has more potential regarding parametric daylighting simulation as it provides more flexibility and option for customization for inputs and outputs by the user.

Saratsis et al. (2017) explored daylight performance in different urban typologies through a computational methodology and with LEED v4 as an evaluation criterion (Saratsis, Dogan, and Reinhart 2017). The authors used a simulation-based parametric method called ‘Urban Daylight’ using New York City as a case study. The ‘urban Daylight’ is a novel tool for simulating and evaluating the daylight potential of urban master planning (Dogan et al. 2012). The authors used floor area ratio (FAR) to quantify the density and calculated spatial daylight autonomy(sDA) to measure daylight availability. The primary parameters in this study are building height, block length, and width, which are used to generate block typologies. The authors claim that the methodology used in this research will help stakeholders to make informed decisions in designing for daylight in dense urban areas. However, this research has limitations as it overestimated the daylight availability due to the assumptions made for the simulation analysis. The authors assume a 100% WWR with a reduced light transmittance of the glazed surfaces, and there is no interior obstruction are the key assumptions that result in the possible overestimation of daylight availability.

Toutou et al. (2018) investigated daylight and energy performance in residential buildings in the context of Egypt, utilizing a parametric modeling based computational framework (Toutou, Fikry, and Mohamed 2018). The analysis building in this study is an existing five-story residential building within an urban context. The authors used $sDA_{[300lux]\ [50\%]}$ metric for daylighting. The key variables in this research are window-to-wall ratios, construction material, glazing material, and shading device configurations. Consequently, they extracted optimum solutions for daylighting and energy performance from numerous simulations. Although this quantitative study follows an effective parametric workflow for daylight and energy performance and optimization, the optimization criteria are not stated clearly.

Parametric methods are incredibly effective for studying daylighting and relevant factors (Eltaweel and Su 2017). This section presented a summary of parametric research on daylighting over the last couple of decades. Researchers utilize this method for complex analysis to provide time-efficient iterations, real-time results, data analysis, and integrated workflow. Parametric-based simulation analysis has been getting popular in recent years to address the complexity of contemporary design challenges and urban density. Application of advanced modeling, iterating, and simulation tools are also increasing to refine the research parameters and the workflow further. The most common software used for parametric research is Grasshopper based on Rhinoceros for parametric modeling. Grasshopper connects to multiple plugins for simulations such as Ladybug, Honeybee, Diva, which can define specific weather properties of a territory and sky conditions. Based on this literature review, the author chose to utilize the software packages – Rhinoceros, Grasshopper with Ladybug, and Honeybee plug-ins. These are discussed in detail in Chapter 4. The significant advantage of the parametric approach is that the user can control and amend all the relevant parameters and components individually or in an integrated manner, and any modification influences the entire model or workflow simultaneously. Therefore, this method is a great tool to analyze and understand daylighting in buildings. However, there are still some limitations in parametric research as the researcher needs to make some assumptions for timesaving and simplification purposes. Because of these assumptions, there are often trade-offs between efficiency and accuracy in all details. The tools and technologies used in such research are also evolving, creating new dimensions in the scope of research, often replacing older tools and making previous studies obsolete.

Chapter 3

Daylighting in High-Density Urban Housing

3.1 Factors of Daylighting in a Dense Urban Context

High construction density, along with tall buildings, are very specific problems related to daylighting in urban environments. In a dense urban area, high-rise buildings that are built in proximity cover part of the sky, shade the windows from daylight and, therefore, reduce daylight ingress and duration of sunlight. In dense urban areas, high-rise buildings form street canyons, and these canyons reduce daylighting ingress inside the buildings. Buildings in proximity tend to obstruct daylight, view to the outside, and sky view. However, building materials used in urban areas, such as brick, concrete, glass, metal, can affect daylight ingress by reflecting and scattering incident light on surrounding building surfaces (Santamouris 2013, 55).

Daylighting in buildings in areas of high density is a challenge for building professionals. High density tall residential buildings, lacking adequate daylighting ingress, create an unhealthy indoor environment. Overshadowing from surrounding tall buildings obstructs direct and diffuse daylight from entering building interiors. Because of this, the use of artificial lighting is the only substitute for daylight in these cases. The negative psychophysical impacts of artificial lighting are well researched and proven (Boubekri 2008). Moreover, dependence on artificial lighting accounts for a substantial amount of energy use. This problem sheds light on the necessity of daylighting in high-density urban housing projects. Factors that affect daylighting in dense urban areas are (Santamouris 2013) –

- Distance between two adjacent facades
- Geometric configurations of an urban street canyon
- Building surface and glazing materials
- external obstructions
- height-to-width ratio of nearby open spaces
- urban block geometry
- orientation
- Window-to-wall ratio
- Size and location of Windows

3.2 The Context of Dhaka, Bangladesh

Dhaka, the capital of Bangladesh, is a fast-growing metropolitan city in south-east Asia. An influx of internal migration and spontaneous growth of population turned Dhaka into a densely built populous city with a demographic of 8.5 million people as of 2016 (Atlas of Urban Expansion, n.d.). With an urban extent of 36,541 hectares (2014), the built-up area density was 552 persons per hectare in 2014, and it is increasing every year (Atlas of Urban Expansion, n.d.).

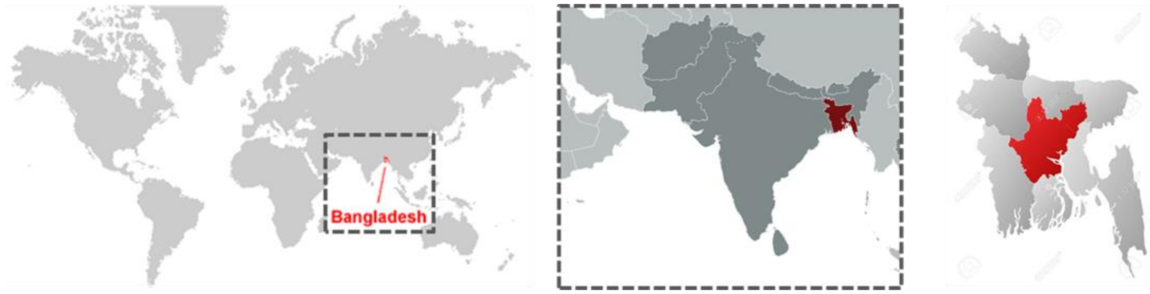


Figure 2: Location of Dhaka, Bangladesh.

The city suffers from extensive uncontrolled densification horizontally, and very recently, vertically in both planned and unplanned developments, resulting in a very compact urban form. The growing trend of constructing taller residential buildings is creating the problem of very dark spaces between buildings and narrow urban street canyons (height: width aspect ratio as narrow as 8:1 to 10:1), which adversely affects the interior living spaces. The spatial growth pattern is predominantly influenced by Dhaka's zoning regulations, which are a two-phase planning strategy consisting of a long-term structure plan and The Dhaka Metropolitan Building Construction Act-2008 (Ahsanullah and Van Zandt 2014). Figure 3 shows the evolution of urban sprawl from 1989 to 2014. The two-way urban sprawl with no consideration of livable environmental factors, such as daylighting, ventilation, and proper infrastructure, including housing, has made Dhaka one of the unlivable cities of the world (The Global Liveability Index 2019). According to the Global Liveability Index report published in 2019, Dhaka is one of the least liveable cities among 140 cities in the world with the lowest score for infrastructure, which includes the availability of good quality housing.

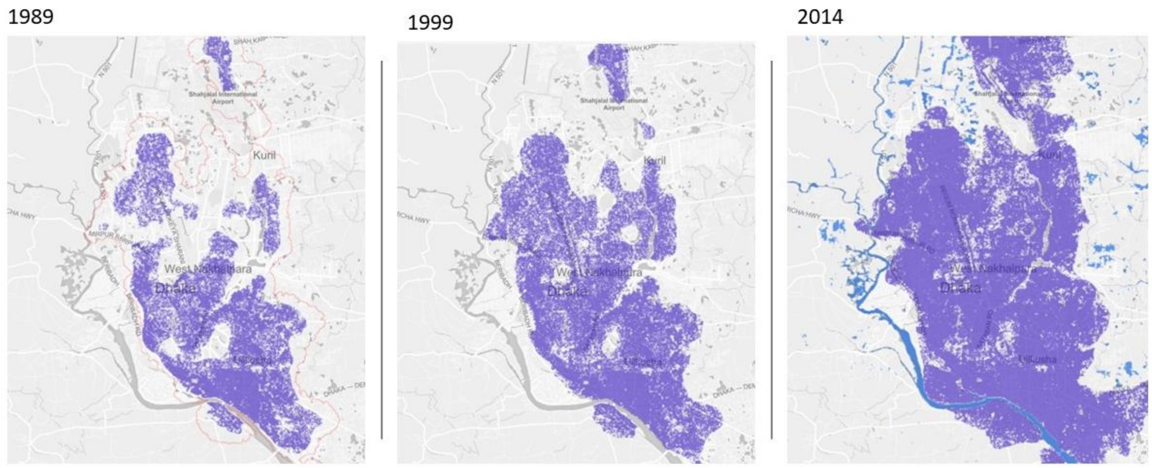


Figure 3: The urban extent of Dhaka, Bangladesh, since 1989
(Source: http://www.atlasofurbanexpansion.org/cities/view/Dhaka, Accessed November 2019).

3.3 The Evolution of Residential Buildings in Dhaka

The characteristics and form of urban residential buildings are a result of ever-evolving codes and regulations as well as climatic, socio-cultural, political, and technological factors. Dhaka’s urban housing scenario is not any different from that (Ghafur 2011).

Early houses during the formation days of the city (17-18th century) were mostly rural. These were small single storied houses with a thatched roof and living spaces clustered around a courtyard. That clustered arrangement also influenced the residential block characteristics during that time. The *mahallas* (neighborhoods) consisted of clusters of these small houses built around *chawks* (town or market squares) or a narrow linear street (Islam 2016). The roads were wider compared to the present time, and the houses were built close to each other, creating a unique neighborhood characteristic, as shown in Figures 4 and 5.

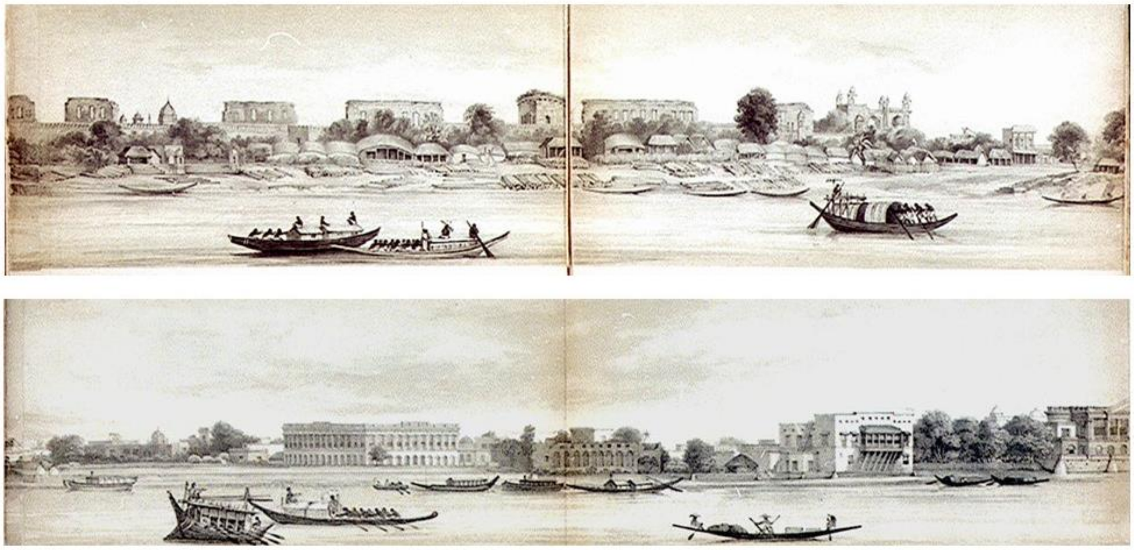


Figure 4: Panorama of the city of *Dacca*

(Source: Lithographed and published by Messrs. Dickinson (1878), https://collections.rmg.co.uk/collections/objects/106029.html, Accessed November 2019).

(a) (b)

Figure 5: (a) Houses along a street in Dhaka, 1872; (b) Houses around a market square or chawk,1904

(Source: British Library, http://ancientdhaka.blogspot.com/, Accessed November 2019).

During the colonial period, these small houses evolved into detached bungalows that are 1-2 storied houses with all the living spaces compactly arranged under a single roof with central hallways and front gardens, as shown in Figure 6 (Islam 2016). After 1947, regular plots were introduced, and the residential buildings became large 2-storied detached houses on these plots (Islam 2016).

Figure 6: Colonial tenement house of the early 20th century, Old Dhaka.

(a) (b)

Figure 7: Walk-up apartments in Dhaka (a) Azimpur Colony (1954); (b) Motijheel Colony (1995)
(Source: http://ss.pwd.gov.bd/buildingdatabase/, Accessed November 2019).

The Dhaka Master Plan 1959 primarily affected the residential block characteristics, which was mostly influenced by western modernity with multi-story, multi-family houses. During the 1970s, after liberation, Dhaka's residential buildings started to grow vertically. At this point, 3-6 storied walk-up apartments, where the provision of an elevator is not obligatory for the building height, were introduced, shown in Figure 7 (Islam 2016). Dhaka went through a developer-built housing phase during the 1980’s-early ’90s. During these periods, zoning regulations had no control over the residential building forms (Ahsanullah and Van Zandt 2014).

In 1996 zoning regulation, setback, and height limits were established, which eventually affected the residential block characteristics. On a forced plot size of more than 1440 sf, the allowable built area was defined by the setbacks on all sides and the 6-story height limitation. The setbacks on each side of the plot were – 4 feet, front setback – 5 feet and rear setback – 6 feet. These plot sizes with setback restrictions resulted in residential blocks with 6-story high compact boxes (the buildings) with an 8 feet wide, narrow dark alley in between the buildings.

At the beginning of this century, residential buildings were built 6-10 stories high. In reaction to that, the new construction rules as the Dhaka Metropolitan Building Construction Rule 2008 was developed as an evolution from the 1996 document, where the idea of Floor Area Ratio (FAR) and Maximum Ground Coverage (MGC) was introduced (RAJUK 2008). This regulation considered the maximum buildable area and mandatory open space based on the plot size and adjacent streets and plots. The previous building codes only specified minimum setbacks from the plot boundary and a 6-storey height restriction. Then the 2008 rules specified maximum FAR and ground coverages based on the plot area and street widths. A trade-off is possible between height and MGC to attain the allowable maximum buildable area. However, for high-rise buildings (higher than ten storeys), the minimum setback requirement is 10 feet (3 meters) on all sides. Table 3.1 presents allowable FAR and MGCs for ranges of plot sizes and street widths for residential type occupancy that are relevant in this research. The 2008 rules also specify requirements for natural light access through windows, skylights, and other openings in addition to artificial means of lighting. Additionally, they stipulate a minimum window-to-wall ratio of 15% for any residential living space.

One of the primary objectives of this new rule is to control density through regulating maximum buildable area, the height of the building, and minimum setback distance between buildings, with minimum standards for a habitable environment. However, there is no effective guideline for ensuring access to daylight in regularly occupied spaces in the 2008 building construction rule.

To ensure density and profit from rentable spaces, developers in both public and private sectors started building multi-story (more than ten stories) residential buildings maintaining the allowable buildable area and 50% ‘mandatory open space.’ This trend resulted in the densely built urban housing block patterns on relatively small plots of land that we see now in inner-city Dhaka.

Since these areas had almost no height restrictions, the developers built high-rise apartments (10-15 stories) on plots that are accessible from the primary and secondary road networks. These buildings create narrow urban canyons, the width of the canyons being an eighth to a tenth of the height, that adversely affects the environmental quality of these high-rise residential buildings. In addition to that, another type of high-rise development can be seen in Dhaka, which is the 'block-based housing development,' several high-rise buildings closely built within a complex. Figure 8 presents examples of such high-rise constructions. There are no specific regulations in the existing building construction rules to control these developments, and these projects have been facing criticism because of substandard environmental conditions.

Ensuring occupant safety is the primary intention of the building codes. As discussed before, in chapter 2, some guidelines also give recommendations for occupant health and comfort. Existing building rules and regulations for Dhaka are yet to consider the factors that affect occupant health and comfort, such as environmental factors like daylight ingress. In an urban context like Dhaka, an increase in density is inevitable because of the housing emergency. However, that should not mean human comfort and well-being be less prioritized to accommodate the density. Building illumination guidelines need to be incorporated into regulations to ensure the health of living spaces, especially in residential buildings in a dense urban context.

Figure 8: Block-based high-rise housing (Source: Author).

Table 3.1: Relevant plot sizes and street widths in this research adapted from the Dhaka Building Construction Rules, 2008.

Plot area in square meters	Occupancy Type: A1 – A4* (Residential buildings)		
	Street width (m)	FAR	MGC (%)
More than 536 - 603	6	4.00	60.0
More than 603-670	6	4.25	57.5
More than 670-804	9	4.50	57.5
More than 804-938	9	4.75	55.0
More than 938-1072	9	5.00	52.5
More than 1072-1206	9	5.25	52.5
More than 1206-1340	9	5.25	50.0
More than 1340	12	5.50	50.0
Any sqm.	18	6.00	50.0
Any sqm.	24	6.50	50.0

Notes: *A2 – Multifamily Apartment Buildings (Dhaka Building Construction Rules 2008, 74)

Recently, many projects in Dhaka incorporated LEED certification criteria for design and construction, along with building codes. Daylighting criteria in LEED v4 are presented in Table 2.2. Nevertheless, it can be questioned whether LEED v4 daylighting criteria are feasible for Dhaka, where densely built high-rise residential buildings are ubiquitous.

3.4 Residential Building Form Typologies in Dhaka

Several residential building form typologies are seen in Dhaka. Some typologies are adapted from the old courtyard houses with living spaces in the perimeters of the buildings with a central courtyard. Other typologies are variations and combinations of the central courtyard and vertical shafts at the outer shell of the buildings. After looking into the residential building forms of Dhaka, the author identified six common residential building form typologies based on their geometry, which are shown in Figure 9. These are simplified massing diagrams for the typologies of residential building forms. The primary geometric types are square and rectangular forms of the building mass. An internal shaft or a lightwell is a ubiquitous feature in these buildings. Diagrams show the shapes of the buildings with external cuts and internal lightwells modified from existing residential buildings in Dhaka. Exterior protrusions and details such as windows, shading devices, are not shown.

The Square 1 & 2 (S1 and S2 henceforth) are typical courtyard buildings with 4-6 dwelling units per floor. These typologies can be seen in low to midrise (4-10 storeys) buildings. The rectangular typologies 1 and 2 (R1 and R2) evolved from the S1 and S2 form types. These types have vertical shafts at the center or the edges of the building. The rectangular 3 (R3) type is ubiquitous in Dhaka city after the enactment of the 2008 Construction Rules, and the number of dwelling units ranges from 4-8 dwelling units per floor. The rectangular 4 (R4) form can be seen in some newly constructed high-rise buildings. The number of stories in rectangular typologies of buildings ranges from 10-15 stories, most recently even higher.

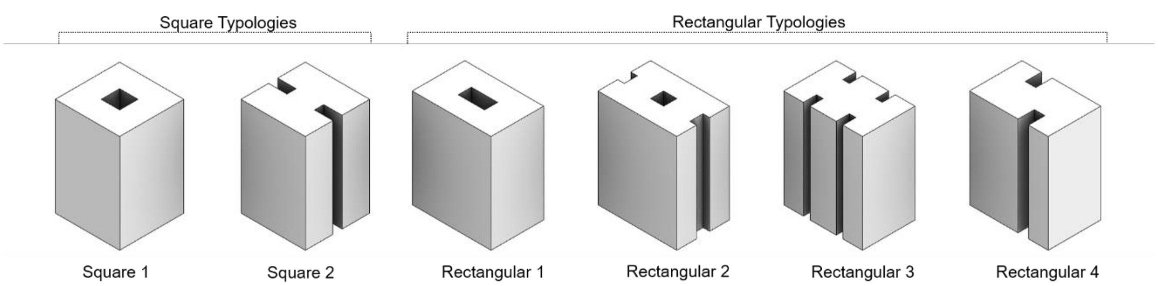


Figure 9: Six commonly identified residential building form typologies in Dhaka (Author 2019).

3.5 Case Example: Japan Garden City

This case study is selected keeping in mind several factors such as the forms of existing building typologies within site, the dense urban residential context, and the project being designed housing with consideration of daylight ingress and airflow in all the dwelling units. This housing project covers a land measuring approximately 40,000 square meters (9.78 acres), with 57% of the property being open space and common facilities (Shafi 2010, Mahmud 2007). However, in reality, it is a very congested and dense housing development with very dark street canyons between the buildings. There are 27 fifteen storied buildings with a total of 1803 residential apartments (Shafi 2010, Mahmud 2007). There are also other ancillary buildings, including a mosque, a commercial mixed-use building, and other service buildings.

The Japan Garden City is a Japan-Bangladesh joint venture, a private sector housing development, located in Mohammadpur residential area, in Dhaka, Bangladesh, shown in Figure 10 [Coordinates: 23°45'51"N 90°21'27"E]. The site is located along a major secondary road. It should be noted that this road is at a slight angle (4 degrees) with the true north direction. The developers intended this housing development to be a self-sufficient housing development with modern amenities designed to ensure a healthy living environment in an urban context like Dhaka (“JAPAN GARDEN CITY LIMITED” n.d.). However, in reality, it is a high-density, high-rise block-based housing development with little regard to occupants’ living environments (Shafi 2010). Moreover, the housing complex also violates setback and ground coverage rules given by the Dhaka Building Construction Rules 2008, which adds to the substandard living conditions in this housing development (Shafi 2010).

This housing development, located in a dense residential zone, was designed to be an environmentally conscious housing project. The housing complex has a spacious, albeit overshadowed, central courtyard (Figure 10c and 11). The developer of this project maintains that the design of the housing ensures unobstructed light and air in all of the buildings (“JAPAN GARDEN CITY LIMITED” n.d.). In reality, indoor living spaces lack sufficient natural light. Even on a bright and sunny day, the interior spaces are dark, and the street canyons are overshadowed by adjacent buildings, which is apparent in Figure 12a and b. The distance between the buildings sometimes is as small as 20 feet (6 meters), creating a dark streetscape, as shown in Figure 12c and d. More than half of the dwelling units depend on artificial lighting even during the daytime.

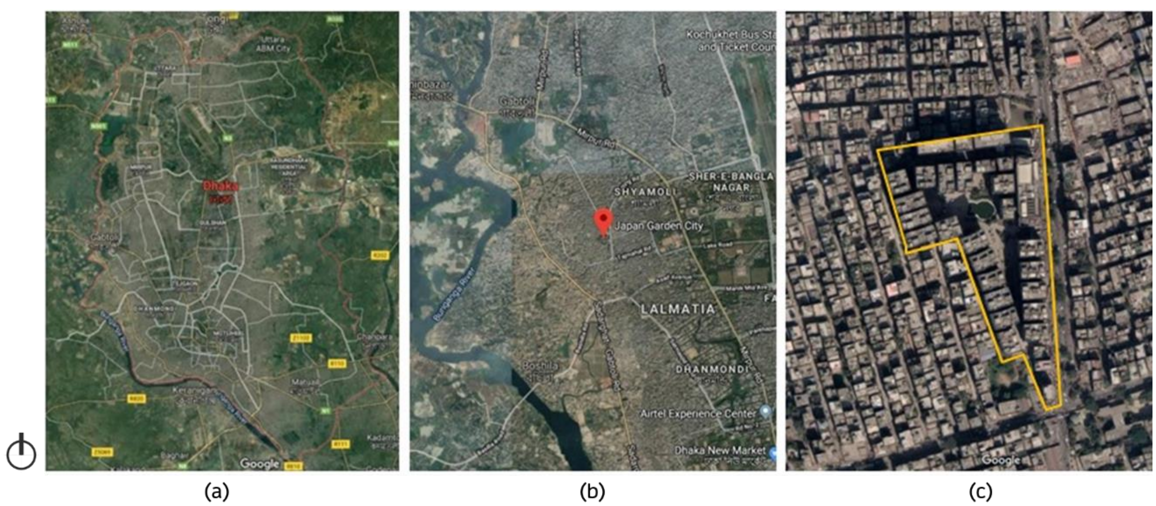


Figure 10: (a) Satelite map of Dhaka; (b) & (c) Location of the Case example.

Figure 11: The Japan Garden City Apartment Complex: View from the courtyard facing towards the East direction (Source: www.flickr.com).

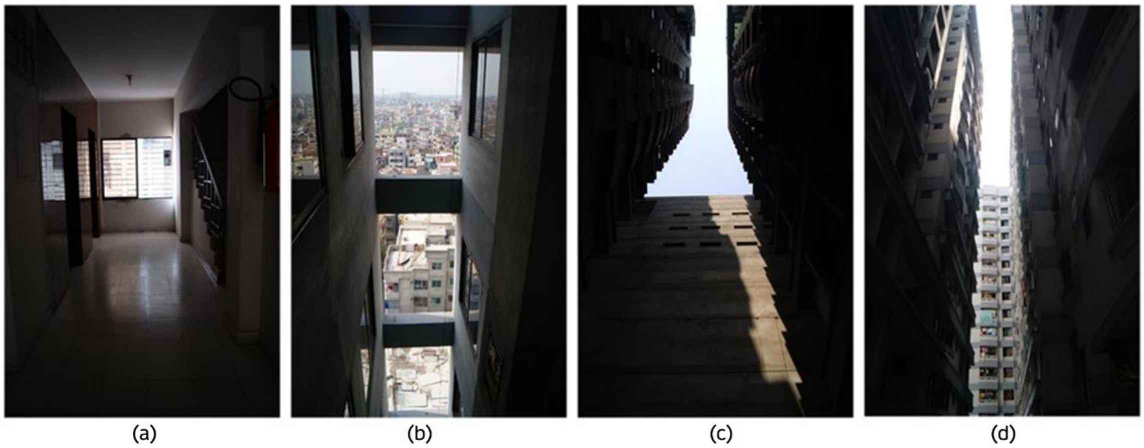


Figure 12: Existing daylight ingress situation in Japan Garden City.
(a) A hallway window; (b) External cut/lightwell; (c) and (d) Narrow spaces between two buildings (Source: Author).

All in all, the conflict between urban density and daylight access remains a persisting challenge. Several factors contribute to this challenge, as discussed in this chapter. In the context of Dhaka, this challenge is unique because of the dense urban form, and it is worthwhile to investigate which factors influence daylighting in building design. To establish specific problems of daylighting in the context of Dhaka, a case study will be analyzed. The following two chapters describe in detail the methodology and the case study analysis.

Chapter 4

Computational Methodology

This chapter lays out the method utilized in this thesis to explore recommendations for daylighting in high-rise residential buildings in Dhaka. The software packages used for the investigation necessarily define the research workflow. Rhinoceros 6 is used for 3D modeling with visual programming software Grasshopper. Within Grasshopper, the environmental plugins Honeybee and Ladybug are primarily used for analysis and simulation. These plugins utilize Radiance and Daysim as validated simulation engines. There are more details in the appendix section. The principal factors relevant to the investigation, weather data, the Radiance parameters, and the workflow applied are described in the following sections.

4.1 Factors Considered for the Computational Approach

4.1.1 Climate of Dhaka

The computational methodology in this research incorporates the climate of Dhaka to explore daylighting in this specific research context.

Corresponding to the Köppen climate classification, the climate of Dhaka is classified as a tropical savanna climate or a tropical wet and dry climate, which is categorized as "Aw" ("Koppen Climate Classification | Description, Map, & Chart | Britannica.Com" n.d.). The yearly average temperature is 31 degrees C (87.8 degrees

F), and the climate is warm almost all year-round but has a few tropical and humid months and dry periods. Dhaka falls under ASHRAE climate zone 1A, which is described as very hot and humid (Beck et al. 2018). The summertime temperature is very high. In 2019, the recorded highest temperature was 40.7 degrees C (105.26 deg F), which is the highest in the last 50 years. Dhaka observes heavy monsoon seasons during the summer months (June through October) with high humidity, while the winter seasons are typically dry.

4.1.2 Sun angles and Sun path

The tropical city of Dhaka has a mainly direct sunlight climate. Conventionally, the principal daylighting strategy is window design with considerations for visual and thermal comfort. In dense areas with high-rise development, overshadowing cuts down a significant amount of incident daylight and window design becomes a secondary concern. In such cases, urban street canyons and the shape of the buildings can be strategic areas for daylighting design. This research explored these specific strategies concerning daylighting in Dhaka. For this exploration, it is crucial to understand the sun's positions and angles throughout the year concerning the location of Dhaka.

The latitude of Dhaka is 23.8° North, and the longitude is 90.4° East. The Sun path diagram and solar chart presented in Figure 13 graphically show the year-round solar positions. These diagrams indicate that the sun altitude angles are high. The altitude angles for Summer and Winter solstices are 89.64 and 42.76, respectively, and the solar declination ranges from positive to negative 23.44 (calculated by the SunAngle program - https://susdesign.com/sunangle/). Dhaka's magnetic declination is zero (Whitsett and Fajkus 2018). The sun path and solar chart diagrams are intended to show how the sun's position throughout the year affects the facades facing the west, southwest, south, southeast, and east, while the north facades have diffused daylight. The solar position is a critical factor for the daylighting design in Dhaka because of the high solar angles.

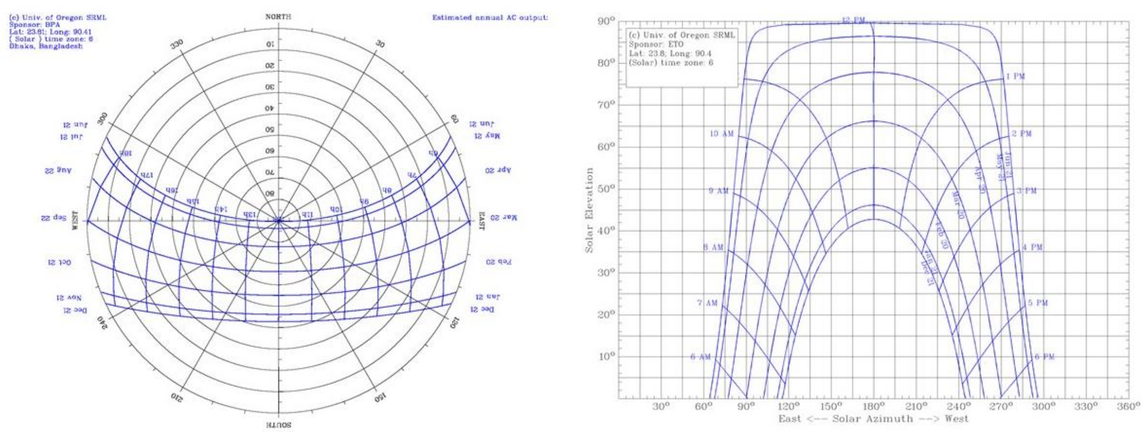


Figure 13: Sun path diagram and solar chart for Dhaka
(Source: http://solardat.uoregon.edu/SunChartProgram.php).

Figure 14 shows the direct sun penetration for the Summer and Winter Solstices and the Equinox days and how that affects the daylight ingress in high-rise buildings built in proximity. The denser the buildings, the less the daylight penetration. Because of the high sun angles, the distance between any two buildings is crucial. High-rise buildings cast shadows on the buildings in proximity.

The sketches in Figure 14 show how increasing this distance allows more sun penetration. These in-between spaces form urban street canyons. Aspect ratios of these canyons could be a crucial indicator to investigate.

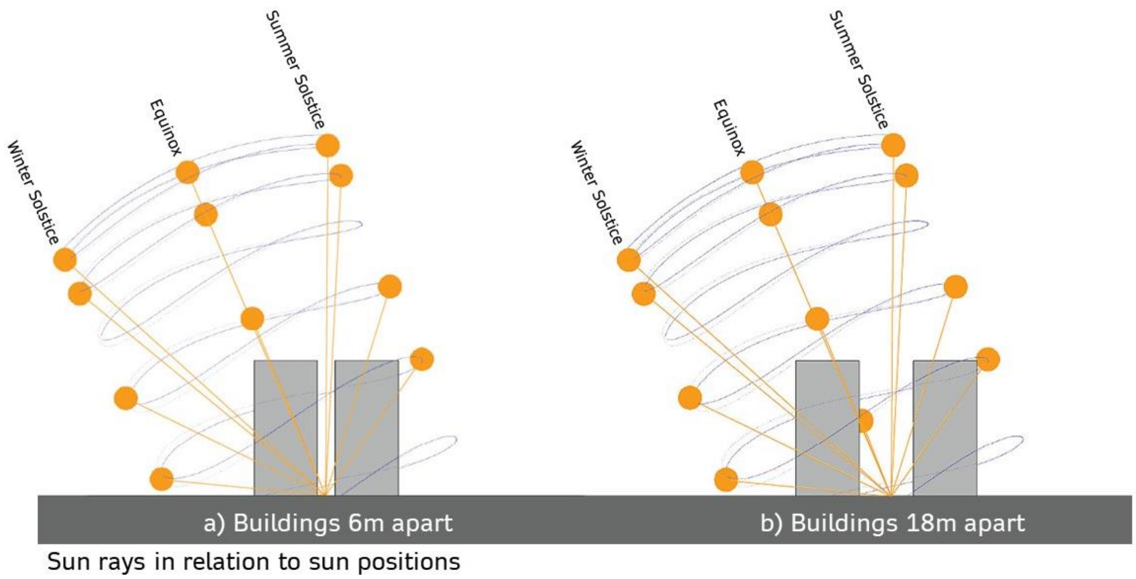


Figure 14: Sun penetration for the Summer and Winter Solstices and the Equinox days, generated with Rhino-Grasshopper-Diva (Author 2019).

The effect of high sun angles in a dense urban area can be understood in the following Figures 15 and 16. The overshadowing analysis shown in Figure 15 was done in the March and September Equinox days and the Summer and Winter Solstices on the case study housing site in Dhaka. Four different times throughout the day were considered for the overshadowing analysis. The times are 8 am, 11 am, 2 pm and 5 pm. Figure 16 shows the combined effect of all these four overshadowing analyses.

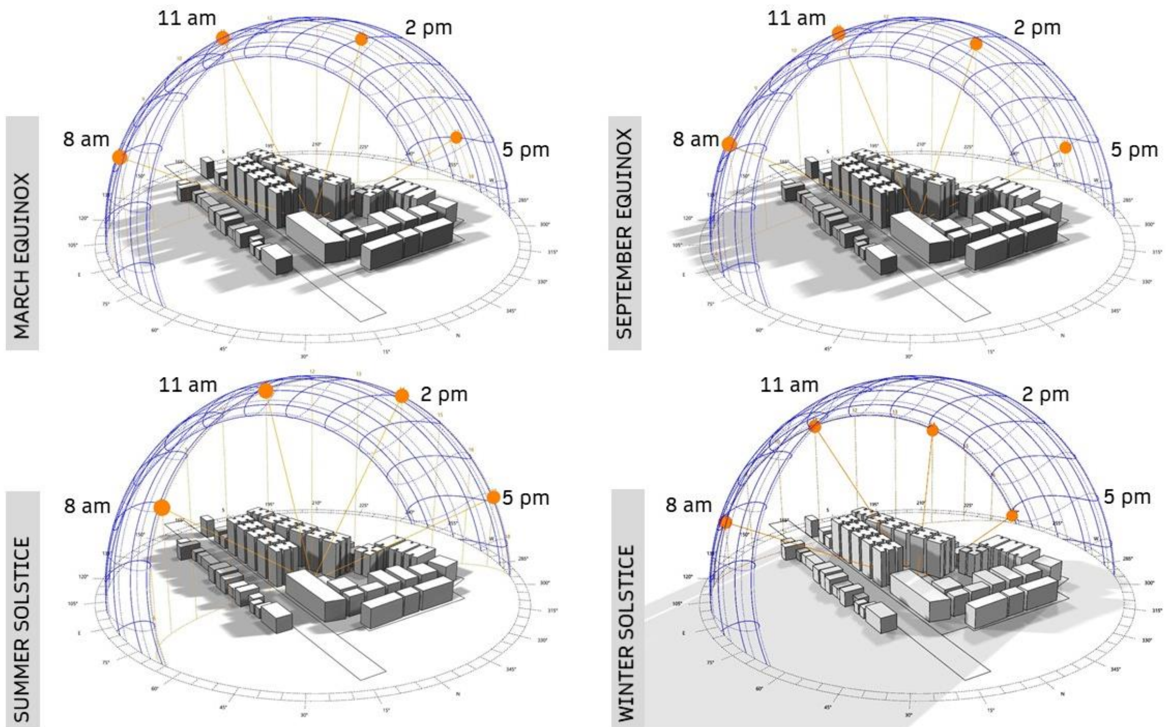


Figure 15: An overshadowing analysis for the Summer and Winter Solstices and the Equinox days, generated with Rhino-Grasshopper-Diva (Author 2019).

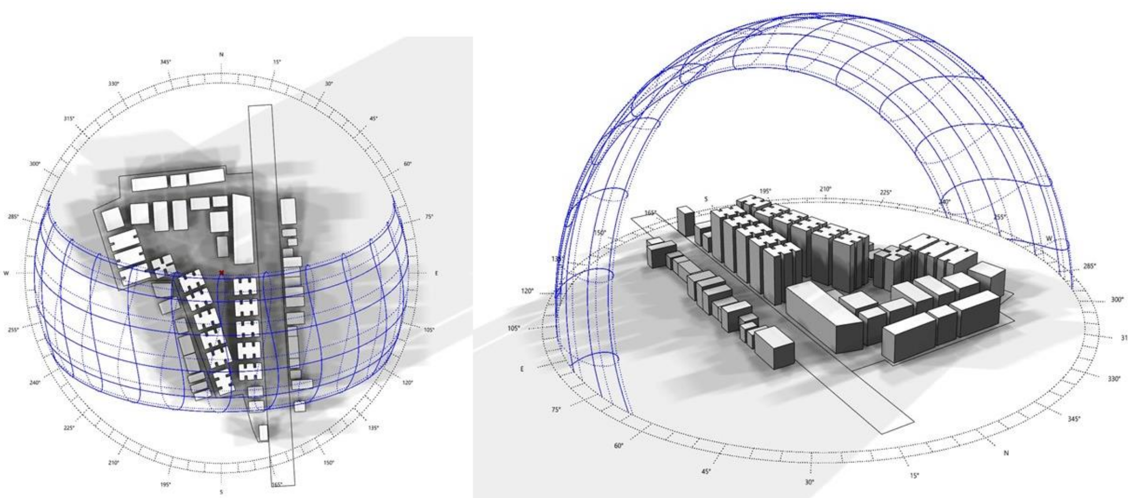


Figure 16: Combined overshadowing analysis, generated with Rhino-Grasshopper-Diva (Author 2019).

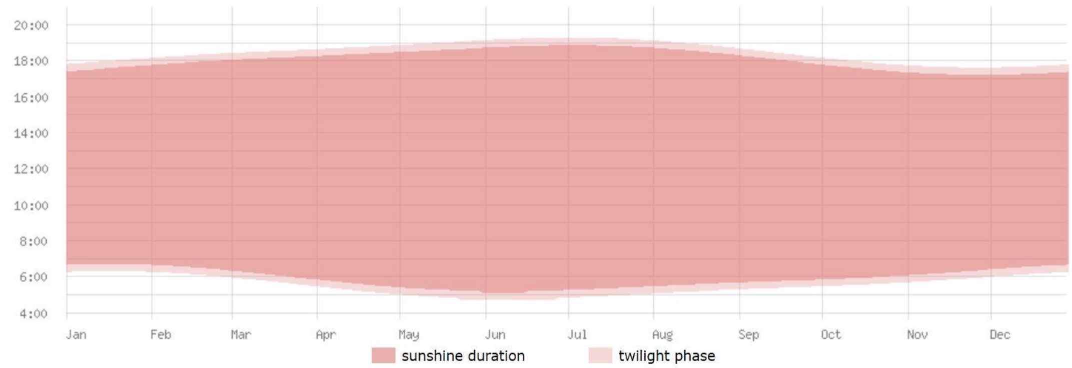


Figure 17: Average length of daylight (shaded region) in Dhaka
(source: https://www.worlddata.info/asia/bangladesh/sunset.php).

These high-rise buildings not only overshadow each other, but they also cast shadows on adjacent low and mid-rise buildings, blocking the daylight most of the time, which is more evident in the two diagrams for the equinox days. The combined shadows in Figure 16 show the extent of year-round overshadowing. From these images, it is evident that overshadowing is a problem in Japan Garden City case study along with many comparable densely built urban areas of Dhaka.

Specific indicators or parameters, such as exploring the building shape and urban canyon geometries for daylight ingress, can be investigated for daylighting in high-rise buildings in the context of Dhaka. To identify what aspects play a vital role in daylighting design in Dhaka's given context, the computational workflow for this research utilizes the weather data of Dhaka.

4.1.3 Weather Data

Weather data files are needed to provide climatic information for simulation analysis. These data files are compiled using a convention that attempts to reproduce a typical year of weather for a specific location, including day-by-day variables. Weather data files are often composed of 12 actual months from different years. It should be noted that solar radiation values are among the least reliable data within weather files because of the technical limitations of gathering this data. The radiation data are mostly estimated through approximations to account for weather conditions (Whitsett and Fajkus 2018).

Typical Meteorological Year (TMY) is such a collection of weather data consisting of hourly values of solar radiation and meteorological components for a year for a specific location. It provides the range of weather events for an analysis location giving annual averages consistent with data collected over a long period of time. TMY data is frequently used in various building simulations because these data represent a typical for the location rather than extremes (Wilcox and Marion 2008). These data files can be downloaded from multiple online sources. One of the most comprehensive and reliable sources of TMY weather data is the EnergyPlus Weather Data for simulations available through the website of the United States Department of Energy (DoE) (Whitsett and Fajkus 2018).

Typical meteorological year (TMY) weather data for Dhaka, Bangladesh, is used in this research for the dynamic sky and daylight conditions. The weather data file (.epw) used in this research is downloaded from the DoE website ("Weather Data | EnergyPlus," n.d.). There are three weather data files available for Dhaka, the file used for data extraction in this study is for the location Tejgaon, Dhaka, which is the closest location to the case study area discussed in chapter 5.

4.1.4 Simulation Parameters

The proposed simulation approach features some fixed and variable parameters in the parametric modeling environment to allow for an understanding of daylight availability and increasing simulation complexity. These variables affect the annual simulation analysis either by adding to the accuracy level or by impacting the daylight availability. This section explains the simulation parameters in the research.

Fixed Parameters

Simulating the daylight: This research utilizes the 2-phase Daysim approach. Daysim calculates the direct daylight from the sun and diffused daylight from the sky separately (Tregenza and Waters 1983). This calculation creates two matrices – direct daylight coefficients and diffused daylight coefficients. The number of direct daylight coefficients depends on the latitude of the research context (Jones and Reinhart 2017). The following equation shows how the two coefficient matrices are used to calculate the irradiance matrix (I) for each point in time of the year (Brembilla et al. 2019; Jones and Reinhart 2017):

$$\left(\begin{array}{c}\text{Direct}\\ \text{Daylight}\\ \text{Co-efficient}\end{array}\right)\left(\text{Sun}\right)+\left(\begin{array}{c}\text{Diffuse}\\ \text{Daylight}\\ \text{Co-efficient}\end{array}\right)\left(\text{Sky}\right)=\mathrm{I}$$

For the diffuse matrix, Daysim uses 148 sources corresponding to the 145 sky divisions given by Tregenza for the indirect light component (Tregenza 1987), and for the direct sunlight, there are 65 representative sun positions for the latitude of Dhaka. These matrices list the radiance of each sun position and sky division for each hour of the year. The values in the result files have units of illuminance (lux) instead of irradiance (W/m^2). Additionally, there are three concentric ring-shaped daylight coefficients for the external ground (Jones and Reinhart 2017).

Geometries: The geometries in the parametric modeling environment are iterated as boundary representations or ‘breps’ of surfaces in the Grasshopper definition. These objects are then defined as the following – (1) the building of interest, (2) the analysis floor level within the building of interest, and (3) context geometries, such as the ground, street, and context buildings. The details are described later in this chapter.

Decomposing surfaces: The analysis floor level is decomposed within the Grasshopper definition. Surfaces are defined as windows, walls, floors, and ceilings.

Since the focus of this study does not deal with material properties, the default Radiance material properties assigned in the software are used for the materials of the various surfaces. Table 4.1 presents details about the Radiance default values for reflectance, specularity, roughness, and transmittance of the materials.

Table 4.1: Radiance generic material definitions.

Material	Reflectance	Specularity	Roughness	Transmittance
Context	0.35	0	0	
Interior Ceiling	0.8	0	0	
Interior Floor	0.2	0	0	
Exterior Floor	0.2	0	0	
Windows				65.4%
Roof	0.8	0	0	
Exterior Wall	0.5	0	0	
Interior Wall	0.5	0	0	

Windows: Window-to-wall ratios in the facades, location, and size of the windows were defined in the Grasshopper definitions using various components. The details are discussed later in this chapter.

Radiance Parameters: In addition to the geometric parameters, the Radiance parameters are considered in this study. Honeybee plugin uses Radiance as a simulation engine. Radiance is an engine that utilizes a backward ray-tracing method, and within the Grasshopper definition, Radiance simulation parameters can be set to specific values. These parameters are inputs that go into the 'analysis recipe' for running annual daylight analysis. These parameters directly affect the rendering or speed of simulations and accuracy of the results. The sDA values can turn out higher or lower than the actual because of overestimation or underestimation of the accurate illuminance levels because of specific settings of these parameters. Useful ranges for simulations are shown in Table 4.2. The table shows only the ambient parameters. Ambient bounces, ambient divisions, and ambient resolutions settings are utilized in the simulations. These ranges are taken from the file 'rpict.options' distributed with Radiance (Jacobs 2012).

Table 4.2: Useful ranges for ambient parameters.

Parameter	Description	Minimum	Fast	Accurate	Very Accurate	Maximum
ab	Ambient bounces	0	0	2	5	8
aa	Ambient accuracy	0.5	0.2	0.15	0.08	0
ar	Ambient resolution	8	32	128	512	0
ad	Ambient divisions	0	32	512	2048	4096
as	Ambient super-samples	0	32	256	512	1024

Here,

ab = This is the maximum number of bounces captured by the indirect backward raytracing calculations.

aa = The ambient accuracy value approximately equals to the error from indirect illuminance interpolation.

ar = Ambient resolution determines the maximum values of ambient density used in interpolation. The maximum ambient value density is the size of the scene multiplied by the ambient accuracy.

ad = Ambient divisions define the number of initial sampling of rays sent from each ambient point into the sky hemisphere to determine the indirect incident light.

as = The number of additional rays applied only to the ambient divisions that show a significant change. It affects the 'patchiness' in the regions where indirect illumination in the incident.

An analysis to assess the applicability of these accuracy levels in this research was done to establish the correlation between the ambient parameters, simulation run time, and the results. Table 4.3 summarises the results.

Table 4.3: Ambient parameters, simulation time, and results.

CASE	AMBIENT PARAMETERS	ELAPSED TIME (minutes)	sDA%
Base	ab- 2 ad- 1000 ar- 300	20 min	20.64
Base + (ab increase)	ab- 5 ad- 1000 ar- 300	20 min	26.98
Base ++ (ab increase)	ab- 8 ad- 1000 ar- 300	20 min	26.94
Case A (min) (varied ar)	ab- 5 ad- 512 ar- 128	22 min	27.05
Case B (max) (varied ar)	ab- 5 ad- 4096 ar- 300	90 min	27.98
Case C (Very Accurate) (varied ar)	ab- 5 ad- 2048 ar- 512	37 min	27.51
Case D (Accurate)	ab- 2 ad- 512 ar- 128	8 min	20.64

In this comparative analysis, first, only the ‘ambient bounces’ values were varied. The ‘base,’ ‘base+,’ and ‘base++’ cases have ab values of 2, 5, and 8, respectively. All these take the same amount of time to simulate. However, an ambient bounce value of 5 provides the best result. Then cases A, B, C, and D utilize the settings shown in Table 4.2. The maximum setting (case B) provided the best results but took the most time to simulate. Comparing all the results and time elapsed for simulation, it seems practical to apply the base+ scenario with an ab value of 5 in the computational analysis. Table 4.4 shows detailed settings of the parameters employed in this research.

Table 4.4: A detailed list of simulation ambient parameters.

Parameter	Setting 1 (Base)	Setting 2 (Base+)
Ambient Bounces (ab)	2	5
Ambient Divisions (ad)	1000	1000
Ambient Resolution (ar)	300	300
Ambient Super-samples (as)	128	128
Ambient Accuracy (aa)	0.25	0.25
Façade window to wall ratio (WWR)	≥ 20%	≥ 20%

In setting 1, the parameters are most stringent, having an ambient bounce of 2. Setting 2 denotes the ambient bounce of 5. Both settings take similar simulation run-time with a significant difference in results. Setting 1 is applied to understand and analyze the worst-case scenarios because of the minimum ambient bounce. Setting 2 is applied for more accurate results.

The following Table 4.5 gives a summary of the fixed parameters relevant to this research.

Table 4.5: Fixed Parameters: Increasing Simulation Accuracy and Complexity.

Parameters	**Details**
2-phase Daysim method to simulate the daylight	(1) Direct sunlight, (2) Diffuse skylight
Geometries	(1) building of interest, (2) analysis floor level, (3) context
Decomposing as specific surfaces	(1) windows, (2) walls, (3) floor, (4) ceilings
Window to wall ratios	20%, 30%
Location and size of the windows	Sill height, Distance between windows
Test points grid size	1-foot resolution
Weather data	TMY weather data for Dhaka (.epw)
Ambient parameters	ambient bounce

Variable Parameters

For the parametric study, specific building-level and urban-level parameters were employed in this research.

The building level parameters are building typology and shape of internal lightwells or external cuts. Here, the building typology refers to the two square and four rectangular typologies of building forms with variable shapes of external cuts and internal lightwells identified in Figure 8 of chapter 3. For equivalence of comparison, the footprint area of the buildings, and the total area of external cuts and lightwells remain the same. For all typologies, the total footprint area is 8800 sf (817.5 sq m), and the total lightwell and external cuts area is 800 sf (74.3 sq m).

The windows were defined keeping the window-to-wall ratio (WWR) at 20%, the recommended minimum by LEED v4.

The urban-level parameters mainly describe the configuration of the urban street canyon. The width of the adjacent streets is varied as a parameter. The external obstruction and orientation are also examined in the urban-level parametric study. Table 4.6 presents these parameters influencing daylight ingress

Table 4.6: Variable parameters: Building and Urban Level Parameters.

	Parameters	**Details**
Building Level		
	Building geometry	Shape, form
	External cuts and internal lightwells	Shape, area
Urban Level		
	Urban street canyons	Width of the adjacent street
	Canyon orientation	N-S vs E-W
	Context	Relative compactness or dispersion
	Obstruction of solar penetration	Overshadowing from adjacent buildings

4.2 Computational Framework

4.2.1 The Workflow

In this research, a computational approach was adopted to analyze daylight availability in the dense urban condition of Dhaka. A workflow was created based on existing research. To calculate the sDA at a building level, the Radiance-Daysim approach is used and validated in many pieces of research (Saratsis, Dogan, and Reinhart 2017); (Christoph F. Reinhart and Wienold 2011). Ladybug and Honeybee plug-ins for Rhinoceros-Grasshopper use the Radiance engine to simulate daylight availability. The parametric workflow shown in Figure 18 is used to model, simulate, and evaluate building geometry and related urban street canyons. The workflow is divided into four sequential phases: (1) modeling the geometries and environment, (2) define and iterate the geometries which include defining the analysis geometry, creation of windows, walls, floors and ceiling, (3) annual daylight simulation, and (4) evaluation based on dynamic daylight availability metrics.

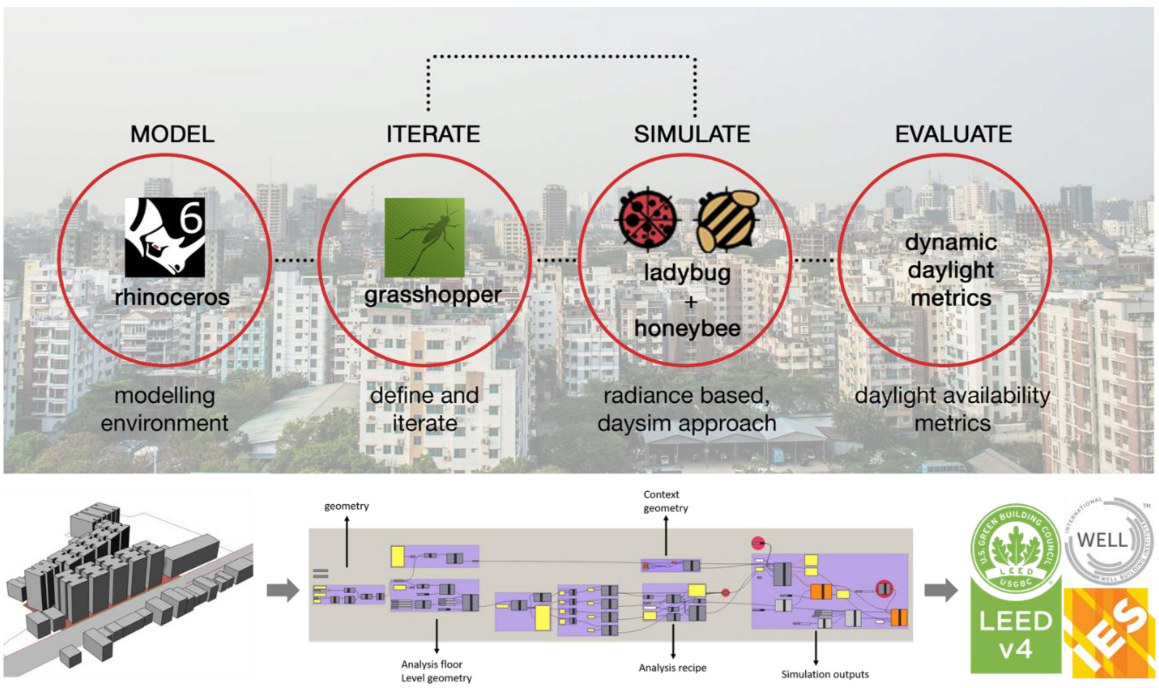


Figure 18: The computational workflow (Author 2019).

4.2.2 Daylight simulation

The methodology used in this research is a computational framework. Several software, plugins, and simulation engines play a role in this framework. Grasshopper is used for parametric modeling, Ladybug and Honeybee are used for daylight simulations and visualization process within which Radiance and Daysim are used as simulation engines. Spatial Daylight Autonomy ($sDA_{[300lux]\ [50\%]}$) daylighting metric is used as an indicator for evaluation referring to the recommendations by LEED v4. The computational methodology followed in this research to define the workflow and utilize for the analysis has three steps- from the setup of the model to the visualization. These are described step-by-step in the subsequent parts in this section.

Step 1: Geometry creation with the context in Rhinoceros

Modeling the geometry is a complex task because it needs to be efficient and precise concerning relevant details. The ways the relevant geometries are modeled will define the complexity and speed of the simulations. The defined spatial extent and resolution of the context should be carefully considered. First, the buildings and the associated urban context, such as the ground, the streets, and adjacent buildings, are modeled. Relevant adjacent buildings are modeled as solids having the minimum number of surfaces that are needed to understand and analyze the effect of those. The building of interest is not modeled in this step. The footprint of the building of interest is modeled as a planar surface in its specific position. The ground plane and related streets are modeled as surfaces. No material is assigned to any of the surfaces modeled in this step.

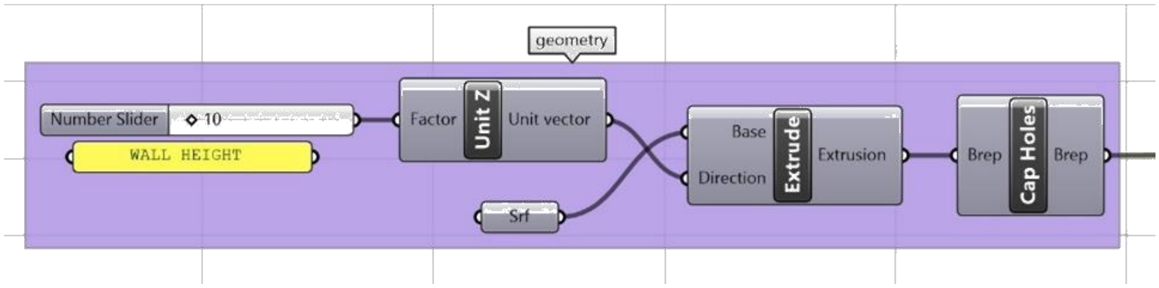


Figure 19: Grasshopper definition of the building of interest (Author 2019).

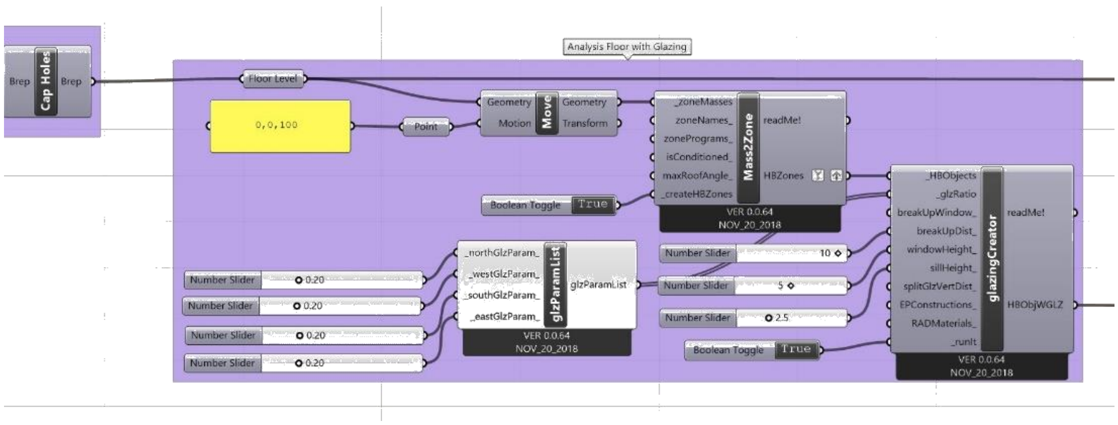


Figure 20: Grasshopper definition of the analysis floor with glazing (Author 2019).

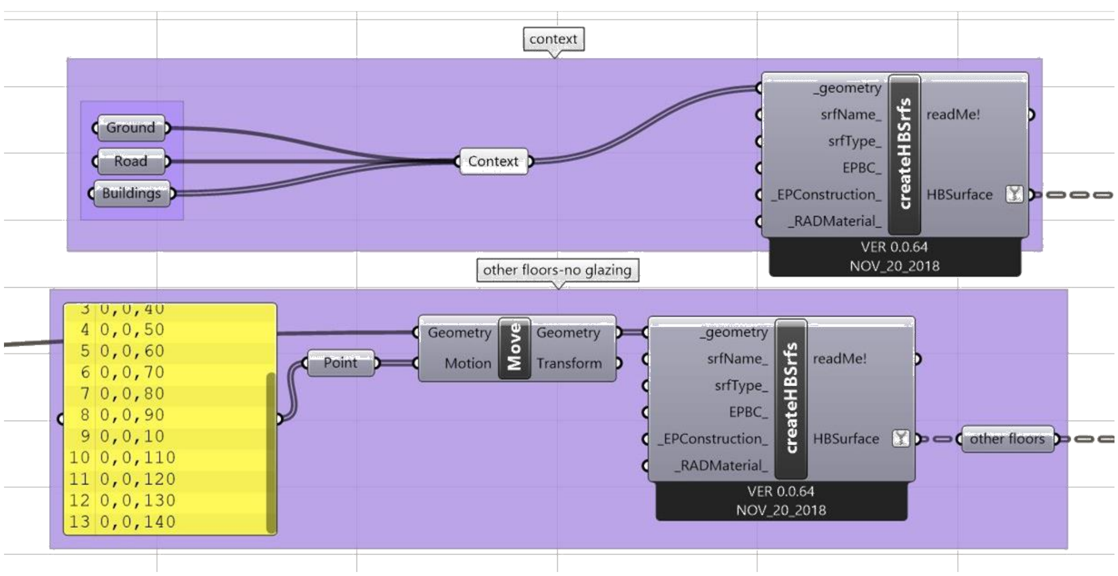


Figure 21: Grasshopper definition of the Context Geometry (Author 2019).

Step 2: Parametric modeling in Rhino-Grasshopper

After modeling the base geometry in Rhino, the footprint of the building of interest set as a surface, and an analysis floor level with glazing are defined in Grasshopper (Figure 19 & 20). The glazing is parametrically defined in this step, inputting window-to-wall ratios for all four sides, the distance between windows, window, and sill heights. Then, various surfaces of the resultant analysis floor with glazing are decomposed as walls, windows, ceiling, and floor.

Next, the context geometry is defined in Grasshopper, as shown in Figure 21. Note that the context geometries are simplified to avoid calculation of a large number of surfaces, and increasing time elapsed for the daylight simulation.

Step 3: Daylight simulation and data visualization

Daylight simulations are run utilizing the environmental plugins – Ladybug and Honeybee. These simulations provided annual daylight autonomy results and $sDA_{[300lux]\ [50\%]}$ percentages that are the percentage of the time during the active hours of occupancy that the test points receive more than the illumination threshold 300 lux. The data generated are analyzed and used for further exploration in this research.

After defining all the geometries in Grasshopper, the 'analysis recipe' for the annual daylight simulation is defined, as shown in Figure 22. To do this, one needs a north direction, weather data, test mesh, test points and resolution, and Radiance

Parameters. In the ‘analysis recipe,’ the north direction is upwards, and the weather data used is described in subsection 4.1.3. The test mesh consists of the decomposed surfaces or analysis floor. The test points are generated using the Honeybee_generate test points component’ with a grid spacing/resolution of 1 foot (0.3 meter) and at 0.75 meter 30” (0.75 meter) above the floor.

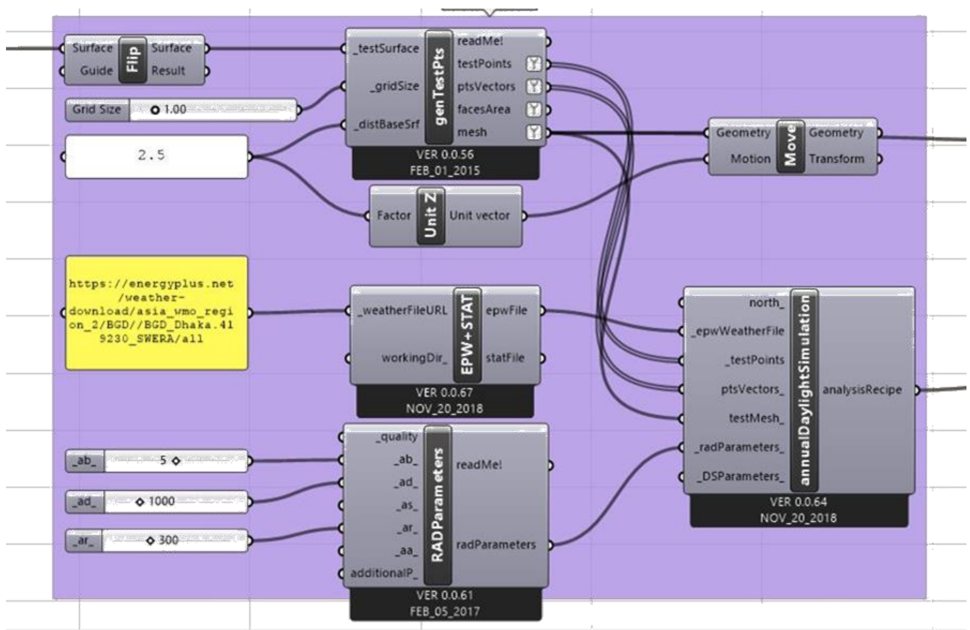


Figure 22: Annual Daylight Simulation Analysis inputs (Author 2019).

The ‘Honeybee_Run Daylight Analysis’ component is the main component used to generate an annual daylighting analysis. For the simulations, the geometries as Honeybee objects, the ‘analysis recipe,’ the number of CPUs were set to this component. Analysis results are converted to sDA values using the ‘Honeybee_Read Annual Analysis Results’ component, and visualizations are done utilizing the data to understand and analyze the results.

4.2.3 Assumptions

The computational methodology used here, while effectively producing relevant results, makes some important simplifying assumptions for simulation to minimize calculating irrelevant objects and shorten the simulation time. A key assumption is that there are no interior walls, partitions, structures, furniture, or other internal obstructions in the building. Another key assumption is, the massing of the building is simplified, not considering the façade treatments such as exterior protrusions, verandas, other overhangs, or shading devices concerning the windows. It should be noted that the sDA computed in this exploration is not the actual sDA required by LEED that complies with IES LM-83 since there are no shading devices, such as blinds, applied in the parametric model. The exterior wall thickness and the building elevator and stairwell core were not deliberately defined in the geometry. The sDA calculated in this research is the output of the Honeybee annual daylight simulation and is referred to as sDA henceforth. Within the limitations imposed by these caveats, this computational framework can be used to effectively calculate research sDA values and generate data necessary for this research.

Chapter 5

Computational Analysis: The Case Study

5.1 Japan Garden City

The daylight availability is computationally analyzed for a building in Japan Garden City. Reiterating the rationale for analyzing this specific case study is that it is a high-density, high-rise residential development, where the existing building forms in the site and this project is a designed housing with environmental considerations. This analysis is done to understand the extent of challenges of designing for daylighting in high-density areas. The Japan Garden City is a block-based housing development which is essentially blocks of closely spaced high-rise buildings within a closed boundary. These types of block-based housing projects are a recent development in Dhaka. There are no specific regulations in the existing building codes to guide these developments (Parveen 2016).

Geometry:

The Japan Garden City site consists of 27 residential highrise buildings of three form typologies – Typology S2, R2 & R3, as shown in Figure 8. There are commercial shopping facilities, including six other service buildings within site. The adjacent road width is approximately 60 feet (18 meters). The surrounding buildings are primarily of residential use with some mixed-use and commercial buildings. The neighboring building heights vary between 4-10 storeys. The model developed here consists of eleven 15-storeys buildings of typology R3 with six dwelling units per floor. A centrally located building along the 18 m street is selected as the ‘building of interest’ for annual daylight availability analysis, as shown in Figure 23. The apartment floor areas range from 1049-1099 square feet (97-103 square meters), and each floor area is approximately 6120 sf (570 square meters). The ground floor is primarily used for car parking. The following Figure 23 shows the Rhino model of the case study buildings on the site. Note that, the true north direction is at a 4 degrees angle with the adjacent secondary road.

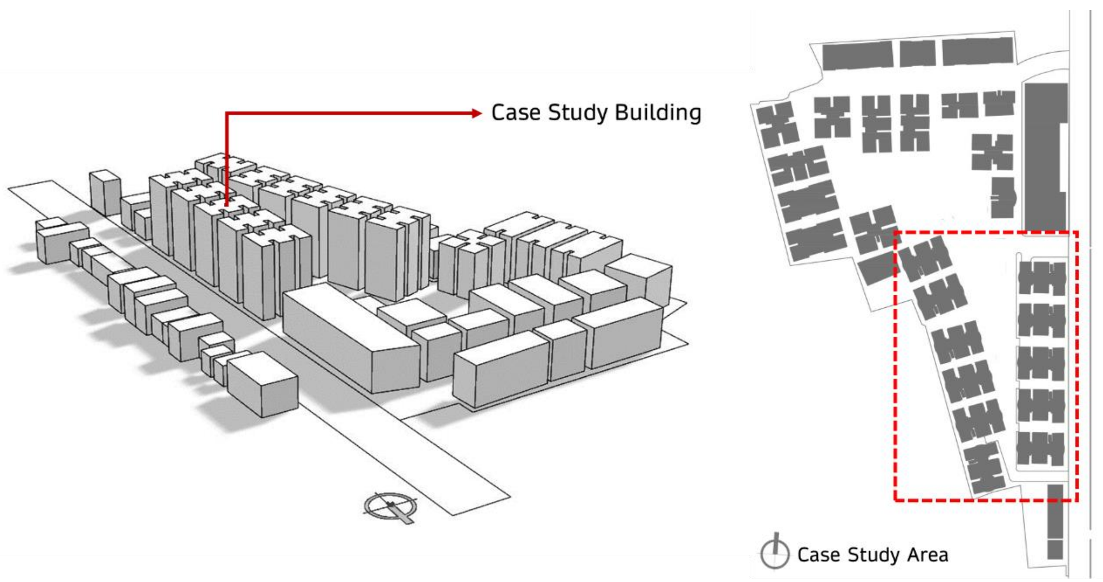


Figure 23: Rhino-Grasshopper model of Japan Garden City (Author 2019).

The simulation analysis focuses on the daylight availability at different levels of the ‘building of interest’ in the model complex, shown in Figure 24. The computational approach described in the previous chapter utilizing the

Radiance/Daysim engines in Grasshopper/Honeybee is applied to simulate and analyze the model building.

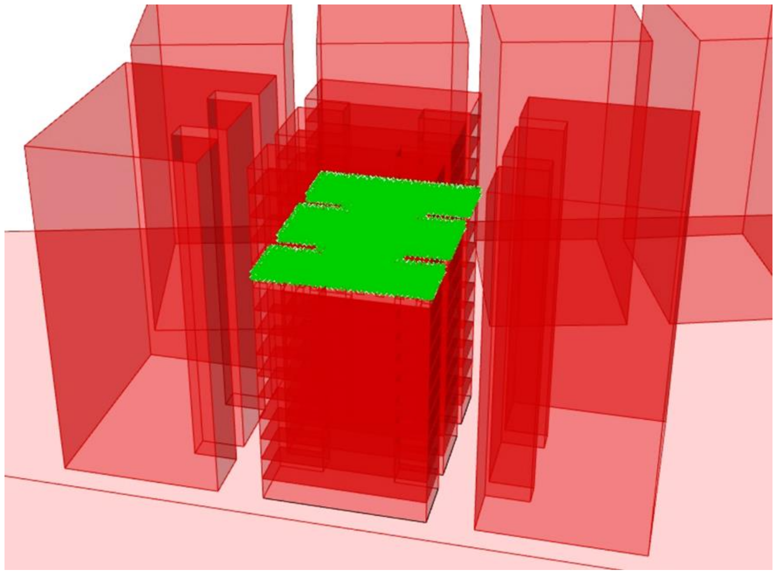
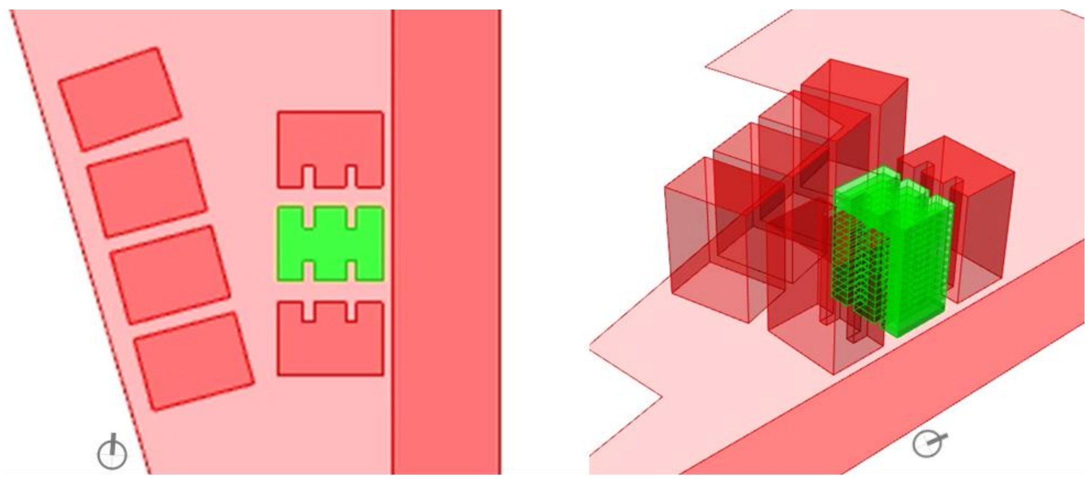


Figure 24: Test points generated at the analysis floor level (Author 2019).

After modeling in the software Rhinoceros, only the relevant geometries are defined in Grasshopper to avoid calculating a large number of surfaces. The window to wall ratio is 30% (glazing parameter 0.3) on the north and south facades and 20% (glazing parameter 0.2) on east and west facades. These ratios are based on the case study building and intuitively generalized for the simulation study. Test points are generated at all the occupied floor levels, 1^{st} through 14^{th} floors, with a square grid spacing of 1 foot (0.3 m) and at 30 inches (0.75 m) above the floor, as shown in Figure 24. The ground floor is not analyzed as it is primarily used for parking. Figure 25 shows the geometries that were defined in Grasshopper. The case study building has an 80 feet X 120 feet rectangular footprint and is 15 storeys high (highlighted in green color). The distance between adjacent buildings is 20 feet (6 meters) on the north and south side. There is a 60 feet wide (18 meters) street on the east. The materials are generic Radiance materials, as mentioned in Table 4.1.

Annual daylight analysis is done using Honeybee with Daysim and Radiance engines to understand the existing daylight conditions and the effects of the building geometry. All the floor levels, except the ground floor, are simulated for annual daylight autonomy, along with the sDA percentages.



(a) (b)

Figure 25: Rhino model extent for simulation (a) plan, (b) isometric view (Author 2019).

5.2 Simulation Outputs

After setting up all the relevant geometries, a series of simulations were run on all fourteen living floor levels of the case study building. For comparison, three floors with annual daylight availability falsecolor graphics are shown in Figure 26. These diagrams illustrate the effect of the surrounding context, such as the different widths of the streets around the analysis building, location of windows, and other geometric features, such as the external cuts. Additionally, these graphics demonstrate the effects of the changing floor levels. The graph in Figure 27 presents all the percentages of sDA for all the floor levels.

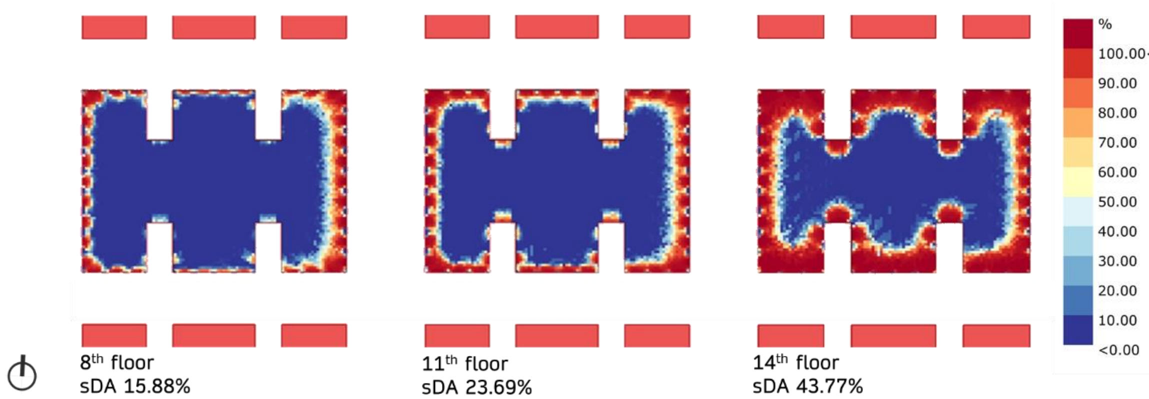


Figure 26: A three-floor comparison of the annual daylight autonomy falsecolor visualization in the case study building (Author 2019).

1st to 14th floor – Spatial Daylight Autonomy % (300 lux, 50%)

Level	sDA%
1	11.43
2	11.72
3	12.09
4	12.36
5	13.12
6	13.72
7	14.96
8	15.88
9	17.66
10	20.78
11	23.69
12	28.02
13	33.4
14	43.77

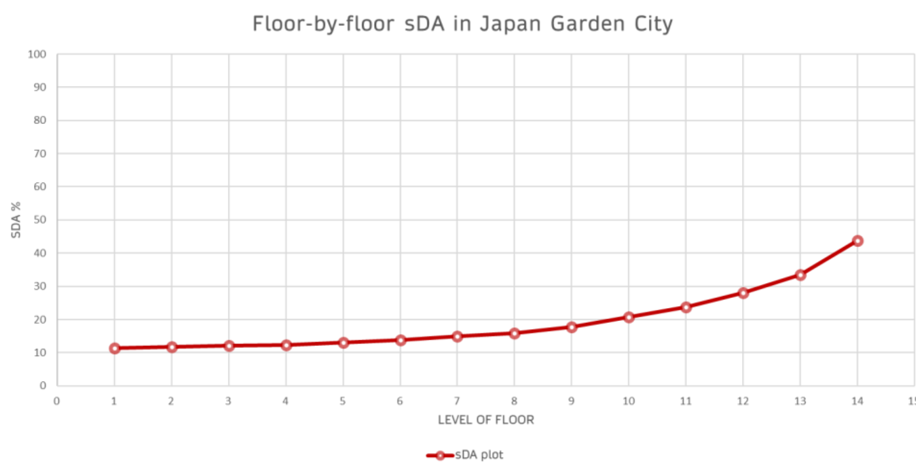


Figure 27: Existing condition floor-by-floor sDA data (Author 2019).

The three-floor-comparison data visualization of annual daylight autonomy shows interesting results because it differs from widely accepted assumptions. The north and south façades receive almost symmetric levels of daylight penetration annually, even though the south façade is expected to receive more direct sunlight due to year-round sun positions and angles. On the other hand, the east and west façades show asymmetric results and receive comparatively more daylight annually, even though WWRs are lower than the north and south façades. The sDA percentages in Figure 27 show that the lower nine floors are comparatively darker and have similar percentages ranging from 11.43% to 17.66%, which was predictable based on the existing condition of the case study housing. The 10^{th} to 13^{th} floors have gradually increasing sDA percentages. The topmost floor level receives the most daylight having a 10% increase from the 13^{th} floor, but the sDA percentages remain less than the LEED v4 recommendation for building-level sDA of 55%. This significant sDA increase from the 13^{th} to 14^{th} floor sheds light on the combined effects of unobstructed direct sunlight penetration and diffused daylight on the topmost floor level, whereas the surrounding buildings obstruct the lower floors. This finding has implications for the daylighting design in Dhaka. Even with high sun angles, the author speculates that lower floors only receive diffused daylight from the sky and surrounding surfaces that create the darker interior spaces.

To better understand the effects of building geometry and obstructions, another series of simulations were done on the case study building as an isolated geometry on a ground plane. All the fourteen floors were simulated to compare the effects of changing the floor levels. Moreover, the impact of unobstructed direct sun penetration can be noted in the isolated geometry and compared with the case study building.

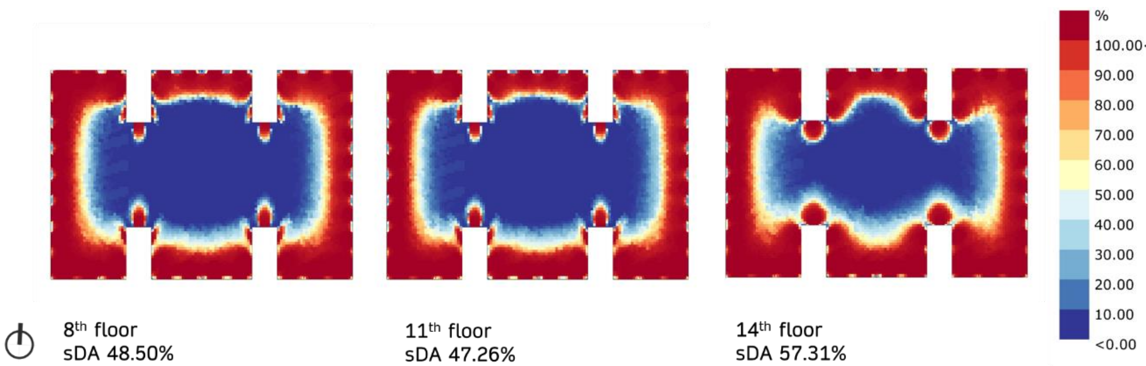


Figure 28: A three-floor comparison of the annual daylight autonomy falsecolor visualization in the isolated geometry (Author 2019).

1st to 14th floor – Spatial Daylight Autonomy% (300 lux, 50%)

Floor Level	sDA%
1	51.64
2	51.94
3	51.77
4	51.33
5	50.33
6	50.14
7	49.29
8	48.5
9	47.95
10	47.62
11	47.26
12	47.84
13	48.96
14	57.31

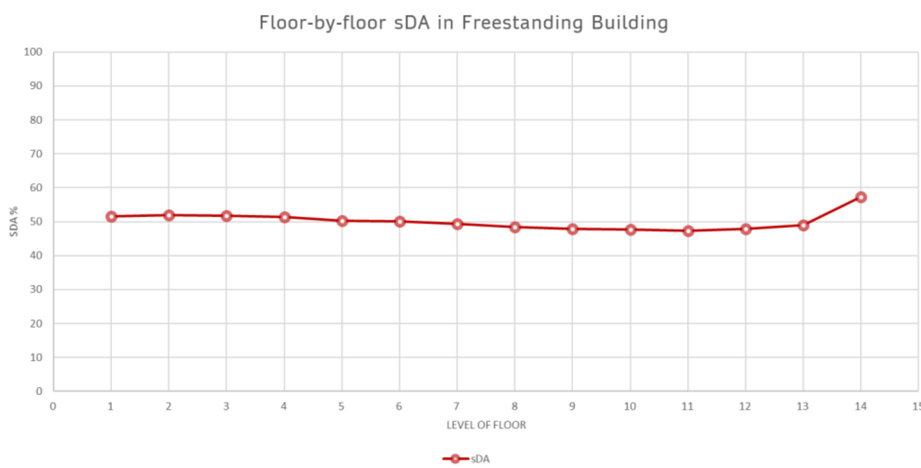


Figure 29: Isolated geometry floor-by-floor sDA data (Author 2019).

Figure 28 shows three floors with annual daylight availability falsecolor graphics, and the graph in Figure 29 presents the percentages of sDA for all the floor levels for the isolated building. The variation of the sDA percentages at different floor levels is not significant except for the topmost floor. The higher sDA at the topmost floor level is because the isolated geometry receives direct unobstructed sunlight as opposed to the existing geometry. The illuminance levels on the north and south sides are not symmetric. Because of the year-round sun positions, the south facade receives more daylight compared to the north. Therefore, the intermediate shaded region between red and blue in the south is longer than that of the north façades, as shown in the falsecolor graphics.

5.3 Discussion

The existing condition of the Japan Garden City case study building is simulated and analyzed to understand daylight availability in a highrise apartment building in a dense urban environment. The graph in Figure 27 shows that the uppermost floor receives the highest illuminance levels that reflect on the annual daylight autonomy graphic of the 14th floor in Figure 26. Then, on the next floor levels, the percentage plummets considerably. This change is due to the adjacent buildings being in direct proximity allow very little daylight penetration, which is particularly evident in the north and south side of the test building. Despite having external cuts that may work as lightwells, the benefits of these can be observed only in the upper five floors (10^{th}-14^{th}) for daylight ingress, whereas there is almost no effect of these lightwells on the lower floor levels. Overshadowing cuts down direct and diffused sunlight significantly except for the topmost floor.

Conversely, on the east side, illuminance levels are relatively significant throughout the year, which is due to the adjacent 60' wide street. It should be noted that the window-to-wall ratio (WWR) is 20% on the east and west facades and 30% on the other two. Even though the WWRs are lower on the east side, the comparatively wider adjacent street allows more daylight ingress. This effect is equally visible on the west side of the test geometry. The tapered canyon shape influences the illuminance levels on the west side.

The almost symmetric illuminance levels in the north and south sides of the case study building could be due to the narrow aspect ratio of the adjacent urban canyons. The neighboring buildings significantly cut down direct sunlight penetration. Figure 30 shows a comparison of the case study building and the isolated building on the 14th floor, where sDA percentages are the highest for each case.

The annual illuminance levels for the case study building are relatively similar from north and south facades. The length of daylight penetration is measured from the edge of the façade to the point where the illuminance levels are less than 50% of a required minimum, visualized as darker shades of the color blue in the falsecolor graphics, to quantify the relative illuminance levels on the north and south sides. In the case study building, this length is approximately 10 ft from the south and 7.5 ft from the north measured at the center of the façades.

Whereas, in the isolated building, the difference of daylight availability in the north and the south sides is more apparent. These lengths for isolated building are approximately 22 ft from the south and 11 ft from the north. This difference can be analyzed by looking at the availability of direct and diffused sunlight. For the isolated building, the effects of direct sunlight are more prominent compared to diffused light penetration. However, in the case study building, where the neighboring buildings obstruct direct sunlight, the influence of direct sunlight is not significant. The diffused light from external surfaces makes the daylight availability relatively similar from both facades, which confirms the relative impact of direct sunlight penetration and diffused daylight due to obstruction from adjacent high-rise buildings.

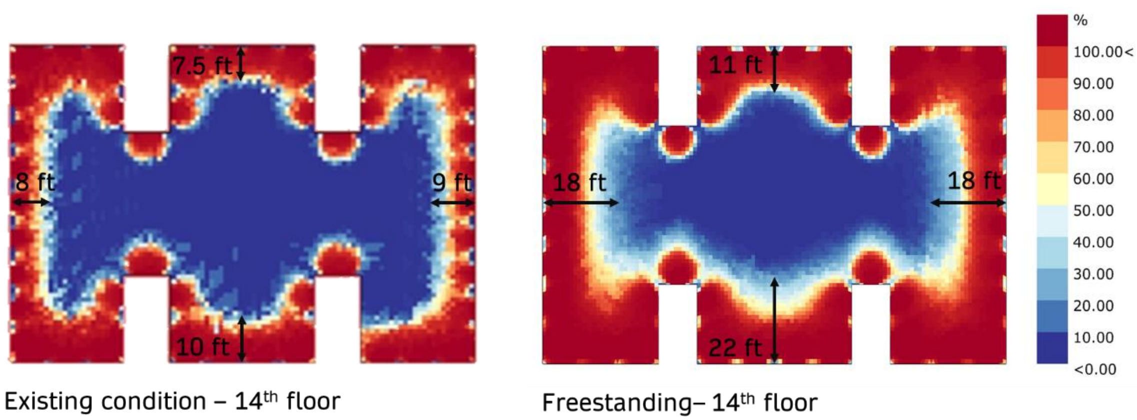


Figure 30: Comparison of the annual daylight autonomy falsecolor visualization in the existing condition and isolated geometry on the 14th floor (Author 2020).

Annual illuminance levels for the case study building are relatively similar from north and south facades. The length of daylight penetration is measured from the edge of the façade to the point where the illuminance levels are less than 50%

of a required minimum, visualized as darker shades of the color blue in the falsecolor graphics, to quantify the relative illuminance levels on the north and south sides. In the case study building, this length is approximately 10 ft from the south and 7.5 ft from the north measured at the center of the façades. Whereas, in the isolated building, the difference of daylight availability in the north and the south sides is more apparent. These lengths for isolated building are approximately 22 ft from the south and 11 ft from the north. This difference can be analyzed by looking at the availability of direct and diffused sunlight. For the isolated building, the effects of direct sunlight are more prominent compared to diffused light penetration. However, in the case study building, where the neighboring buildings obstruct direct sunlight, the influence of direct sunlight is not significant. The diffused light from external surfaces makes the daylight availability relatively similar from both the facades, which confirms the relative impact of direct sunlight penetration and diffused daylight due to obstruction from adjacent high-rise buildings.

Therefore, the author hypothesizes that the external cuts and lightwells and higher façade window-to-wall ratios only have a significant influence on daylight availability if the width of related urban street canyons is considered. To verify this hypothesis, the following chapter presents a parametric exploration.

Chapter 6

Parametric Exploration: Building Geometry & Urban Canyons

This chapter presents the parametric exploration of the building geometry and related urban canyons. The study is done first, at the building level, and then extended to the urban level. This part of the research employs specific parameters (shown in Table 4.6) to simulate hypothetical urban scenarios. This investigation helps to understand and identify the effects of building geometries and urban street canyons on daylighting in a dense city. Consequently, building orientations are also studied to understand how the buildings and urban canyons relate to each other.

6.1 Building Level Study

6.1.1 Simulation

The building level study focuses on the geometric aspects mentioned in Table 4.6. Each of the geometries was defined as an isolated building on a ground plane with no external obstructions. The window-to-wall ratio is 0.2 (20%), and all the materials remained as Radiance default materials (Table 4.1) in the analysis. The building of interest is assumed to be a 15-story residential building. After modeling the building in Rhino and iterating it in Grasshopper definition, all the floor levels of each building typology were simulated in series for annual daylight analysis.

6.1.2 Outcomes

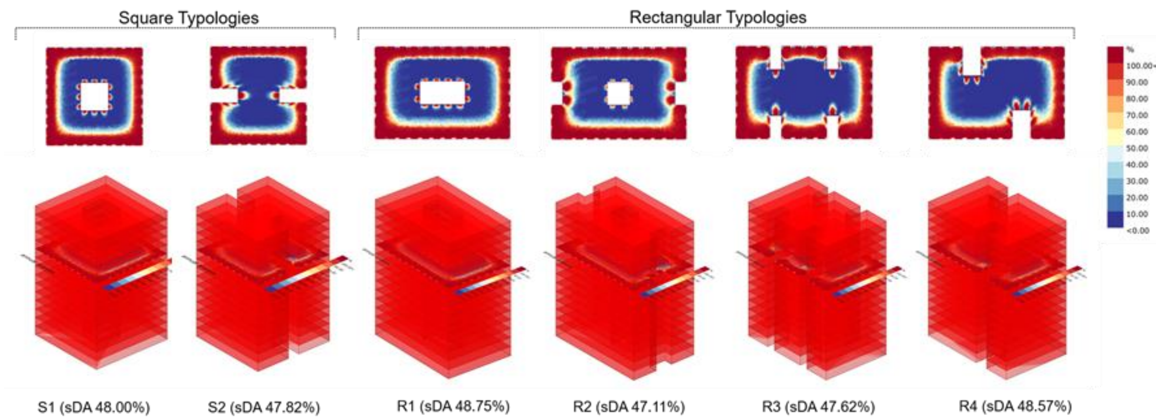


Figure 31: Building level study for daylight availability for the 10th floor (Author 2020).

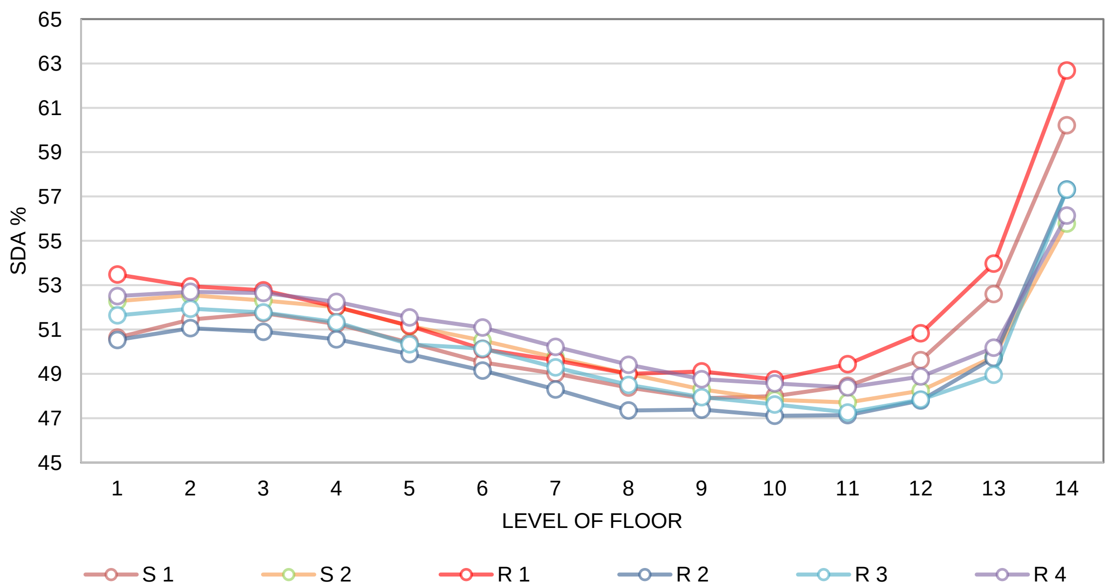


Figure 32: Floor-by-floor sDA plot for the six typologies (Author 2020).

Figure 31 shows annual daylight autonomy false-color graphics on the tenth-floor level for all six building typologies for comparison. The effect of changing floor levels on $sDA_{[300lux]\ [50\%]}$ percentages is shown in Figure 32, where the graph presents the sDA values on all the floors except the ground parking level.

Note that the scale range in the y-axis is different from the graph shown in Figure 29 for a closer look at the variations of the sDA values.

These data visualizations demonstrate that the sDA percentages for a specific floor level in all building typologies vary within a small range, approximately from 2 to 7, whereas the variation is highest (sDA 63%-56%) in the 14^{th}-floor level. The sDA percentages for all floor levels in a specific building typology vary within the range of approximately from 7.7 to 13.9. The variations for each typology are as follows - S1-12.3, S2-8.8, R1-13.9, R2-10.2, R3-10, and R4-7.7. The R4 type presents the minimum difference in floor-to-floor sDA percentages, whereas the R1 shows the highest variation. On the other hand, Figures 31 and 32 depict that, among the rectangular types, the type R1 receives slightly more daylight than the other types, especially in the floor levels from 9^{th} to 14^{th}. Although type R4 has the longest perimeter length and thus more glazed surfaces, the upper floors get comparatively lower percentages of sDA than R1. One reason for this could be that the R1 type has uninterrupted facades without any external cuts that benefit from the unobstructed direct sunlight. Figure 31 also shows that these exterior cuts decrease the direct sunlight ingress. The types R2, R3, and R4, have wider shaded regions (orange to light blue in falsecolor map) between red and blue extremes, mostly near the windows, whereas R1 type has uninterrupted red color adjacent to the perimeter and the less shaded area between the two extremes. A similar effect can also be seen in S1 and S2 types. These external cuts may be beneficial to reduce glare and overexposure to direct sunlight. The impacts of having these external cuts were also explored in the urban level investigation discussed later in this chapter.

The sDA percentages in all cases are somewhat at a good level principally because of unobstructed direct sunlight exposure. In all cases, topmost floors have the highest sDA. It is intriguing that in an isolated geometry, the lower floor levels receive more daylight compared to the middle levels. One assumption can be made here that this is due to the diffused sunlight reflected from the ground surface penetrating the building interiors through the glazed openings. The upper floors receive more daylight than the lower ones because the sunlight can reach these floors even when the sun position is high, whereas the lower floor levels do not receive direct sunlight when the sun is at a higher position in the sky.

In the isolated geometry study, the diffused daylight from the ground, the sun positions, and the external cuts in the façades play crucial roles in daylight ingress. Interestingly, the data also shows that the shape and geometry of these typologies do not have any significant effect on spatial daylight autonomy for isolated buildings, and all the typologies seem to have an almost similar level of daylight ingress year-round (Figure 32). The isolated geometry sDA values serve as references for the urban level analysis.

6.2 Urban Level: Street Canyons

For the urban level simulations, only rectangular typologies (R1-4) were investigated because these are more common in present urban Dhaka. In these simulations, urban street width and orientation were primary parameters. An abstract geometric type, a solid rectangular building with no external or internal lightwell, is included in this study (named R0) to see how the other four rectangular types perform compared to R0. Each of the five rectangular typologies is simulated and analyzed in a hypothetical urban scenario consisting of 3 X 3 grids of repeating geometry with streets with specified widths. The urban level study for five rectangular typologies incorporate the following scenarios–

i. North-south (N-S) building orientation, 20’ streets
ii. East-West (E-W) building orientation, 20’ streets
iii. North-south (N-S) building orientation, 30’ streets
iv. East-West (E-W) building orientation, 30’ streets
v. Wider East-West (E-W) streets
vi. Wider North-south (N-S) streets

Figures 33 and 34 show the data visualization matrices from the thirty annual daylight simulations for the 10th floor of the five rectangular types in the six hypothetical urban scenarios. The two matrices show results utilizing the two settings of parameters from Table 4.4.

Predictably, the matrices depict that having a longer building perimeter, and thus, having more glazed surfaces allow more daylight ingress. Therefore, type R4 performs slightly better than the other types. In contrast to the building level study, type R1 did not perform better than the other types in the urban level study. The external cuts may be more useful in urban scenarios than isolated geometry because the diffused light reflected or scattered from surfaces of nearby buildings influence daylight ingress. There are slight improvements in the sDA with an increase in the perimeter length and glazed surfaces. For example, the percentage increase of sDA for R1 to R4 is 13.5% (calculation based on data shown in Figure 33).

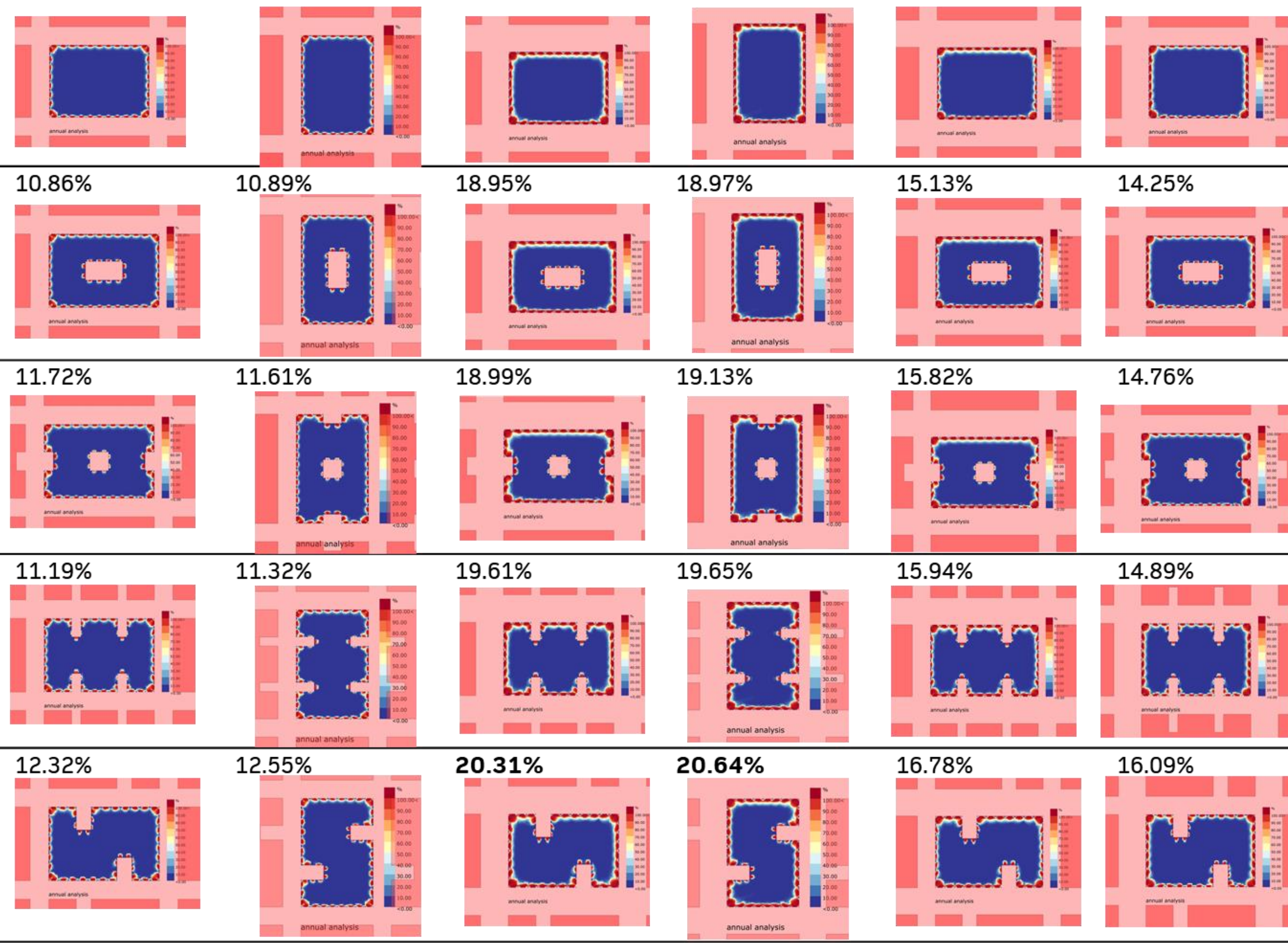
On the other hand, increasing street widths around the building from 20 ft (6 m) to 30 ft (9 m) resulted in significantly higher spatial daylight autonomy percentages. The percentage sDA increases for the five typologies are as follows, R0 – 87.3%, R1 – 74.5%, R2 – 62%, R3 – 75.2%, and r4 – 67% (calculation based on data shown in Figure 33). This outcome reinforces the hypothesis that the geometric configuration of urban street canyons, in this case, the width of the street canyon, plays a vital role in daylight autonomy. In comparison, building shapes seem to have less effect on daylight autonomy.

Also, ambient bounce increases from 2 to 5 show a significant increase in the results (Figure 34). Moreover, having different street widths in the N-S and E-

W directions also shows variations in sDA%. The positioning of the longer side of the building along the wider street performs better in terms of daylight ingress. Furthermore, the correlational study of street width and daylight availability in Figures 35 and 36 show that increasing the width of the street can be effective to attain the LEED v4 recommendations of 55% sDA.

Setting 1
ab 2

Existing types	Exterior Perimeter	N-S Building, 20' Streets	E-W Building, 20' Streets	N-S Building, 30' Streets	E-W Building, 30' Streets	Wider EW streets	Wider NS streets
R0 (80' X 110')	380'	8.9%	8.93%	16.67%	16.68%	12.98%	12.28%
R1 (80' X 120')	400'	10.86%	10.89%	18.95%	18.97%	15.13%	14.25%
R2 (80' X 120')	440'	11.72%	11.61%	18.99%	19.13%	15.82%	14.76%
R3 (80' X 120')	500'	11.19%	11.32%	19.61%	19.65%	15.94%	14.89%
R4 (80' X 120')	560'	12.32%	12.55%	**20.31%**	**20.64%**	16.78%	16.09%



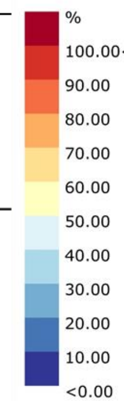


Figure 33: Urban level Daylight Availability Study at floor level 10 – Setting 1 (Author 2020).

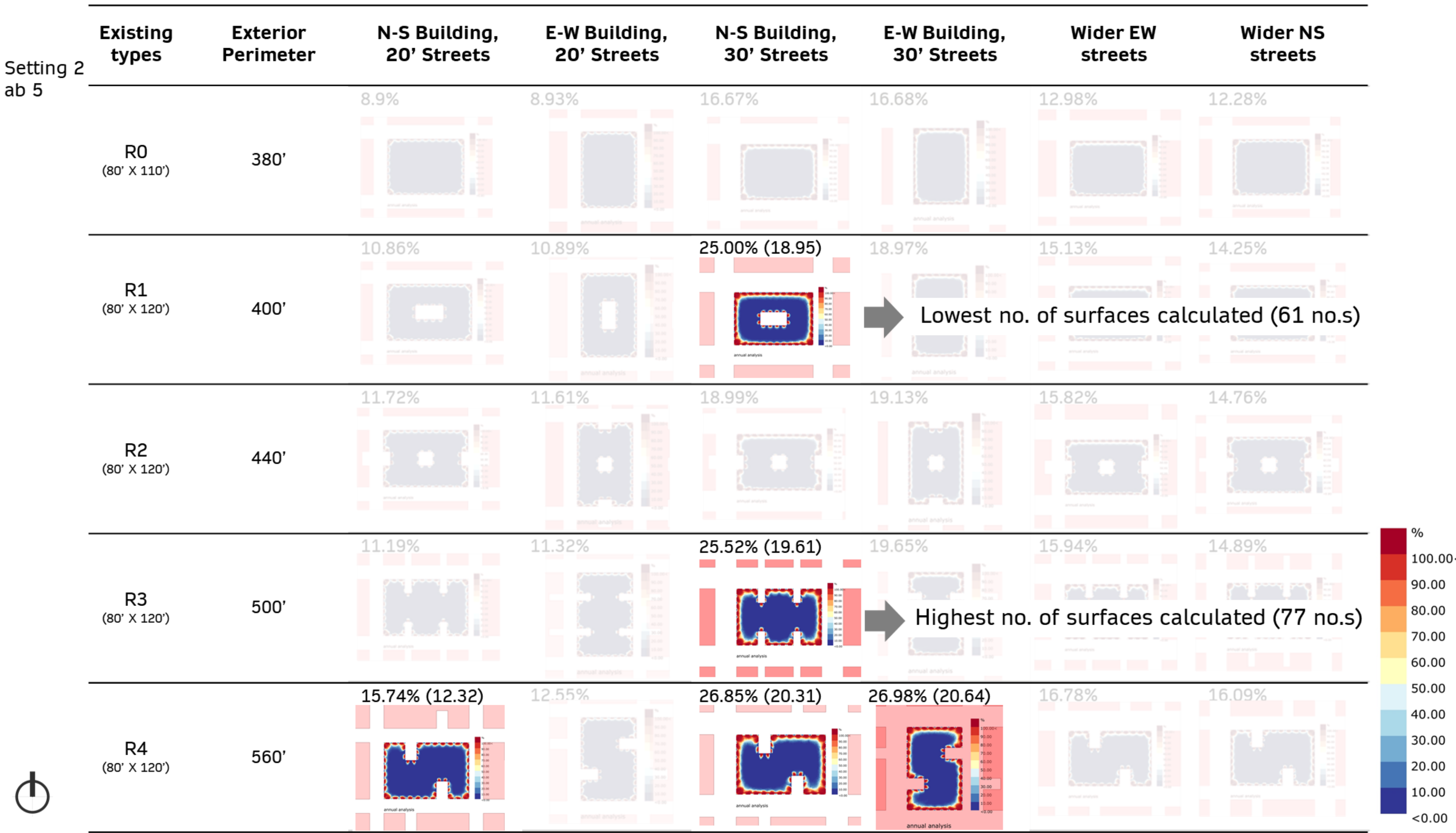


Figure 34: Urban level Daylight Availability Study at floor level 10 – Setting 2 (Author 2020).

6.3 Discussion

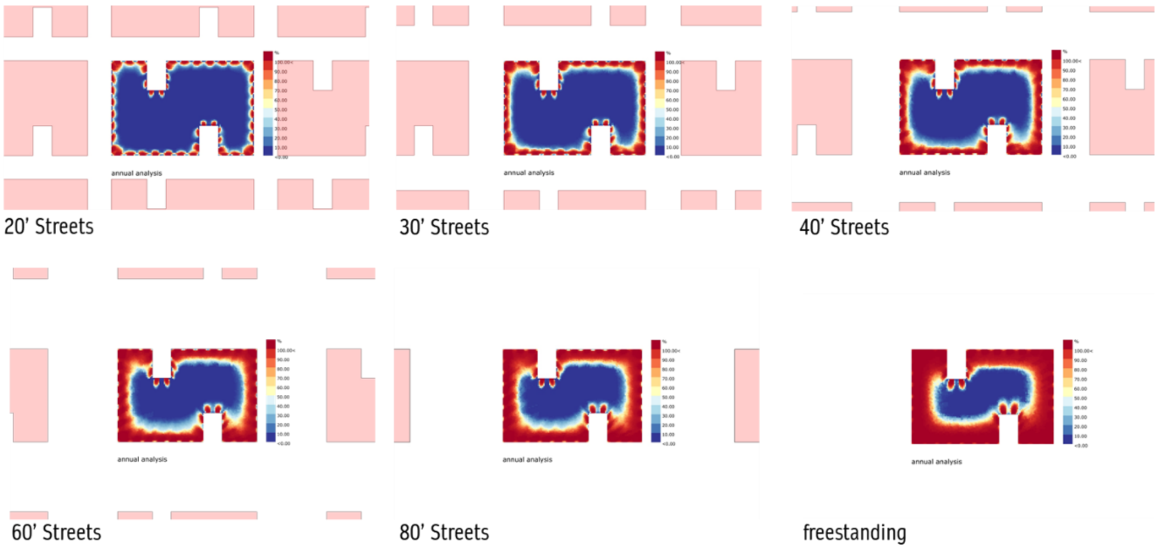


Figure 35: DA graphics showing relation to increasing street widths (Author 2020).

Street Width(m)	sDA (%)
6m (20')	15.74
9m (30')	26.85
12m(40')	35.15
15m(50')	41.57
18m(60')	46.97
24m(80')	54.36
Isolated	67.06

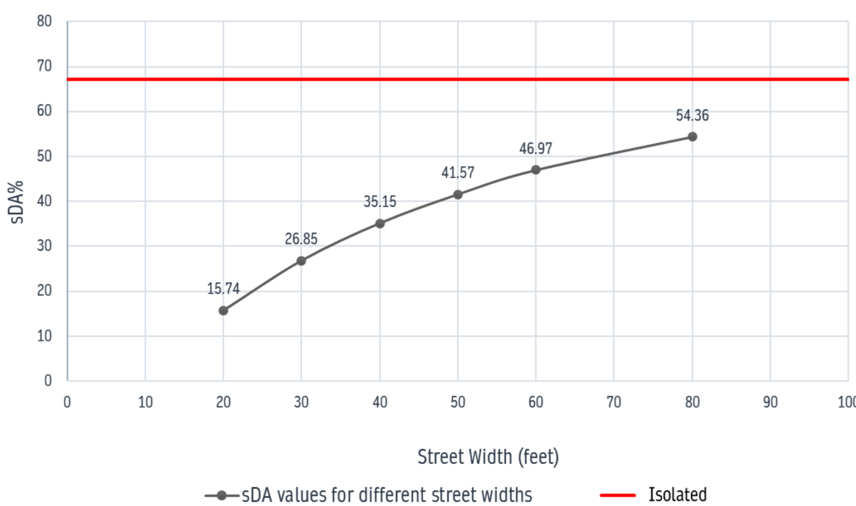


Figure 36: sDA - Street widths graph (Author 2020).

Designing for daylight ingress is a challenging task in Dhaka's existing urban compactness. The investigations in this study indicate that the width of the urban street canyons is a crucial geometric parameter for daylighting in Dhaka's high-rise housing context. The analysis was extended by increasing the street width in hypothetical urban settings for R4 type in a 3X3 grid, as shown in Figure 35. Street widths were varied from 20 ft (6 m) to 80 ft (24 m) (see Table 3.1 for the rationale for these street widths), where sDA gradually increased from 15.7% to 54.4%, graphically presented in Figure 36. The red line in Figure 36 depicts the sDA for an isolated building. This analysis shows that street width needs to be approximately 80 ft to fulfill the LEED V4 criteria for daylighting, which is a limiting factor for the dense urban fabric of Dhaka. A strategy can be explored by prioritizing the location of specific living spaces that most benefit from daylighting, such as along the periphery of the building where the LEED v4 daylight autonomy criteria can be achieved.

It should be noted that considering these findings, it is also crucial to identify a practical threshold for spatial daylight autonomy in residential buildings, particularly in density. LEED v4 recommends that for individual buildings, building-level sDA is above 55%, and the illuminance threshold is 300 lux, which means 55% of commonly occupied spaces have illuminance levels above 300 lux for more than 50% of the occupied hours. On a different note, the recommended level of illuminance for different residential spaces given by several sources, including the IES Lighting Handbook, ranges from 200-500 lux (Reynolds, et al. 2011; DiLaura and IESNA 2011). Dogan et al. (2015) studied different typologies of the floor plan in mid to high-rise buildings in an urban setting and proposed LEED v4 $sDA_{[300lux][50\%]}$ recommendation of 55% to be modified to 45% for regularly occupied spaces (Dogan, Saratsis, and Reinhart 2015). In a similar vein, it can be meaningful to translate the 300lux minimum illuminance level threshold to 200 lux, specifically for residential buildings.

All things considered, the findings from this parametric study elicits the importance of related urban street widths for daylighting design for high-rise development in dense Dhaka. However, attaining existing recommended levels of daylight availability remains a matter of inquiry in such a dense context. Potentially these recommendations can be rethought for a dense urban residential setting, where land is scarce, and tall buildings are ubiquitous. Further investigation may be needed to explore the feasibility of a 40-45% sDA with an illuminance threshold of 200 lux ($sDA_{[200]\,[50\%]}$) in a dense urban context.

Chapter 7

Conclusion

This research aimed to delve into the challenges of daylighting design in compact urban contexts of Dhaka, Bangladesh, focusing on high-rise residential development. The intent was to identify the specific challenges regarding solar access at the building and the urban level. The author intended to find out which building and urban scale geometric parameters affect daylight ingress and accordingly give recommendations for daylighting in new high-rise residential buildings in Dhaka. This research followed a computational methodology to conduct annual daylight availability analyses.

This chapter presents the key findings of this research, the recommendations based on these findings, limitations of the study, and the next steps for further explorations.

7.1 Research Findings

In this thesis, the author started with the premise that specific geometric parameters have an impact on daylight availability in the dense high-rise residential developments in Dhaka. The building forms and urban canyon configurations were primarily identified for investigation concerning daylight autonomy. LEED v4 daylight credit option 1 was the evaluation criteria for this daylighting exploration. The author also proposed a computational framework for the daylight availability analysis based on contemporary research and tools.

The literature review indicated that daylighting design remains a challenge in the urbanization era. Cities are becoming denser with high-rise buildings, which create urban canyons with narrow aspect ratios and thus creating the problem of overshadowing. The situation is much worse in developing countries. In a compact city such as Dhaka, the situation is dire, having an unhealthy and unsustainable built environment. While many researchers showed window design and optimization strategies, to find solutions for similar daylighting challenges, this research focused on building geometry and canyon configuration, which is not well researched in the context of Dhaka. Additionally, various contemporary researchers present the effectiveness of computational analysis with state-of-the-art tools. The author proposed an effective computational workflow for this research based on the validated tools and findings of existing scientific literature.

The daylighting analysis in this research indicates that, in the extreme urban scenarios of Dhaka, the width of urban street canyons has a significant effect on daylight autonomy. For example, a ten feet width increase from a twenty feet street increases the sDA calculations at least 60% from the respective cases with twenty feet streets. In comparison, building shape and form has some, albeit minimal, impact on daylight ingress. For example, up to a 13.5% sDA increase is observed for buildings with external cuts (R4) compared to buildings with internal lightwell (R1). A conclusion can be drawn considering these findings, that it is critical to address the width of the urban canyon while designing for such density. Additionally, the urban street widths adjacent to the longer façades of the high-rise developments are critical for daylighting in the living spaces of residential apartments built in density, along with other factors traditionally addressed in daylighting design. Therefore, the regularly occupied spaces in residential buildings of Dhaka, such as the bedrooms, study areas, and family living areas, should be located along the longer side of the building façade to benefit from daylight.

The building level parametric study shows that the internal lightwells in high-rise residential buildings performed poorly regarding daylight ingress, allowing daylight ingress only on the top 4-5 floors in a 15 storey building, whereas the external cuts are effective for all floors. On the other hand, the case study shows that the external cuts in an urban scenario are effective only for the upper 4-5 floors. Therefore, the urban configuration affects the external cuts, but not on the internal lightwells for high-rise buildings. This is maybe due to the overshadowing form buildings in proximity and the varying direct sun penetration from floor to floor, with more direct sunlight access on the upper floor levels.

Another finding from the parametric study is that the street width needs to be approximately 80 ft to attain the LEED V4 daylight criteria of $sDA_{[300lux]\ [50\%]}$ 55%. The street width is a limiting factor for achieving this LEED v4 criterion in the existing dense urban fabric of Dhaka. Therefore, the location of specific living spaces that most benefit from daylighting can be strategically designed, such as along the periphery of the building where the LEED v4 daylight autonomy criteria can be achieved.

7.2 Recommendations

Considering the research findings, the author provides the recommendations outlined below.

Geometric aspects of urban street canyons, specifically the street width is crucial for daylight ingress in urban contexts like Dhaka. The existing codes for Dhaka city have very limited regulations for daylighting in building design. Planning and building construction rules can consider this aspect to review the existing rules of access road width, setback, FAR, and MGC. The New York City zoning and setback laws can be a reference to review.

A critical argument of this research is that there is a need to modify the existing recommendations for threshold minimum levels and percentages regarding daylight autonomy given by various building guidelines for application in residential buildings in density. IES guidelines have specific illuminance level recommendations for different residential spaces ranging from 200 to 500 lux depending on weighting factors such as occupants age or the type of task carried out in that space. For example, the ambient lighting level in a bedroom can be about 200 lux, whereas a study area might need task lighting of 500 lux. Then the question arises whether the illuminance threshold of 300 lux in LEED v4 is practical for residential buildings. It can be argued that this threshold minimum can be 200 lux considering residential use of the building. Additionally, the LEED criteria for 55% of sDA has been questioned by researchers recently. Dogan et al. (2015) show that a 45% sDA is sufficient and useful for building-level analysis. A recommendation is that a lower threshold for minimum illuminance levels such as 200 lux and lower sDA percentage may be effective in residential daylight autonomy analysis in dense cities.

Another argument is that the proportion of the buildings investigated in this research is problematic because daylight penetration is challenging in deep plan buildings. The study building dimension is 80’X120’, which is a ‘block’ proportion. The plot size and existing building codes primarily dictate the proportions of buildings in Dhaka. These ‘block’ type buildings are more common than linear types in dense residential areas. The author recommends that a linear proportion of the buildings may be more effective in daylighting design, i.e., a building with dimensions 50’X120’.

7.3 Limitations of this research

While this research attained the overarching research aim, it is essential to note several limitations. This research utilizes an efficient computational methodology for complex daylight simulations in a compact urban context. Nevertheless, there is a trade-off between computation time and accuracy. The assumptions made to reduce the computation time of the simulations limits the results to be entirely accurate. The modeled geometry was simplified, excluding interior obstructions, such as dynamic shades, walls, and exterior geometric details, such as shading devices, verandas. Because of the simplified geometry, there is a possibility of overestimation of the daylight availability. Adding shades would have a more significant effect on the building's top floors, where it is more exposed to direct sunlight. However, it can be argued if sDA calculations should include shades in residential applications.

Another limitation is that the model did not eliminate the stair, elevator core, and circulation in the analysis floor level. Because of this simplifying assumption, the sDA calculations may be lower than the actual scenario. LEED v4 specifies $sDA_{[300]\ [50\%]}$ 55% for regularly occupied areas, where the stair, elevator core, and circulation areas are not considered as regularly occupied spaces. Eliminating these areas from the defined model would provide higher sDA calculations.

The author is also aware of the most recent version of LEED v4.1 daylighting criteria, which introduced a new minimum for option 1 that gives 1 point for $sDA_{[300]\,[50\%]}$ value for the regularly occupied floor area of at least 40%. This version has also moved away from sDA calculations for residential buildings.

7.4 Future Research

From the outcomes of this research, the following future research possibilities are proposed by the author:

- This research was conducted on a single case study and a set of building geometries with specific urban layouts. Time constraints did not allow further investigation on different building geometries and urban layouts, which could have led to a comprehensive understanding of parameters regarding daylighting in density. Further investigation is needed to evaluate the building and urban parameters through the analysis of more building geometries and urban layouts in the context of different dense cities.
- The computational framework created for this research has the potential to grow and expand even further with additional simulation parameters to achieve more complexity and precision for more sophisticated daylight analysis. For example, elimination of circulation areas, adding dynamic shades etc. can add more complexity in the modeling environment and precision in

the daylight availability analysis. The effect of the materiality of the context geometry can also be explored.

- A comparative analysis with cities that already incorporated daylighting in zoning laws, such as New York City, can be done to find out whether these rules have meaningful implications on Dhaka's existing urban fabric. This analysis also calls for further research to understand the correlation between FAR rules and sDA calculations. Additionally, research is needed to identify critical indicators in zoning and building construction rules concerning daylight autonomy.
- Further research is needed to understand the implications of building proportion concerning the plot size and area concerning daylight autonomy.
- Further analysis can be done with 200 lux illuminance threshold and attainment of sDA of 40-45% ($sDA_{[200lux]\ [50\%]}$)
- The relation between daylight autonomy, thermal comfort, and energy consumption can be investigated.

Appendix A: Terminology

Annual Sunlight Exposure (aSE): The percentage of the horizontal work plane that exceeds a specified direct sunlight illuminance level (usually over 1000 lux) more than a specified number of hours (usually 250 hours) annually over a specified daily schedule with all operable shading devises retracted ("Illuminating Engineering Society – The Lighting Authority" n.d.).

Autodesk Ecotect: Ecotect is an environmental analysis tool used by designers and researchers to simulate building performance. Autodesk discontinued this tool.

Daylight: The Illuminating Engineering Society (IES) defines daylight as direct sunlight and diffused skylight ("Illuminating Engineering Society – The Lighting Authority" n.d.).

Daylighting: There are many definitions of daylighting based on the building profession or building sectors for which it is being used. Following are the five Sample Definitions for Daylighting, quoted as it is, given by Reinhart C F and Galasiu A in 2006, based on different aspects of daylighting (Reinhart and Galasiu 2006):

1. Architectural definition: The interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment.

2. Lighting Energy Savings definition: The replacement of indoor electric illumination needs by daylight, resulting in reduced annual energy consumption for lighting.

3. Building Energy Consumption definition: The use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting).

4. Load Management definition: Dynamic control of fenestration and lighting to manage and control building peak electric demand and load shape.

5. Cost definition: The use of daylighting strategies to minimize operating costs and maximize output, sales, or productivity.

Daylight Autonomy (DA): Reinhart and Walkenhorst define daylight autonomy as a percentage of annual daylight hours that a specified point in space is above a required minimum illumination level (Reinhart and Walkenhorst 2001). This required minimum level of illuminance is referenced from a published guideline such as the IES handbook and then added to the acronym, for example, DA300lux. It was initially conceptualized by the Association Suisse des Electriciens in 1989 and later developed by Reinhart. In the present day, DA is referred to as a 'dynamic daylight metric.' It is expressed in percentage (%).

Daylight Availability: Daylight availability is the illuminance from sun and sky at a specific location or space that impacts a building exterior on a horizontal, vertical, or other light admitting surface.

Daylight Factor (DF): The daylight factor is defined as the ratio of the internal illuminance at a point in a building to the external horizontal illuminance without shading under an overcast sky standardized by the International Commission on Illumination (CIE) (Christoph F Reinhart, Mardaljevic, and Rogers 2006; Moon and Spencer 1942).

Daysim: It is a validated, Radiance-based daylighting analysis software that models the annual amount of daylight in and around buildings.

DesignBuilder: It is an EnergyPlus based software tool used for building simulations, such as energy, lighting, carbon, and comfort (https://designbuilder.co.uk/).

DIVA: Design Iterate Validate Adapt, a plugin for Rhinoceros-Grasshopper, which runs validated environmental analysis and simulations.

Falsecolor graphic: Falsecolor or pseudocolor refers to a rendering method used to visualize software generated results using a group of colors in an image (Anderson 2014).

Floor Area Ratio (FAR): It is the ratio between the plot/lot area and the sum of the floor areas of building or buildings erected on the plot (BNBC Part 3, Chap. 1 2012).

Geometry: The shape and relative arrangements of a modeled building consisting of planar polygons, surfaces, solids, meshes, etc.

Grasshopper: It is a visual programming language and environment that runs within the Rhinoceros 3D computer-aided design application.

High-rise in the context of Bangladesh: According to Bangladesh National Building Code (BNBC), a high-rise is a building for human occupancy having a height of 20m or more measured from the centerline of the adjacent street level or the lowest level to the highest floor level or the protected openings of highest isolated refuge area of the building that a fire department access vehicle is capable of reaching (BNBC Part 3, Chap. 1 2012).

Honeybee: A plugin for Grasshopper that creates, runs, and visualizes daylight simulations using validated engines such as Radiance and Daysim.

Illuminance: Illuminance is the amount of light received on a unit area of a surface. In other words, it is the density of light or the quantity of light on a surface. The unit of measure is lux.

Insight 360 for Revit: Insight is a design and analysis tool with advanced simulation engines for building performance analysis integrated into Revit developed by Autodesk (https://www.autodesk.com/products/insight/).

Ladybug: It is a plugin for Grasshopper that performs a detailed analysis of climate data to produce customized, interactive visualizations for environmentally informed design.

Luminance: The Intensity of light per unit of projected area reflected, transmitted, or leaving from a surface in a given direction. The unit is cd/m^2.

Maximum Ground Coverage (MGC): MGC is the ratio between the total covered area by the building and the total land area expressed in percentage.

Radiance: A validated lighting simulation, analysis, and visualization tool.

RadianceIES: A 3D tool for daylight prediction simulation and rendering interior lighting prior to construction. (https://www.iesve.com/).

Ray-tracer: A rendering technique for generating an image by tracing the path of light as pixels in an image plane and simulating the effects of its encounters with virtual objects.

Reflectance: The amount of light bouncing off a surface compared to the amount of light hitting the surface.

Rhinoceros: A 3D Modeling software used to create, edit, analyze, document, render, animate, and translate curves, surfaces, and solids, point clouds, and polygons, etc.

Roughness: Roughness is a component of surface texture that is quantified by the deviation of the normal vector of a surface from its ideal form. Large deviations mean the surface is rough, small deviations mean the surface is smooth.

Setback: A minimum distance between the site lines (front, sides, and rear) and the structure or building erected on a site.

Solar Irradiance or Insolation: Solar irradiance is a measurement of solar power per unit area expressed in watts per square meter (W/m^2). It is often integrated over a certain period to report the radiant energy emitted into the environment and expressed as joules per square meter (J/m^2). This integrated solar irradiance is also called solar insolation.

Sky View Factor (SVF): A Sky View Factor (SVF) represents the ratio between the radiation received and emitted by a surface from or to the sky (Oke 1981). An SVF of zero means the entire sky is blocked from view by obstacles. SVFs help in the comprehension of an area's potential direct sunlight exposure in a certain amount of time.

Solar altitude angle: The solar altitude angle is the angle between the sun's rays and the horizontal plane (www.sciencedirect.com/solar-altitude-angle). It relates to the solar azimuth angle and latitude of a specific location. The angle values north of the equator are positive, and those south of the equator are negative (Kalogirou, 2013).

Solar irradiation: Solar irradiation refers to the amount of solar radiation incident on a surface, which is calculated per unit area and expressed in kW/m^2 (John Mardaljevic and Rylatt 2003).

Spatial Daylight Autonomy ($sDA_{[300lux][50\%]}$): It is a measure of what percentage of space receives daylight of illuminance levels exceeding a specified level, typically at least 300 lux, for a certain percentage over an analysis period, e.g., 50% of the annual occupied hours. It is expressed in percentage (%).

Specularity: Specularity or specular reflectance is the ratio of the reflected light to the incident light by a boundary interface. Specular reflection occurs when the incident light is immediately reflected in the medium where it comes from. The visual appearance of specular reflections is called specularity.

Transmittance: Transmittance is defined by the ratio of radiant flux transmitted to the incident radiant flux. It describes the properties of a surface material's effectiveness in transmitting radiant energy.

Typology: In the sense of classification.

Urban Street Canyon: An urban street canyon is a relatively narrow street created by continuously lined up tall buildings along both sides (Nicholson 1975).

Velux Daylight Visualizer: It is a lighting simulation tool for daylight analysis in building developed and distributed by VELUX Group. (https://www.velux.com/)

Vertical Sky Component (VSC): Vertical Sky Component (VSC) denotes the amount of sky visible from a given point expressed as a percentage. The UK Building Research Establishment (BRE) describes VSC as the ratio of the direct sky illuminance at a reference point on the vertical wall, to the simultaneous horizontal illuminance under and unobstructed sky (Littlefair 1991). The Standard CIE Overcast Sky model is used for sky illuminance distribution.

Appendix B: Glossary of Abbreviations

BNBC	Bangladesh National Building Code
BREEAM	Building Research Establishment Environmental Assessment Method, a building sustainability assessment, rating, and certifying system
Brep (Grasshopper)	Boundary Representation of a 3-dimensional object
DA	Daylight Autonomy
DIVA	Design Iterate Validate Adapt
DoE	Department of Energy
FAR	Floor Area Ratio
IES	Illuminating Engineering Society, the lighting authority
LBC	Living Building Challenge, a sustainability standard, and certification system to encourage a regenerative built environment
LEED	Leadership in Energy and Environmental Design, a widely used green building rating system
MGC	Maximum Ground Coverage
sDA	Spatial Daylight Autonomy
TMY	Typical meteorological year
WELL Building Standard	A performance-based system for measuring, certifying, and monitoring features of the built environment that impact human health and wellbeing
WWR	Façade Window-to-wall Ratio

Bibliography

Ahsan, Tahmina. 2016. "High-Rise Residential Buildings in Dhaka, Bangladesh: Strategies for Socially and Environmentally Sustainable Practice," Ph.D. diss., The University of Adelaide.

Ahsan, Tahmina, Soebarto, Veronica, and Williamson, Terence. 2014. "Key predictors of annual electricity use in high-rise residential apartments in Dhaka, Bangladesh." The University of Adelaide.

Ahsanullah, Saiful Islam, and Shannon Van Zandt. 2014. "The Impact of Zoning Regulations on Thermal Comfort in Non-Conditioned Housing in Hot, Humid Climates: Findings from Dhaka, Bangladesh." *Journal of Housing and the Built Environment* 29, no. 4 (November): 677–97. https://doi.org/10.1007/s10901-013-9373-2.

Al-Sallal, Khaled, ed. 2016. *Low Energy Low Carbon Architecture: Recent Advances & Future Directions.* Vol. 12. CRC Press.

Ander, Gregg D. 2003. *Daylighting performance and design*. John Wiley & Sons.

Anderson, Katherine, and Ladan Ghobad. 2018. "Daylighting and Energy Simulation Workflow in Performance-based Building Simulation Tools (C053) (P)." In *2018 Building Performance Analysis Conference and SimBuild*. ASHRAE, 2018.

Anderson, Kjell. 2014. *Design energy simulation for architects: Guide to 3D graphics*. Routledge.

Bainbridge, David, and Ken Haggard. 2011. *Passive solar architecture: heating, cooling, ventilation, daylighting and more using natural flows.* Chelsea green publishing.

Bainbridge, David, and Ken Haggard. 2011. "Natural Lighting." In *Passive solar architecture: heating, cooling, ventilation, daylighting and more using natural flows.* Chelsea green publishing.

Baker, Nick, and Steemers, Koen. 2014. *Daylight Design of Buildings: A Handbook for Architects and Engineers.* Routledge.

Baker, Nick, and Koen Steemers. 2000. *Energy and Environment in Architecture: A Technical Design Guide*. New York: E&FN Spon.

Bangladesh National Building Code, BNBC. 2012. “General Building Requirements, Control, and Regulation.” Part 3, Chap. 1. Dhaka, Bangladesh.

Beck, Hylke E., Niklaus E. Zimmermann, Tim R. McVicar, Noemi Vergopolan, Alexis Berg, and Eric F. Wood. 2018. “Present and Future Köppen-Geiger Climate Classification Maps at 1-Km Resolution.” *Scientific Data* 5, no. 1 (December): 180214. https://doi.org/10.1038/sdata.2018.214.

Boubekri, Mohamed. 2008. *Daylighting, Architecture and Health*. Routledge.

Boubekri, Mohamed. 2008. *Daylighting, Architecture and Health: Building Design Strategies*. 1. ed. Amsterdam: Elsevier / Architectural Press.

Boubekri, Mohamed. 2014. *Daylighting design: planning strategies and best practice solutions*. Birkhäuser. https://doi.org/10.1515/energyo.0106.00002.

Brandi, Ulrike. 2006. *Lighting Design: Principles, Implementation, Case Studies*. München: DE GRUYTER. https://doi.org/10.11129/detail.9783034615693.

Brembilla, E., D.A. Chi, C.J. Hopfe, and J. Mardaljevic. 2019. “Evaluation of Climate-Based Daylighting Techniques for Complex Fenestration and Shading Systems.” *Energy and Buildings* 203 (November): 109454. https://doi.org/10.1016/j.enbuild.2019.109454.

Brown, G. Z. 1985. *Sun, Wind, and Light: Architectural Design Strategies*. New York: Wiley.

Burge, Sherwood, Alan Hedge, Sheena Wilson, Jon Harris Bass, and Alastair Robertson. 1987. "Sick building syndrome: a study of 4373 office workers." *The Annals of Occupational Hygiene* 31, no. 4A: 493-504.

Calcagni, B., and M. Paroncini. 2004. “Daylight Factor Prediction in Atria Building Designs.” *Solar Energy* 76, no. 6: 669–82. https://doi.org/10.1016/j.solener.2004.01.009.

Capra, Fritjof. 2009. "The new facts of life: Connecting the dots on food, health, and the environment." *Public Library Quarterly* 28, no. 3: 242-248.

Cheng, Vicky, Koen Steemers, Marylene Montavon, and Raphaël Compagnon. 2006. “Urban Form, Density and Solar Potential,” Paper presented at *PLEA2006 - The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6-8 September 2006.* https://infoscience.epfl.ch/record/84787/files/PLEA2006_UrbanFormDensityAndSolarPotential.pdf

Compagnon, R. “Solar and Daylight Availability in the Urban Fabric.” *Energy and Buildings* 36, no. 4 (April 2004): 321–28. https://doi.org/10.1016/j.enbuild.2004.01.009.

Costanzo, Vincenzo, Gianpiero Evola, and Luigi Marletta. 2017. “A Review of Daylighting Strategies in Schools: State of the Art and Expected Future Trends.” *Buildings* 7, no. 4 (May 13): 41. https://doi.org/10.3390/buildings7020041.

DeKay, Mark. 2010. “Daylighting and Urban Form: An Urban Fabric of Light.” *Journal of Architectural and Planning Research* (April): 35-56.

Dewan, Ashraf, and Robert Corner, eds. 2014. *Dhaka Megacity*. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-6735-5.

Dewri, L. V., M. M. Amin, M. S. Sen, and R. Faridi. 2012. "A comprehensive study on the real estate sector of Bangladesh." *Real Estate and Housing Association of Bangladesh*: 1-83.

DiLaura, D., Kevin W. Houser, R. G. Mistrick, and R. G. Steffy. 2011. "The lighting handbook 10th edition: reference and application." *Illuminating Engineering Society of North America*: 120.

DiLaura, David L, and Illuminating Engineering Society of North America, IESNA. 2011. *The Lighting Handbook: Reference and Application.* Illuminating Engineering Society of North America.

Dogan, Timur, and Ye Chan Park. 2017. "A new framework for residential daylight performance evaluation." In *Proceedings of the International IBPSA Building Simulation Conference, San Francisco, USA*, pp. 170-178.

Dogan, Timur, Emmanouil Saratsis, and Christoph Reinhart. 2015. "The optimization potential of floor-plan typologies in early design energy modeling." In *Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association, December 7-9, 2015, Hyderabad, India.* International Building Performance Simulation Association (IBPSA). https://dspace.mit.edu/bitstream/handle/1721.1/109221/Reinhart_The%20optimization.pdf?sequence=1&isAllowed=y

Dubois, Catherine, Claude Demers, and Andre Potvin. 2007. "The influence of daylighting on occupants: comfort and diversity of luminous ambiences in architecture." In *Proceedings of the Solar Conference*, vol. 2, p. 720. American Solar Energy Society; American Institute of Architects.

Edmonds, I. R., and P. J. Greenup. 2002. "Daylighting in the tropics." *Solar energy* 73, no. 2: 111-121.

Ellis, Eugenia V., Elizabeth W. Gonzalez, David A. Kratzer, Donald L. McEachron, and Greg Yeutter. 2013. "Auto-tuning daylight with LEDs: sustainable lighting for health and wellbeing." In the *ARCC conference repository*.

Eltaweel, Ahmad, and Yuehong Su. 2017. "Parametric Design and Daylighting: A Literature Review." *Renewable and Sustainable Energy Reviews* 73 (June): 1086–1103. https://doi.org/10.1016/j.rser.2017.02.011.

Eltaweel, Ahmad, and Su Yuehong. 2017. "Using Integrated Parametric Control to Achieve Better Daylighting Uniformity in an Office Room: A Multi-Step Comparison Study." *Energy and Buildings* 152 (October): 137–148. https://doi.org/10.1016/j.enbuild.2017.07.033.

Erlendsson, Örn. 2014. "Daylight Optimization-A Parametric Study of Atrium Design: Early Stage Design Guidelines of Atria for Optimization of Daylight Autonomy."

Farea, Tareq G., Dilshan R. Ossen, and A. Isah. 2012. "Common configuration of light-well in high-rise residential buildings in Kuala Lumpur." *4th International Network for Tropical Architecture (iNTA), National University of Singapore*: 1-8.

Francis, Andrew. 2008. "Right of Lights Ahead!" *Journal of Building Appraisal* 4, no. 1 (March): 5–13. https://doi.org/10.1057/jba.2008.18.

Galasiu, Anca D., and Christoph F. Reinhart. 2008. "Current Daylighting Design Practice: A Survey." *Building Research & Information* 36, no. 2 (March): 159–74. https://doi.org/10.1080/09613210701549748.

Gardner, Carl, and Barry Hannaford. 1993. *Lighting design: an introductory guide for professionals.* Halsted Press.

Ghafur, Shayer. 2011. "imprints of the Changing Doctrines on Housing in Dhaka." *400 Years of Capital Dhaka and Beyond*, no. 3: 153-68.

Gou, Zhonghua, ed. 2020. *Green Building in Developing Countries: Policy, Strategy, and Technology*. Green Energy and Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-24650-1.

Guzowski, Mary. 2018. *Art of Architectural Daylighting: Design and Technology.* London, UK: Laurence King Publishing.

Guzowski, Mary. 2000. *Daylighting for Sustainable Design*. New York: McGraw-Hill.

Hachem, Caroline, Andreas Athienitis, and Paul Fazio. 2011. "Investigation of Solar Potential of Housing Units in Different Neighborhood Designs." *Energy and Buildings* 43, no. 9 (September): 2262–73. https://doi.org/10.1016/j.enbuild.2011.05.008.

Hachem, Caroline, Andreas Athienitis, and Paul Fazio. 2011. "Parametric Investigation of Geometric Form Effects on Solar Potential of Housing Units." *Solar Energy* 85, no. 9 (September): 1864–77. https://doi.org/10.1016/j.solener.2011.04.027.

Heschong, Lisa. 1979. *Thermal Delight in Architecture.* MIT Press.

Hraska, Jozef. 2015. "Chronobiological Aspects of Green Buildings Daylighting." *Renewable Energy* 73 (January): 109–14. https://doi.org/10.1016/j.renene.2014.06.008.

Ibarra, Diego, and Christoph F. Reinhart. 2009. "Daylight factor simulations–how close do simulation beginners 'really' get." In *Building Simulation*, vol. 196, p. 203.

IES Daylight Metrics Committee. 2012. "IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), Daylight Metrics Committee. Approved Method IES LM-83-12." Illuminating Engineering Society of North America.

Islam, Nazrul, and S. Shafi. 2010. "Globalization and Transformation of Dhaka City." In *Accumulation and by Accumulation: Transformative Cities in the New Global Order,* 74-91. New Delhi: Sage.

Islam, Zareen Habiba. 2016. “Changing Housing Scenario of Dhaka and Its Impact on Social Interaction.” *Cities People Places : An International Journal on Urban Environments* 1, no. 2 (April 30): 16. https://doi.org/10.4038/cpp.v1i2.8.

Jacobs, Axel. 2012. "Radiance tutorial.": 32.

Jones, Nathaniel L., and Christoph F. Reinhart. 2017. "Speedup potential of climate-based daylight modeling on GPUs." In *Building Simulation Conference*, pp. 1438-1447.

Kalogirou, Soteris A. 2013. *Solar energy engineering: processes and systems*. Academic Press.

Kitsinelis, Spiros. 2012. *The Right Light: Matching Technologies to Needs and Applications*. 0 ed. CRC Press. https://doi.org/10.1201/b12010.

Konis, Kyle, and Stephen Selkowitz. 2017. *Effective Daylighting with High-Performance Facades*. Green Energy and Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-39463-3.

Kotani, Hisashi, Masaya Narasaki, Ryuji Sato, and Toshio Yamanaka. 2003. “Environmental Assessment of Light Well in High-Rise Apartment Building.” *Building and Environment* 38, no. 2 (February): 283–89. https://doi.org/10.1016/S0360-1323(02)00033-1.

Kotani, Hisashi, Ryuji Satoh, and Toshio Yamanaka. 2003. “Natural Ventilation of Light Well in High-Rise Apartment Building.” *Energy and Buildings* 35, no. 4 (May): 427–34. https://doi.org/10.1016/S0378-7788(02)00166-4.

Lau, S. S. Y., Baharuddin, W. Y. W. Lee, D. K. C., Leung, A. M. Ye, A. Amato, K. W. Chau, and S. K. Wong. 2006. "Reconsidering daylighting design parameters for tall buildings in a densely built city." *Architectural Science Review* 49, no. 3: 285-294.

Mahmud, M. A. 2007. "Management of Growth and Planned Development of Dhaka City: The Necessity of Proper Enforcement of Planning Standards." In *Urbanization in Bangladesh: Patterns, Issues and Approaches to Planning.*, by Sarwar Jahan and K. M. Maniruzzaman, 43-54. Dhaka: Bangladesh Institute of Planners.

Mardaljevic, J, L Heschong, and E Lee. 2009. "Daylight Metrics and Energy Savings." *Lighting Research & Technology* 41, no. 3 (September): 261–83. https://doi.org/10.1177/1477153509339703.

Mardaljevic, John, and Mark Rylatt. 2003. "Irradiation Mapping of Complex Urban Environments: An Image-Based Approach." *Energy and Buildings* 35, no. 1 (January): 27–35. https://doi.org/10.1016/S0378-7788(02)00077-4.

Mayhoub, Ms, and Dj, Carter. 2010. "Towards Hybrid Lighting Systems: A Review." *Lighting Research & Technology* 42, no. 1 (March): 51–71. https://doi.org/10.1177/1477153509103724.

Moon, P., and Domina E. Spencer. 1942. "Transact." *IES (USA)* 37: 707.

Mridha, Abul Mukim Mozammel Haque, and Gary T. Moore. 2011. "The Quality of Life in Dhaka, Bangladesh: Neighborhood Quality as a Major Component of Residential Satisfaction." In *Investigating Quality of Urban Life*, edited by Robert W. Marans and Robert J. Stimson, 45:251–72. Dordrecht: Springer, Netherlands. https://doi.org/10.1007/978-94-007-1742-8_11.

Nancy, Ruck, Ø. Aschehoug, S. Aydinli, J. Christoffersen, G. Courret, I. Edmonds, R. Jakobiak, et al. 2000. *"Daylight in Buildings-A Sourcebook on Daylighting Systems and Components."* Lawrence Berkeley National Laboratory: 9910-47493.

Ng, E. 2001. “A Simplified Daylighting Design Tool for High-Density Urban Residential Buildings.” *Lighting Research & Technology* 33, no. 4 (December): 259–69. https://doi.org/10.1177/136578280103300417.

Oke, Tim R. 1981. "Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations." *Journal of climatology* 1, no. 3: 237-254.

Owen, David. 2009. *Green Metropolis: Why living smaller, living closer, and driving less are the keys to sustainability.* Riverhead Book: New York.

Parveen, Rehnuma. 2016. “Energy Independent Residential Development for Dhaka City, Bangladesh,” Ph.D. diss., The University of Adelaide.

Power, James P. 2018. “Overview of Light and Air Legal Requirements in New York City.” *New York Law Journal* 260, no. 2 (July 3). https://www.law.com/newyorklawjournal/2018/07/02/070318nypower/.

Rajdhani Unnayan Kartripakkha. 1997. *"Dhaka Metropolitan Development Plan (1995 - 2015) Volume-I: Dhaka Structure Plan Rajdhani Unnayan Kartripakkha (RAJUK)."* Dhaka, Bangladesh.

Rajdhani Unnayan Kartripakkha. 2008. *Dhaka Mahanagar Building Construction Rules 2008.* Dhaka, Bangladesh. http://www.rajukdhaka.gov.bd/rajuk/page/web/devcontrol/DhakaImaratNirmanBidhimala-2008.pdf

Rassia, Stamatina Th., and Panos M. Pardalos, eds. 2012. *Sustainable Environmental Design in Architecture*. Vol. 56. Springer Optimization and Its Applications. New York, NY: Springer New York. https://doi.org/10.1007/978-1-4419-0745-5.

Reinhart, Christoph F, and Anca D Galasiu. 2006. "Results of an Online Survey of the Role of Daylighting in Sustainable Design." NRC-IRC Report 3, no. 1.

Reinhart, Christoph F, John Mardaljevic, and Zack Rogers. 2006. “Dynamic Daylight Performance Metrics for Sustainable Building Design” 3, no. 1: 25.

Reinhart, Christoph F, and Oliver Walkenhorst. 2001. “Validation of Dynamic Radiance-Based Daylight Simulations for a Test Office with External Blinds.” *Energy and Buildings* 33, no. 7: 683–97.

Reinhart, Christoph F., and Jan Wienold. 2011. “The Daylighting Dashboard – A Simulation-Based Design Analysis for Daylit Spaces.” *Building and Environment* 46, no. 2 (February): 386–96. https://doi.org/10.1016/j.buildenv.2010.08.001.

Reinhart, Christoph Frank. 2014. *Daylighting Handbook: Fundamentals, Designing with the Sun.* Vol. 1. Building Technology Press.

Reynolds, John S., Alison G Kwok, Walter T Grondzik, and Benjamin Stein. 2011. *Mechanical and Electrical Equipment for Buildings.* Germany: Wiley.

Samalavicius, Almantas. 2011. *Ideas and Structures: Essays in Architectural History*. Wipf and Stock Publishers.

Samuelson, Holly, Sebastian Claussnitzer, Apoorv Goyal, Yujiao Chen, and Alejandra Romo-Castillo. 2016. "Parametric energy simulation in early design: High-rise residential buildings in urban contexts." *Building and Environment* 101: 19-31.

Santamouris, Mat, ed. 2013. *Environmental Design of Urban Buildings: An Integrated Approach.* Routledge.

Saratsis, Emmanouil, Timur Dogan, and Christoph F. Reinhart. 2017. “Simulation-Based Daylighting Analysis Procedure for Developing Urban Zoning Rules.” *Building Research & Information* 45, no. 5 (July 4): 478–91. https://doi.org/10.1080/09613218.2016.1159850.

Shafi, Salma A. 2010. "Implementation of National Building Code." In *Rights Workshop at National Press Club of Dhaka, Bangladesh*.

Shishegar, Nastaran. 2013. "Street Design and Urban Microclimate: Analyzing the Effects of Street Geometry and Orientation on Airflowand Solar Access in Urban Canyons." *Journal of Clean Energy Technologies*, 52–56. https://doi.org/10.7763/JOCET.2013.V1.13.

Steemers, Koen. 2013. "Environmental issues of building design." In *Environmental design of urban buildings*, pp. 70-86. Routledge.

Strømann-Andersen, Jakob, and Peter Andreas Sattrup. 2011. "The urban canyon and building energy use: Urban density versus daylight and passive solar gains." Energy and Buildings 43, no. 8.

Thanachareonkit, A., J. L. Scartezzini, and M. Andersen. 2005. "Comparing Daylighting Performance Assessment of Buildings in Scale Models and Test Modules." *Solar Energy* 79, no. 2 (August): 168–82. https://doi.org/10.1016/j.solener.2005.01.011.

Thomas, Randall, Tim Grainger, B. Gething, and M. Keys. 1999. "Photovoltaics in buildings: a design guide." *Department of Trade and Industry (DTI), UK*: 9-11.

Toutou, Ahmed, Mohamed Fikry, and Waleed Mohamed. 2018. "The Parametric Based Optimization Framework Daylighting and Energy Performance in Residential Buildings in Hot Arid Zone." *Alexandria Engineering Journal* 57, no. 4 (December): 3595–3608. https://doi.org/10.1016/j.aej.2018.04.006.

Tregenza, Peter R., and I. M. Waters. 1983. "Daylight coefficients." *Lighting Research & Technology* 15, no. 2: 65-71.

Tregenza, Peter, and Michael Wilson. 2013. *Daylighting: architecture and lighting design*. Routledge.

United Nations Department of Economic and Social Affairs. 2016. *The World's Cities in 2016*. Statistical Papers - United Nations (Ser. A), Population and Vital Statistics Report. UN. https://doi.org/10.18356/8519891f-en.

Vardoulakis, Sotiris, Bernard E.A Fisher, Koulis Pericleous, and Norbert Gonzalez-Flesca. 2003. "Modeling Air Quality in Street Canyons: A Review." *Atmospheric Environment* 37, no. 2 (January): 155–82. https://doi.org/10.1016/S1352-2310(02)00857-9.

Veitch, Jennifer A., and Shelley L. McColl. 2001. "A critical examination of perceptual and cognitive effects attributed to full-spectrum fluorescent lighting." Ergonomics 44, no. 3: 255-279.

Von Moos, S. 2009. *Le Corbusier: Elements of a Synthesis*. 010 Publishers.

Wahid Sadique, Khandakar Md. 2008. "Financial appraisal for high-rise apartment projects in Dhaka city."

Whitsett, Dason, and Matt Fajkus. 2018. *Architectural Science and the Sun: The poetics and pragmatics of solar design*. Routledge.

Wilcox, Stephen, and William Marion. 2008. "User's Manual for TMY3 data sets."

Wong, Ing Liang. 2017. "A Review of Daylighting Design and Implementation in Buildings." *Renewable and Sustainable Energy Reviews* 74 (July): 959–68. https://doi.org/10.1016/j.rser.2017.03.061.

Wu, Wei, and Edward Ng. 2003. "A Review of the Development of Daylighting in Schools." *Lighting Research and Technology* 35, no. 2 (June 1): 111–25. https://doi.org/10.1191/1477153503li072oa.

Zielinska-Dabkowska, Karolina M. 2018. "Make Lighting Healthier." *Nature* 553, no. 7688 (January 18): 274–76. https://doi.org/10.1038/d41586-018-00568-7

Websites

". JAPAN GARDEN CITY LIMITED ::." Accessed November 1, 2019. https://www.jgclbd.com/abou.html.

"68% of the World Population Projected to Live in Urban Areas by 2050, Says UN | UN DESA | United Nations Department of Economic and Social Affairs." Accessed April 29, 2019. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html.

"Atlas of Urban Expansion - Dhaka." Accessed October 31, 2019. http://www.atlasofurbanexpansion.org/cities/view/Dhaka.

"Building – 2030 Palette." Accessed April 29, 2019. http://2030palette.org/building/.

"CIBSE - SLL Publications." Accessed December 26, 2019. https://cibse.org/society-of-light-and-lighting-sll/lighting-publications.

"Daylighting | WBDG - Whole Building Design Guide." Accessed October 7, 2019. https://www.wbdg.org/resources/daylighting.

"Daylight Modeling | WELL Standard." Accessed October 7, 2019. https://standard.wellcertified.com/light/daylight-modeling.

"DGNB System – Sustainable and Green Building." Accessed December 26, 2019. https://www.dgnb-system.de/en/index.php.

"Dhaka, Bangladesh Weather Averages | Monthly Average High and Low Temperature | Average Precipitation and Rainfall Days | World Weather Online." Accessed October 31, 2019. https://www.worldweatheronline.com/lang/en-us/dhaka-weather-averages/bd.aspx?PageSpeed=noscript.

"Dhaka Population 2019 (Demographics, Maps, Graphs)." Accessed October 31, 2019. http://worldpopulationreview.com/world-cities/dhaka-population/.

"Epwmap." Accessed November 1, 2019. https://www.ladybug.tools/epwmap/.

"Global Liveability Ranking." Accessed December 26, 2019. http://www.eiu.com/topic/liveability.

"Health & Happiness Petal | Living-Future.Org." Accessed October 7, 2019. https://living-future.org/lbc/health-happiness-petal/.

"Health and Wellbeing." Accessed December 26, 2019. https://www.breeam.com/domrefurbmanual/content/05hea/hea00.htm.

"Home." Accessed December 26, 2019. https://www.cen.eu/Pages/default.aspx.

"Illuminating Engineering Society – The Lighting Authority." Accessed December 16, 2019. https://www.ies.org/.

"Koppen Climate Classification | Description, Map, & Chart | Britannica.Com." Accessed October 31, 2019. https://www.britannica.com/science/Koppen-climate-classification.

"LEED Green Building Certification | USGBC." Accessed December 26, 2019. https://new.usgbc.org/leed.

"Light | WELL Standard." Accessed October 7, 2019. https://standard.wellcertified.com/light.

"Living Building Challenge 4.0 Basics | Living-Future.Org." Accessed October 7, 2019. https://living-future.org/lbc/basics4-0/.

"Right To Daylight – Eneref Institute." Accessed May 21, 2019. https://eneref.org/impact/righttodaylight/.

"SETTING RENDERING OPTIONS." Accessed March 1, 2020. https://floyd.lbl.gov/radiance/refer/Notes/rpict_options.html.

"Sustainable by Design:: Sunangle." Accessed March 1, 2020. https://susdesign.com/sunangle/.

"UO SRML: Sun Chart Program." Accessed March 1, 2020. http://solardat.uoregon.edu/SunChartProgram.php.

"Urbanization | United Nations Population Division." Accessed May 19, 2019. https://www.un.org/en/development/desa/population/theme/urbanization/index.asp.

"Weather Data | EnergyPlus." Accessed September 12, 2019. https://energyplus.net/weather.