BIOMIMICRY INSPIRED DESIGN FOR DAYLIGHTING THROUGH ROOF OF MULTIPURPOSE HALL

By

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Dedication

Mashrafe Bin Mortaza
Captain of Bangladesh National Cricket Team
who inspire me to work hard and fight back against any tough situation

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Abstract

In institutional buildings, a multipurpose hall is often the single large interior space that relies majorly on artificial lighting while conducting functions during day time which mostly coincide with daylight hours. Maximum use of daylight in building design is necessary to reduce the energy demand created by artificial lighting during day hours. Studies show that electrical lighting energy use can be reduced by 25-50% with advanced lighting sources, design strategies and controls; and by 75% with the addition of daylighting. Modification of multipurpose hall roof inspired by Biomimicry concept, which is based on the study of nature´s models (designs and processes) as an inspiration to be replicated to solve human problems, could be an effective option for daylighting to ensure energy savings and visual comfort. The aim of this research is to explore the opportunities of creating biomimicry designs of a multipurpose hall roof and analyse the effectiveness of different biomimicry inspired roof configurations to ensure maximum use of daylight ensuring energy savings and visual comfort of users. The 3D models of case multipurpose hall with different biomimicry inspired roof strategy were first generated in the ECOTECT. Next, the decisions were verified with DAYSIM simulation program to ensure the compliance of the decisions with dynamic annual climate-based daylight performance metrics. A roof configuration based on morphodesign approach, (i.e. related with shapes and structures of Dolichopteryx longpipes) was found as most superior biomimicry inspired configuration among the studied options for multipurpose hall in aneducational building located at Chattogram. Further study was conducted with different roof opening angel along with different ceiling to roof depth. Flat platform with a 50° roof opening angel and 900 mm ceiling to roof depth of the biomimetic roof configuration was found as the best biomimetic roof among the studied experimental parametric configurations at the task plane throughout the year for the case multipurpose hall. It is expected that, the findings of this research will inspire architects and designers to adapt the concept of biomimicry in improving design especially for effective daylight distribution in architecture design through the roof.

Keywords

Biomimicry, multipurpose hall, roof configurations, daylighting, simulation.

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List of Abbreviation

AUST	Ahsanullah University of Science and Technology
BMD	Bangladesh Meteorological Department
BNBC	Bangladesh National Building Code
BUET	Bangladesh University of Engineering & Technology
CBDM	Climate-Based Daylight Modelling
CIE	International Commission on illumination
DA	Daylight Autonomy
DDS	Dynamic Daylight Simulation
DF	Daylight Factor
DoA	Department of Architecture
EIA	Environmental Impact Assessment
ERC	External Reflected Component
GrACe	Green Architecture Cell
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
IRC	Internally Reflected Component
ISO	International Organization for Standardization
IUB	Independent University of Bangladesh
PCIU	Port City International University
PUC	Premier University Chattogram
SC	Sky component
SAD	seasonal affective disorder
UDI	Useful Daylight Illuminance
USA	United States of America

1. CHAPTER ONE: INTRODUCTION

Preamble

Statement of the problem

Aim and objectives

Overview of research methodology

Scope and limitations

Structure of the thesis

CHAPTER 1 INTRODUCTION

1.1 Preamble

Architecture is considered as one of the major biomimetic fields demanding to learn from the nature to enhance and improve living environment. Biomimetic approach helps in discovering new techniques and concepts that can enrich the building systems (Debnath, 2014). In terms of design application, biomimicry is often considered as a way of understanding the process of creative thinking and creative problem solving (Looker, 2013), through the mechanism of traducing principles of a living organism function and turning it into a solution of a problem (Volstad and Boks, 2012).

The term „biomimicry‟ first appeared in scientific literature in 1962 and grew in usage particularly amongst material scientists in the 1980s. Some scientists preferred the term „biomimetics‟ or, less frequently, „bionics‟ (Pawlyn, 2011). Vincent (2006) defines it as „the abstraction of good design from nature‟; while for Benyus (1997) it is „the conscious emulation of nature‟s genius‟. It starts with study of figures, propositions, forms and structure. It was not until the end of the 20th century it became possible to adopt natural processes and ecosystems in built environments (Bar-Cohen, 2011). Biomimetic area of research struggles to define the discipline as „mimicking the functional basis of biological forms, processes and systems to produce sustainable solutions‟. In order to ensure a sustainable development, now-a-days many researchers have focused on biomimicry (Yanez, 2014; Volstad and Boks, 2012).

On the other hand, the use of daylight as the principle light source is an integral part of sustainable building design, because daylighting has been recognized as a useful source of energy savings and visual comfort in buildings. Designers often tend to rely on electric lighting due to lack of daylighting provision in the buildings. Multipurpose halls in academic buildings are primarily used for seminars, conferences, debate competitions, workshops, juries, exhibitions and similar functions, where individuals in the room rightfully expects to get clear vision of the event or performance. Preliminary observations show that most of the time multipurpose halls located in different universities of Bangladesh function under artificial means of lighting. This not only fails to provide a stimulating environment for better visual communication but also at the same time creates pressure on the overall energy demand.

Studies have shown that, daylight has a significant impact on human productivity, health and behaviour (Bakke and Nersveen, 2013). In most of the cases, buildings placed in the compact urban context of Bangladesh fail to provide adequate daylighting during daytime into the multipurpose halls. Artificial lighting becomes necessary in these rooms to run events. Without having adequate daylight, usage of artificial lighting for a longer period can cause serious damage to human body and productivity. Strategies for improving luminous environment in multipurpose halls should be established for incorporation in the design process.

This research proposes and analyses concept of biomimicry and biomimicry inspired roof configurations for getting maximum utilization of sun power. Simulation programs (ECOTECT and DAYSIM) were used to analyse different roof strategies by mimicking nature to indicate suggestions for improving daylighting in the multipurpose hall.

1.2 Problem Statement

Construction and the building sector is categorized as one of the most polluting industries in the world, but at the same time it is also considered as one of the opportunities and challenges for the society to become more environmentally friendly through: the minimization of the negative impacts produced; the reduction of carbon emissions; improving energy efficiency; and contributing with the well-being of the population, under the philosophy of sustainability. As a consequence, sustainable construction has seen a rapid and growing interest in the last decade (Pearce et al., 2005). There are many steps to achieve sustainability inside the construction industry, but one of the most important is the application of sustainability principles (Pearce and Ahn, 2012).The application of sustainable concepts in the architectural design results in the reduction of energy consumption and energy demands from users and use less quantity of materials and produce less waste (Pollalis, 2012). One of these impressive sustainable principles is biomimicry. Biomimicry offers enormous potentials and concepts that can improve and develop the architectural systems. Hence biomimicry can be the approach which will guide the technological development in the field of sustainability (Debnath, 2014). Following the ideas around biomimicry, the present research problem is focused on developing passive design strategies in a multipurpose hall of an educational building to aim visual comfort and effective daylighting without needs of artificial lights (or least use of it) during daytime. The research question is how some organisms (animals, plants) manage daylight and sunlight and how the morphological characteristics can be transformed into parametric algorithms, which can generate biomimetic roof configurations to maximise the use of daylight in building design to reduce the energy demand created by artificial lighting during day hours.

1.3 Aim and Objectives

The aim of this research is to explore the opportunities of creating biomimicry designs of a multipurpose hall roof to ensure effective use of daylight to ensure energy savings and visual comfort of users. To achieve this aim following four objectives are developed.

Objective 1: Tounderstand the concept and philosophy of biomimicry to create a passive design that allows effective use of daylight in a tropical zone, i. e. Bangladesh.

Objective 2: To select an appropriate organism to get inspiration to initiate a design concept through biomimicry for daylighting deep planed building/space with single large span roof e.g. multipurpose halls.

Objective 3: Todevelopa feasible biomimicry inspired roof configuration as a passive design technique for daylighting multipurpose halls.

Objective 4: Toidentify an effectiveparametric configuration of the feasible biomimicry inspired roofdesign to ensure standard lighting levels according to the activities of the users in a multipurpose hall.

1.4 Overview of the Research Methodology

This section provides a brief overview of the research methodology for the thesis. A detailed description of the research methodology, used for this research, has been discussed in Chapter 3. Figure 1.1 shows a flow diagram of the research process, which integrates the main research methods: literature review, case study and simulation analysis.

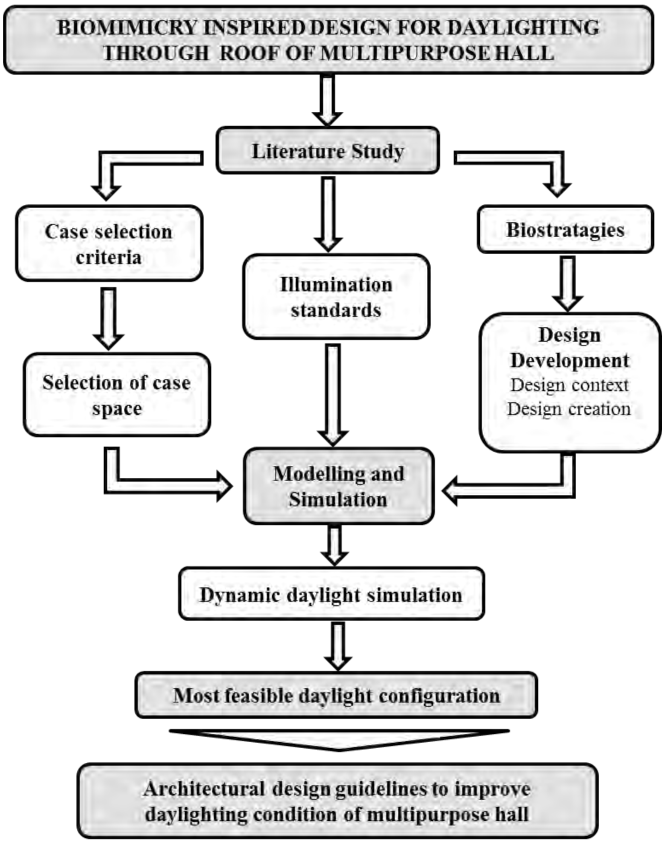


Figure 1.1: Flow diagram of the research process.

The research starts with a literature review to understand Biomimicry concept and study of biomimetic architecture. To create a design from the fundamentals of biomimicry, it is necessary to establish a structure that allows the designer or any researcher to know the concept first in order to apply the principles behind biomimicry. Literature study was also done as a guide consisting of basic steps to follow the bio-strategies, design adaptation process, to know the problem-based research (Section 3.3) under biomimicry concept; and to study the design context, organisms and relevant daylighting strategies, design creation, roof monitor configuration, standards and evaluation criteria for simulation study.

Then the researchfocused on gathering information about how nature manages light (Section 3.4.3). The geographical context (e.g. location and sky conditions), architectural information of case hall (e.g. room size and capacity), requirements (national and international lighting levels regulations), and the construction site information (e.g. hall location, orientation, present lighting condition, work plane height, indoor and outdoor photographs) were collected to understand the nature of expected luminous environment and to develop a digital model in order to run lighting simulations with the help of software (Section 3.5).

Based upon previous researchesand case studies, six roof configurations were evaluated (Section 3.5.5)by mimicking the shape and structure of *Dolichopteryx Longpipes* fish eye (Figure 3.14)for simulation study under the climatic context of Chattogram.Annual dynamic Climate Based Daylight Modeling (CBDM) simulation was done by using ECOTECT- RADIANCE- DAYSIM software.

From the applied methodology, findings were compiled to recommend architectural design guidelines for biomimicry inspired designto improve the daylighting condition of multipurpose hall in tropics.

1.5 Scope and Limitation of the Research

In this research, recommendations and design guidelines are made considering simple modifications ofbiomimetic roof configurationsthat can be applied easily in the context of Bangladesh. This study concentrates on strategies for daylight inclusion in a multipurpose hallto save energy for lighting andensure visual comfort only. In addition lighting is also related with aesthetics, sound transmission, economics, glare control, ventilation, safety, security and subjective concerns of privacy and view of a space. Considering time and resource constraint for the research, the said concerns were kept beyond the scope of this thesis, which may be addressed by further studies.

1.6 Structure of the Thesis

Chapter 1 is an introduction to the thesis; describes subjects that might be necessary for understanding this research, problem statement with the aim, objectives, brief methodology and limitations.

Chapter 2 focuses on the outcome of the literature review, based on established research and published sources, to provide a knowledge base for this research, which helped to focus on the issues on which the simulation is conducted later.

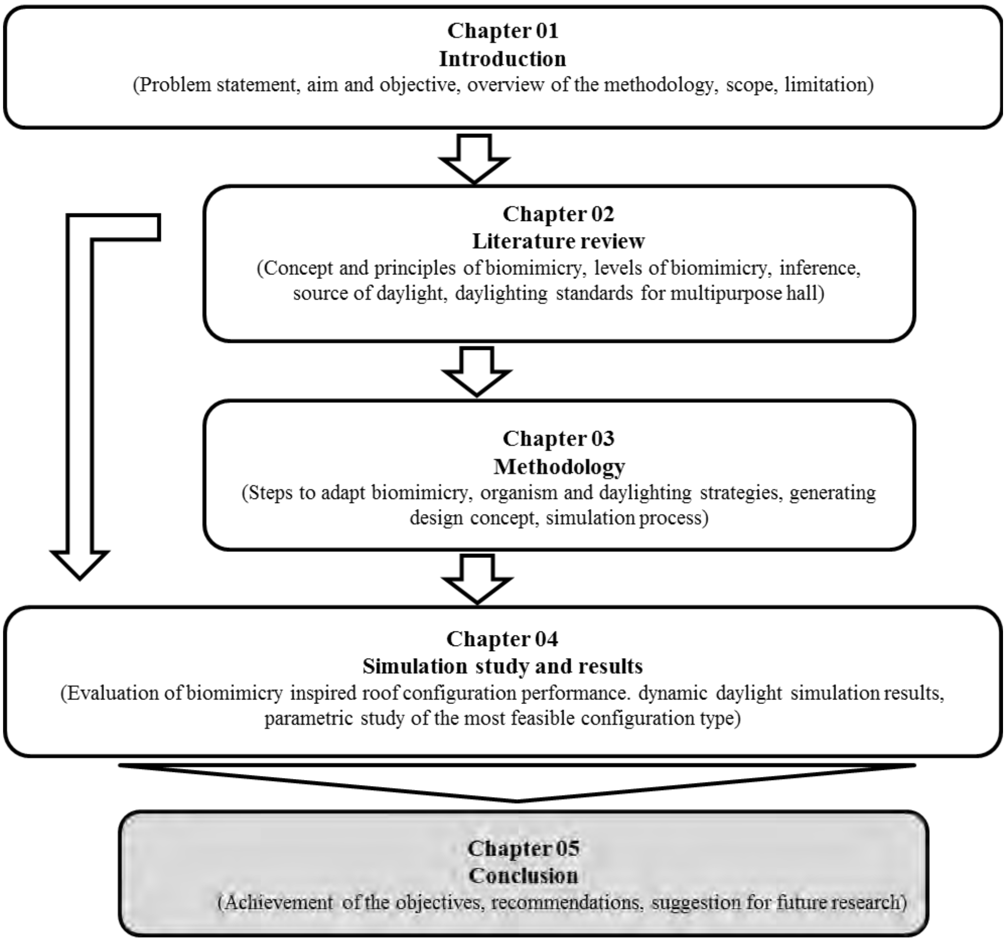


Figure 1.2: Organization of the chapters and structure of the thesis.

Chapter 3 describes the criteria of the selection of the case space and detail steps of the methodology for simulation study for this research. This chapter alsoprovides a general climatic overview of Bangladesh based on published data from different resources, such as thesis, books and papers.

Chapter 4 provides the detail description and output of the simulation exercise. This chapter divided into two major portions. In the first portion Dynamic climate based daylight modelling (CBDM) simulation are conducted to find out the most feasible biomimicry inspired roof configuration for the case hall and the second portion describes the parametric study to propose the best parametric configuration of the feasible biomimetic configuration.

Chapter 5 discusses the biomimetic architecture design strategies for incorporation of useful daylight illumination in multipurpose hall. This chapter also provides some general recommendations along with some directions and guidelines for future research, in the field of biomimetic architecture and daylighting within the context.

1.7 Summary

The research started to overcome some constraints mentioned at Section 1.2. With the gradual development of the research from the literature review and incorporation of research findings at different stages made objectives, methodology and limitations of the research more defined, refined and detailed. Appendix A presents a summary of the key findings of the research in relation to the objectives, methodologies and concerned chapters.

2. CHAPTER TWO: LITERATURE REVIEW

Preamble
Concept and principles of biomimicry
Levels of biomimicry
Inference
Source of daylight
Daylighting standards for multipurpose hall
Critical findings from literature review
Summary

CHAPTER 2 LITERATURE REVIEW

2.1 Preamble

The first chapter of this thesis introduces the research. This chapter discusses the outcome of the literature review to describe basic information required to understand the biomimicry and its process of implementation in architecture along with daylighting standards for multipurpose hall. This chapter mainly consists of six major parts. The first part discusses the concept and principles of biomimicry. The second part discusses on how to adapt biomimicry in architecture. The third part describes the organism and daylighting strategies. The fourth part discusses the daylight as a potential source of lighting. The fifth part highlights on national, international and local illumination standards for multipurpose hall in educational buildings. Finally, the key findings of this chapter have been highlighted. The methodology for simulation studies and field investigation are discussed in the next chapter (Chapter 3), developed with respect to the outcomes of this chapter.

2.2 Concept of Biomimicry

Biomimicry is a relatively new discipline that studies nature‟s finest ideas and then attempts to imitate these designs and processes to solve human problems. It is simple innovation inspired by nature or as Janine Benyus (1997), one of the leading researchers of biomimicry states- Now-a-days it could be said that it is the conscious emulation of life‟s genius on the path to a sustainable future.The core concept is that nature over 3.8 billion years has already used its imaginative prowess to solve many of the problems that society is currently grappling over times. Nature has found what works, what is appropriate, and most importantly what lasts here on Earth (McKosky, 2012).

2.2.1 Principles of Biomimicry

Benyus (1997) encourages people to engage in behaviour that is in harmony with earth processes. To that end, she offers a primer into nature‟s secrets. Indeed, many who have analyzed her work conclude that these secrets are hiding in plain sight and have been so hard to identify because they are so familiar, so obvious (Sue et al.,2013). Benyus (1998) holds that nature has nine basic operating principles that can be used as a beneficial model for human behaviour. She further posits these laws, strategies and principles found to be consistent over generations, and over cultures. More importantly, they can be observed by individuals who are interested in perpetuating a high standard of living in harmony with nature. These life principles reflect the inherent characteristics of ecosystems (Figure 2.1).

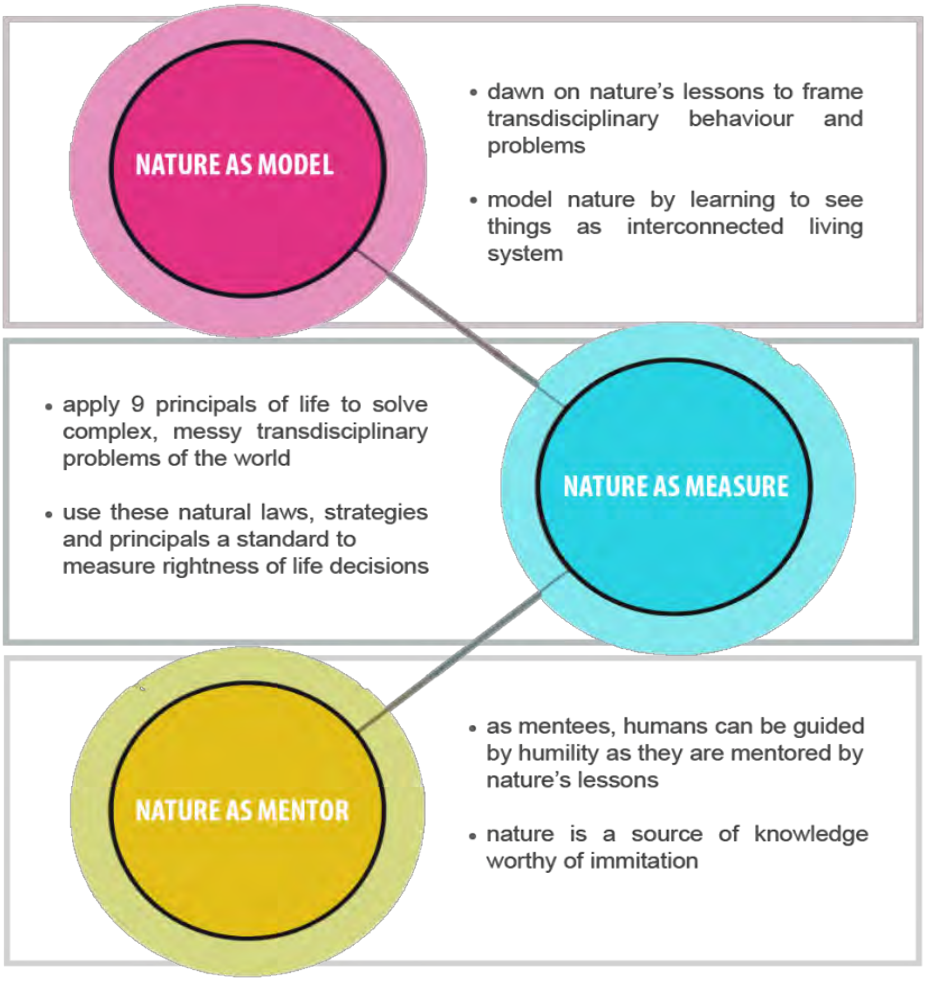


Figure 2.1:Nature as Model, Measure and Mentor (after McGregor, 2013)

In effect, natureruns on the natural sunlight and other “natural sources" of energy, such as wind. Almost all energy comes from sunlight. Nature knows how to gather energy efficiently. Leaves follow the sun and photo synthesis is 95% efficient (plants use the sun to turn light into sugar, the natural food that the plant lives on - and then humans eat the plant). The photosynthetic process also uses water and releases the oxygen that is an absolutely must have to stay alive. Nature does this by using contemporary sunlight rather than heirlooms of sunlight (fossil fuels). Some of the important features are discussed below (Benyus, 1997):

Nature uses only the energy and resources that it needs. Nature draws on the interest rather than the entire natural capital at its disposal. It does not draw-down resources, meaning it does not deplete resources by consuming them unnecessarily. In order to make optimal and maximum use of the limited habitat, each organism finds a niche, using only what it needs to survive and evolve.

Nature always fits form to function, efficiently and elegantly. Nature builds something that works because it was built within the confines of available resources. Also, the shape that something takes depends upon what it is intended to do. Furthermore, nature's designs are organic and only as big as they need to be to fit their function, rather than being linear (squares and blocks) and oversized, with a focus on form. Nature optimizes rather than maximizes. Organisms in nature co-evolve, adapting to the changes of others (i.e., they fit form to function).

Nature recycles and finds uses for everything. In nature everything becomes recyclable; everything has a use. Waste should be valuable because it will be reused again for another purpose. Nature wants waste; it needs it to sustain itself (waste equals food or sustenance). Nature does not generate waste, as such; it does not foul its own nest because it has to live in it. In closed systems, each co-existing element consumes the waste of another as its lifeline. From this perspective, the word waste goes away because waste means to fail to take advantage of something.

Nature rewards cooperation and integration and makes symbiotic relationships work because nature is all about connections between relationships. Nature knows that individuals do not always have to go it alone. In fact, sometimes individuals cannot do it alone. Moreover, nature allows predation and competition to exist through cooperation. Natural ecosystems operate on a symbiotic, complex network of mutually beneficial relationships. Working together is rewarding and necessary.

Nature depends on and develops diversity of possibilities to find the best solution(s) (rather than a one-size-fits-all, homogeneous approach). Nature also depends upon randomness, more so than reason, because randomness creates anomalies that open opportunities for diversity. The randomness of entropy (the breakdown of order) allows for flexibility. A wide variety of plants and animals creates the bank of diversity. The entire habitat is used, not just bits and parts of the system. Also, a system must be as diverse as its environment in order to remain viable. Systems respect regional, cultural and material uniqueness of a place. Systems are flexible, allowing for changes in the needs of people and communities - allowing for emergent diversity.

Nature requires local expertise and resources. Just as nature requires a rich biodiversity to adapt to change and to grow, local ecosystems require a rich range of interlocking resources and the involvement of many local species to create a vibrant natural community. Locals are familiar with the boundaries within which they are living and are familiar with other species who share this space and who have developed their own adaptive expertise. Nature does not need to import from outside. If it is not there, it cannot be used. Natural ecosystems are tied to the local land; hence, sustainability requires reliance on local expertise and indigenous knowledge.

Nature curbs excesses from within and “overbuilding" by curbing excesses from within. Nature has no ego to drive it. It remains in balance with the biosphere, the part of the earth and its atmosphere in which living organisms exist, that is capable of supporting life.

Nature taps into the power of limits and manages not to exceed them. Species flourish within the boundaries that surround them. They do not seek elsewhere for resources, and they use existing materials sparingly. Nature depends upon its constant internal feedback mechanisms for information on how to maintain balance. Nature makes the most efficient use of its surrounding resources. Nature uses limits as a source of power, a focusing mechanism, always conscious of maintaining life-friendly temperatures, harvesting within the carrying capacity of the boundaries and maintaining an energy balance that does not borrow against the future. Otherwise, she would perish at her own hand. Learning to live with finite resources is a source of powerful creativity. Limits create power. This idea is the opposite of seeing limits as a dare to overcome the constraints due to scarcity and to continue expansion. Nature teaches to flourish within boundaries.

2.2.2 Levels of Biomimicry

Through an examination of existing biomimetic technologies it is apparent that there are three levels of mimicry; the organism, behaviour and ecosystem (Ahmar, 2011). The organism level refers to a specific organism,such as a plant or animal and may involve mimicking part of or the whole organism. The second level refers to mimicking behaviour, and may include translating an aspect of how an organism behaves, or relates to a larger context. The third level is the mimicking of whole ecosystems and the common principles that allow them to successfully function. (Zari, 2007).

Within each of these levels, a further five possible dimensions to the mimicry exist. The design may be biomimetic for example in terms of what it looks similar to (form), what it is made out of (material), how it is made (construction), how it works (process) or what it is able to do (function). The differences between each kind of biomimicry are described in Figure 2.2 and Figure 2.3 are exemplified by looking at how different aspects of a termite, or ecosystem a termite is part of could be mimicked(Zari, 2007).

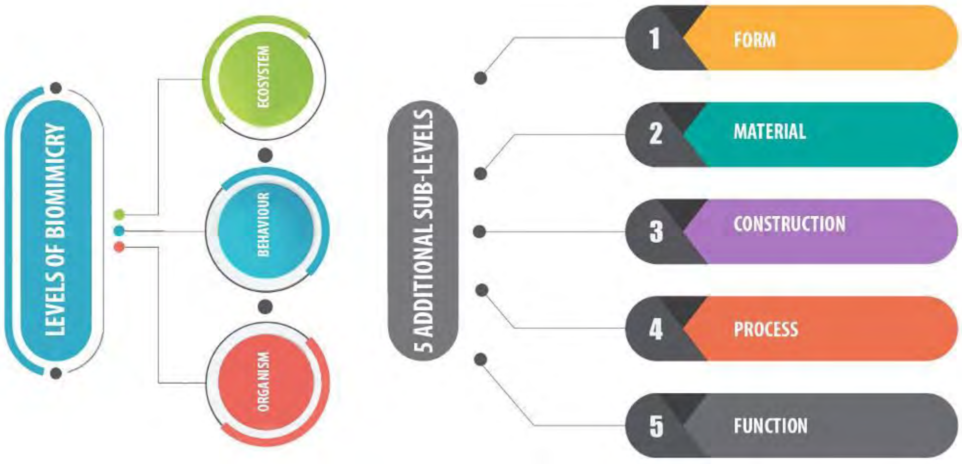
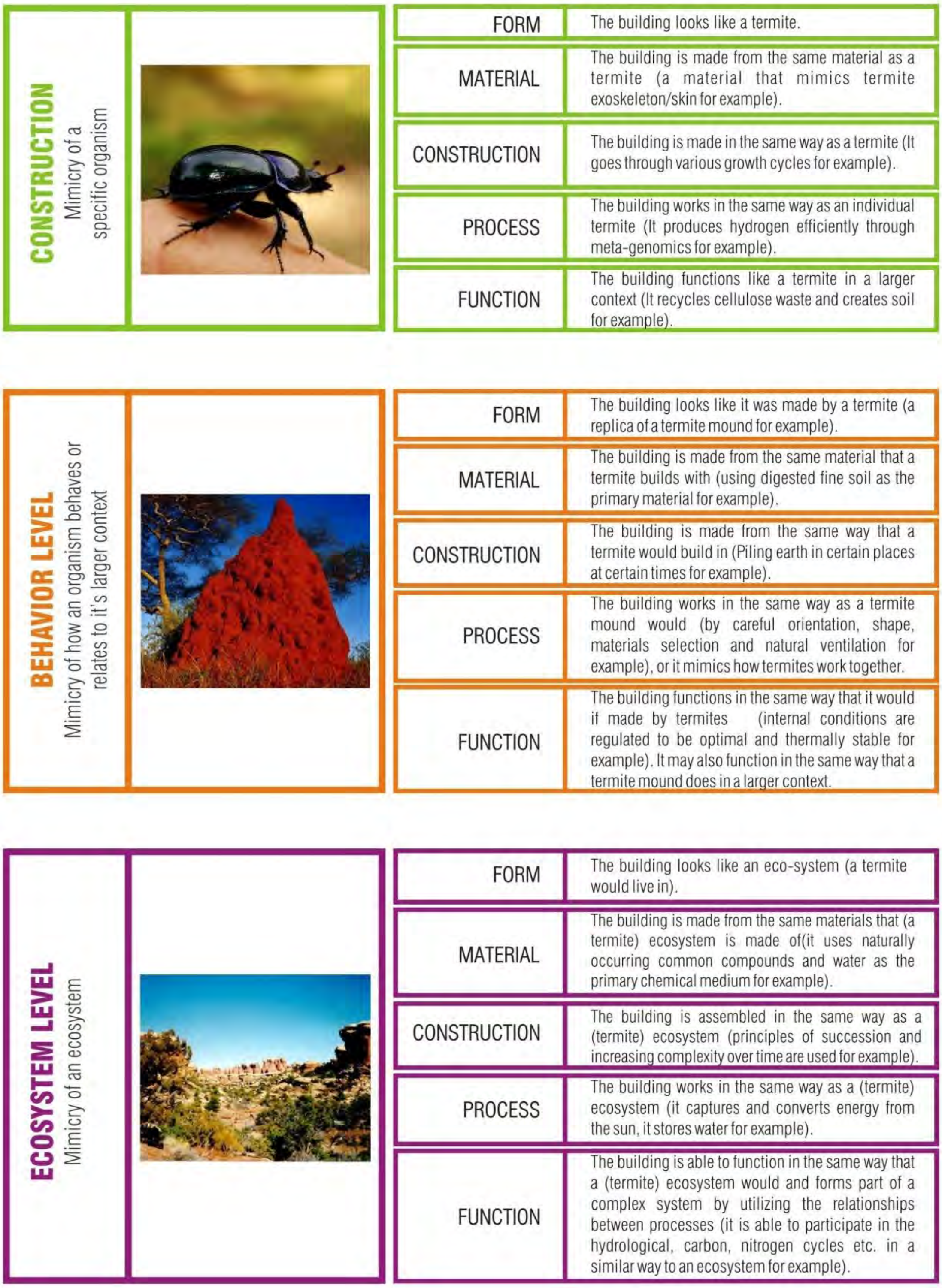


Figure 2.2:Levels of biomimicry (after Ahmer, 2011)



CONSTRUCTION Mimicry of a specific organism		
	FORM	The building looks like a termite.
	MATERIAL	The building is made from the same material as a termite (a material that mimics termite exoskeleton/skin for example).
	CONSTRUCTION	The building is made in the same way as a termite (It goes through various growth cycles for example).
	PROCESS	The building works in the same way as an individual termite (It produces hydrogen efficiently through meta-genomics for example).
	FUNCTION	The building functions like a termite in a larger context (It recycles cellulose waste and creates soil for example).

BEHAVIOR LEVEL Mimicry of how an organism behaves or relates to it's larger context		
	FORM	The building looks like it was made by a termite (a replica of a termite mound for example).
	MATERIAL	The building is made from the same material that a termite builds with (using digested fine soil as the primary material for example).
	CONSTRUCTION	The building is made from the same way that a termite would build in (Piling earth in certain places at certain times for example).
	PROCESS	The building works in the same way as a termite mound would (by careful orientation, shape, materials selection and natural ventilation for example), or it mimics how termites work together.
	FUNCTION	The building functions in the same way that it would if made by termites (internal conditions are regulated to be optimal and thermally stable for example). It may also function in the same way that a termite mound does in a larger context.

ECOSYSTEM LEVEL Mimicry of an ecosystem		
	FORM	The building looks like an eco-system (a termite would live in).
	MATERIAL	The building is made from the same materials that (a termite) ecosystem is made of(it uses naturally occurring common compounds and water as the primary chemical medium for example).
	CONSTRUCTION	The building is assembled in the same way as a (termite) ecosystem (principles of succession and increasing complexity over time are used for example).
	PROCESS	The building works in the same way as a (termite) ecosystem (it captures and converts energy from the sun, it stores water for example).
	FUNCTION	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilizing the relationships between processes (it is able to participate in the hydrological, carbon, nitrogen cycles etc. in a similar way to an ecosystem for example).

Figure 2.3:Levels of biomimicry and application scopes (after Zari, 2007)

It is expected that some overlap between different kinds of biomimicry exists and that each kind of biomimicry is not mutually exclusive. For example, a series of systems that is able to interact, for example an ecosystem would be functioning at the ecosystem level of biomimicry. The individual details of such a system may be based upon a single organism or behaviour mimicry; however, much similar to a biological ecosystem is made up of the complex relationships between multitudes of single organisms (Zari, 2007).

2.3 Inference

It is observed from numerous studies that buildings inspired from plants, organisms and natural forms have different characteristics. Among them some are suitable for solving natural ventilation issues and some are more efficient to solve daylighting problems. Some are potential to solve acoustic and some are only inspiration for the aesthetic value of the buildings (Vaisali, 2011).

2.3.1 Building inspired by plants /flower

Buildings inspired by plants or flowers are usually resistant to imposed forces and good for structural stability. Controlled entry for sunlight can be designed by mimicking plants or flowers. Regulation of internal temperature is another significant character of buildings inspired from plants or flower. It is observed that acoustical solutions are also found by mimicking different plants and flowers. Aesthetically buildings inspired by plants and flowers are always good and unique (Figure 2.4).

Figure 2.4: Plants and flowers (Pawlyn, 2011)

2.3.2 Building inspired by organisms

The characteristics of buildings inspired by organisms are similar to the buildings inspired by plants or flowers. They are also resistant to imposed forces and good for structural stability. Controlled entry for sunlight can be designed by mimicking organisms. Regulation of internal temperature is also another significant character of buildings inspired from organisms. It is observed that acoustical solutions are also found by mimicking different organisms. Aesthetically buildings inspired by organisms are also exceptional (Figure 2.5).

Figure 2.5:Organisms(Pawlyn, 2011)

2.3.3 Building inspired by natural forms

Buildings inspired by natural forms are very effective for channelling of wind. A significant characteristic of these buildings is they can increase thermal mass capacity. Mimicking natural forms are always inspiring to create dynamic forms. Another important role of buildings inspired by natural forms is energy efficiency. Architectural acousticis also a great concern in the buildings inspired by natural forms (Figure 2.6).

Figure 2.6: Natural forms(Pawlyn, 2011)

2.4 Biomimicry for daylight

In building design there are several scopes to apply different levels of biomimicry. It is evident from numerous studies that different bio-strategies and their application in architecture have been tried to solve different architectural issues and those innovative architectural solutions are found environment friendly, energy efficient and aesthetically unique. The introduction of biomimicry for daylighting to the building interior has the potential to enhance the quality of the environment while providing the opportunities to save energy and reduce emission of greenhouse gasses. Such as,

L’institute Du Monte Arabe

Biomimetic application of organism level is L‟institute Du Monte Arabe which is inspired from Iris of eye and constructed with steel, glass and aluminium (Figure 2.7). The facade of this building is cladded with screens with automated lens. It Controls the amount of sunlight entering the building and keeping it cool and flooding room with natural light.

Figure 2.7: L’institute Du Monte Arabe inspired from iris of eye ((Nouvel and Arab World Institute, 2008)

Sinosteel International Plaza

Sinosteel International Plaza inspired from Bee Hive is an example of Organism level of biomimicry (Figure 2.8). This building is constructed with concrete, steel and glass. The windows are designed in five different sizes of hexagon, placed in an energy-efficient configuration regarding natural light. Minimum possible energy used in the form of conventional energy.

Figure 2.8: Sinosteel International Plaza inspired from Bee hive (Vaisali K. 2011)

Habitat 2020

By mimicking stomata of leaves the skin of Habitat 2020 has been designed as living skin and achieved the organism level of biomimicry (Figure 2.9). The exterior designed as living skin which serves connection between exterior and interior, similar to stomata on leaf surface. The surface automatically positions itself according to the sunlight and let it in. These biomimetic design considerations solved many energy efficient issues for example electricity is not required for artificial lightingby using natural light.

Figure 2.9: Habitat 2020 inspired from Stomata of leaves (Anous,2011)

Through the process of applying biomimicry to technical designs, one of the most helpful and powerful tools is the modelling of designs to test them using software, the mathematical algorithms based on physics are the key to determine how biological models can be translated into real applications. For applying biomimicry to daylight modelling, following technical aspect of daylight is needed to be considered.

2.5 Source of daylight

The sun is the source of natural light energy and the path of the sun determines the available sunlight at a particular building location. The solar altitude and the solar azimuth are the two angles through which the sun's position can be defined at a reference point on earth's surface (Figure 2.10). The overcast sky, clear sky, and partly cloudy sky are three light conditions to be considered in daylighting design, according to the IESNA Lighting Handbook (IESNA, 2000).

The light may reach at a workspace via a number of paths (A.G.S. 2000). Direct sunlight is, no doubt, the brightest source. The other sources are the bright overcast sky, which is brighter than the clear blue sky (Ahmed, 1987). Daylight entering through windows under clear conditions illuminates an indoor point from five different sources as the day progresses. These are the sun, the circum-solar sky, the ground, opposite surfaces and the blue sky, with light entering downwards, upwardsand horizontally (Evans, 1980). The available daylight that can replace artificial lighting is both direct sunlight and diffuse light from the sky.

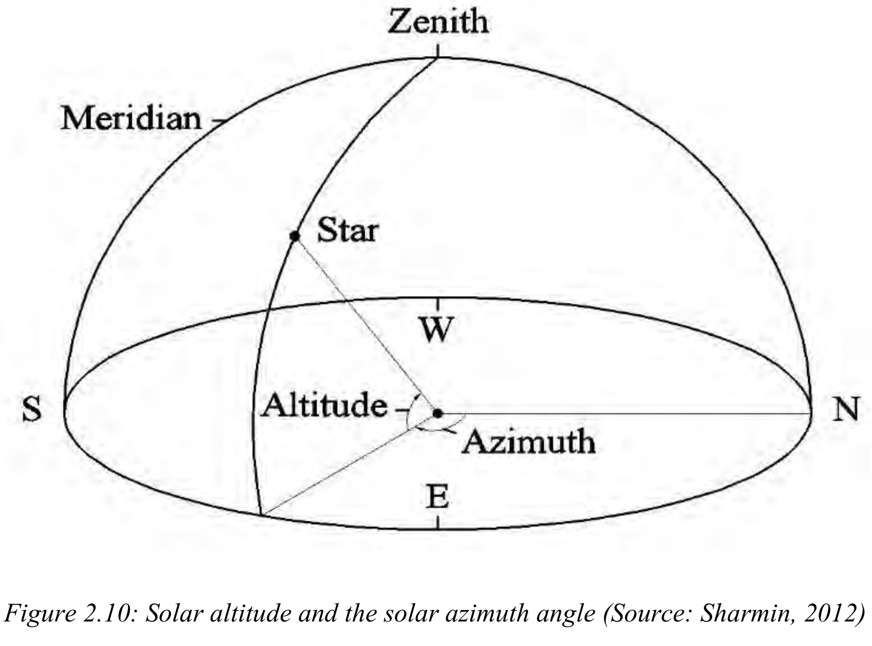


Figure 2.10: Solar altitude and the solar azimuth angle (Source: Sharmin, 2012)

2.6 Components of daylight

Light from the sky reaching a particular point in a room is composed of three distinct components as mentioned below (Figure 2.11).

a. Sky Component

b. Externally reflected component

c. Internally reflected component

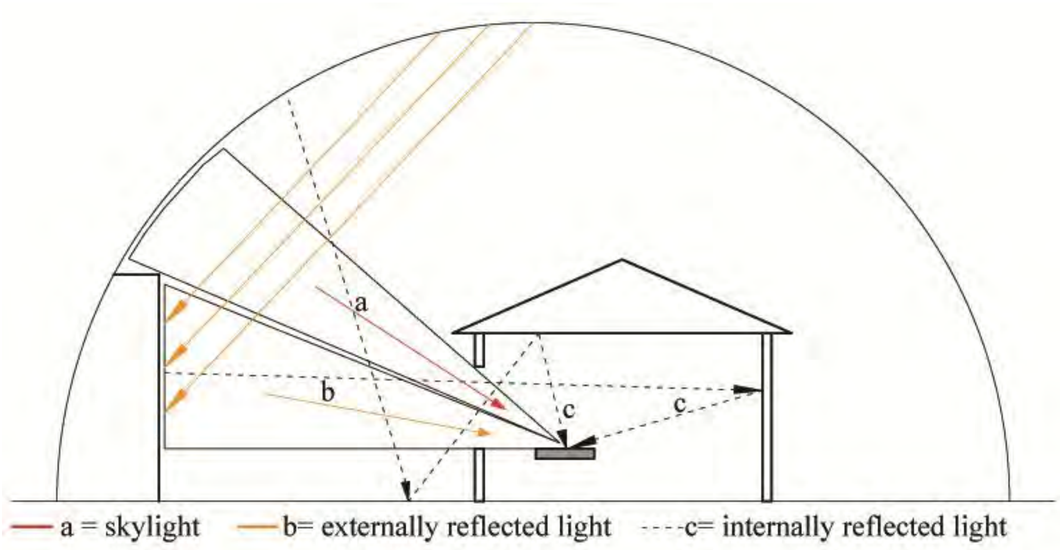


Figure 2.11: The components of daylight at a point in a room. (Source:Koenigsberger, 1975)

2.6.1 Sky Components

Sky component (SC) is the luminance received at a point in the interior of a building, directly from the sky (Figure 2.11). The SC normally refers to the diffuse sky, i.e. it is not used to describe direct sunlight. This component depends upon there being a view of the sky from the point in the room being considered. It is the view of the sky that gets larger as the point considered approaches the window, and thus it is mainly the sky component that leads to the strong variation of light intensity in a side lit room (Joarder, 2007).

2.6.2 Externally reflected Component

The externally reflected component (ERC) is the luminance in the interior due to light reflected from external obstructions (Figure 2.11). The ERC is particularly relevant in dense urban situations, where owing to the closeness of buildings, a view of the sky may be limited or even completely absent for all but positions very close to the window. The ERC will tend to corner from a low angle, close to horizontal. Depending on reflectivity of the obstruction, this may penetrate deeper into the space than the sky component, but because of the absorption of light by the external obstruction it will generally, be much weaker (Joarder, 2007).

2.6.3 Internally Reflected Component

The internal reflected component (IRC) is the luminance received at a point composed of light received indirectly from daylight that is inter-reflected around the internal surfaces of the space. It is obvious from Figure 2.11that any light that is reflected from below the horizontal must be reflected a second time on the ceiling or upper walls of the room, in order to illuminate the horizontal (upward- facing) plane, and will thus end up as the internally reflected component (Joarder, 2007).

2.7 Benefits of daylight

2.7.1 Human performance

The three ways in which lighting conditions affect individual performances are through the visual systems, through the circadian system and through the perceptual system. The circadian system establishes an internal biological rhythm by which humans set a daily cycle of dark-light within the 24-hour diurnal cycle (Ahmed, 2014).

It is said to be the platform from which individuals operate to perform their activities, showing decreased performance during the circadian night in comparison to the circadian day. Research suggests that the sensitivity of the circadian system to light exposure varies significantly over the 24-hour day (Veitch, 2003).Lack of daylight during the day can phase-shift the circadian rhythm, as can excessive electric light during the night (Fontoynont, 2004). The most common disorder due to lack of daylight exposure is called seasonal affective disorder (SAD) (Ahmed, 2014).

There are so many external influences that the impact of lighting alone is hard to isolate, which can be masked by uncontrolled variations in other influences. The reason for preference of windows in spaces is that they provide daylight, sunlight, ventilation, information about the passage of time and weather conditions and about events outside the building (Ahmed, 2014).

Research shows that, daylight is preferred over electric lighting and windows are valued for the space to increase visual and psychological stimulation (Boyce, 2003).

2.7.2 Psychological

Daylight, due to its changing nature throughout the day and in different seasons, has the capacity to create drama in spaces. Depending on the weather, daylight can create low-contrast (during overcast days) or high-contrast environments (during bright sunny days). In offices, those working close to windows are considered more privileged that those who do not have such access. Psychologically, those further away from daylight feel deprived of this right to natural light (Ahmed, 2014).

Working for a long time in architecture design studio needs sufficient daylight penetration in sense of Cortisol, known also as the „stress hormone,‟ is a corticosteroid hormone produced by the adrenal cortex. It follows a diurnal pattern with high values during the day and low values at night (Hollwich, 1979; Scheer, 1999).

2.7.3 Physiological

Light affects individuals‟ bodies in two ways. In the first, light impinges on the retina of human eyes and, through vision system, affects metabolism, endocrine and hormone systems. In the second, it interacts with body skin by way of photosynthesis and produces vitamin D (Boubekri, 2008).

Studies show that, ultra-violet rays have proved to be essential to man and when most of the daylight hours have to be spent indoors, provision must be made to supply the ultra-violet rays indoors (Ahmed, 2014).This can be achieved most economically by providing daylightingand its effects on humans is found to be beneficial, making daylight indispensable for mental and physical well-being. Ultra-violet rays of a certain range can also be the cause for skin cancer, but at the lower latitudes that range is largely screened out from sunlight by the outer atmosphere (Ahmed, 2014).Studies indicate that monotonous lighting, while producing visual efficiency, is often associated with mental fatigue.

A window can convey the changing effects of daylight, every hour of the day, and so provides the inmate mental relief. In recognition of the importance of daylight for human health, in the Netherlands health regulations forbid buildings where staff sit further than 6m away from a window (Muneer, 2000). Vertigo is a common ailment of inmates of buildings without external windows and these occupants soon lose sense of time and weather condition (Ahmed, 2014).

2.7.4 Energy savings

The most obvious vehicle for energy saving in buildings is in exploiting the most abundant source of light available to human - daylight (Philips, 2004). Many building owners and architects have reported energy savings received from daylighting. Looking at the energy consumption of commercial buildings in the United States demonstrates the importance of saving energy.

According to the Commercial Buildings Energy Consumption Survey (CBECS), educational buildings used 649 trillion BTU of total energy, which is 11 percent of total energy consumption for all commercial buildings (EIA, 2003). Much of a school's energy budget is for lighting. This can be greatly reduced with well-designed natural lighting (DQLSL, 2007). A reduction in the energy consumption of a building can be achieved by decreasing the need for, or use of artificial light (Sharmin, 2011).

Reduced peak electricity demand is a major benefit for buildings that experience their greatest load during daylight hours. Cooling loads can also be reduced in buildings occupied during daylight hours, since daylight provides more energy as visible light and less as heat, compared to electrical lighting (Robertson, 2002). In general, lighting consumes about 25%-40% of electricity in any building (Subramanian, 2016). The energy savings from reduced electric lighting through the use of daylighting strategies can directly reduce building cooling energy usage an additional 10 to 20 percent. Consequently, for many institutional and commercial buildings, total energy costs can be reduced by as much as one third through the optimal integration of daylighting strategies (Ander, 1986). Given the current strong dependence on fossil fuels for electricity generation, any reductions in the consumption of electricity for lighting and cooling can ultimately lead to the lower production of greenhouse gas emissions (Sharmin, 2011).

2.7.5 Productivity

The use of natural light in buildings can increase productivity of the occupants of buildings and therefore positively impact on the finances of an organization (Heschong, 2003). The first study on schools was performed in three districts in the USA. The Heschong-Mahone research team (1999) analyzed standardized math and reading test scores of more than 21,000 elementary school students from the three districts of Orange County, CA, Seattle, WA, and Fort Collins, CO for over one year. California students with the most daylighting showed a progress of around 20-26 percent in their test scores over the entire year, while Seattle and Fort Collins students reported an increase of 7-18 percent at the end of the year (HMG, 1999).

Another study based itself on the earlier daylighting and student performance studies conducted by the Heschong-Mahone research team. Using multiple regression analysis, more than 8,000 students from 450 classrooms were analyzed in their academic performance (HMG, 2002). A detailed analysis was also made of the effect of factors such as indoor lighting, windows, views and other room factors on the student performance. Pleasant views from windows were found to affect students positively, whereas glare, direct sun penetration, and negligence to window control and shading were found to affect student performance in a negative manner. The two studies by the Heschong Mahone Group are significant in establishing that daylighting has a direct effect on student performance (Sharmin, 2011).

The study by Dunn et al. (1985) reviewed past research and literature on the effect of lighting on student performance and character and confirmed the fact that good lighting (daylighting and artificial) can contribute immensely to the psychological and physical well-being of a student. Students were shown to achieve better when tested in rooms with the required foot-candles of light, in contrast with their scores in low, dimly lit rooms (Dunn, 1985).

2.8 Environmental benefits of skylighting

As the sky is generally brighter at its zenith under overcast conditions, than near the horizon, horizontal roof lights admit more daylight per square meter of glazed area, than do vertical windows. A horizontal roof light, therefore, is proportionately three times more effective as a source of daylight than a vertical window (AGS, 2000).

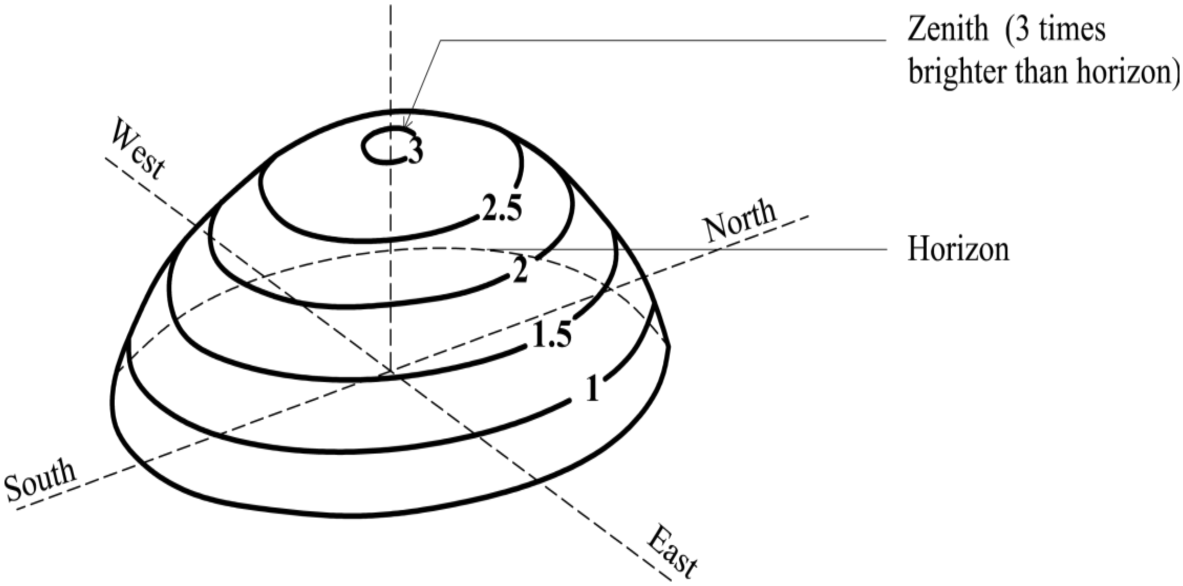


Figure 2.12: Variation of luminance in overcast sky (Egan, 2002).

At 90° the sky is three times brighter than the horizon, at 60° it is about 2.5 times brighter than the horizon, at 45° it is two times brighter than the horizon, and at 30° it is 1.5 times brighter than the horizon (Egan, 2002) (Figure 2.12).In addition, skylights cast daylight over a space in a more uniform way (Figure 2.13), and are less likely to be obstructed either internally or externally.

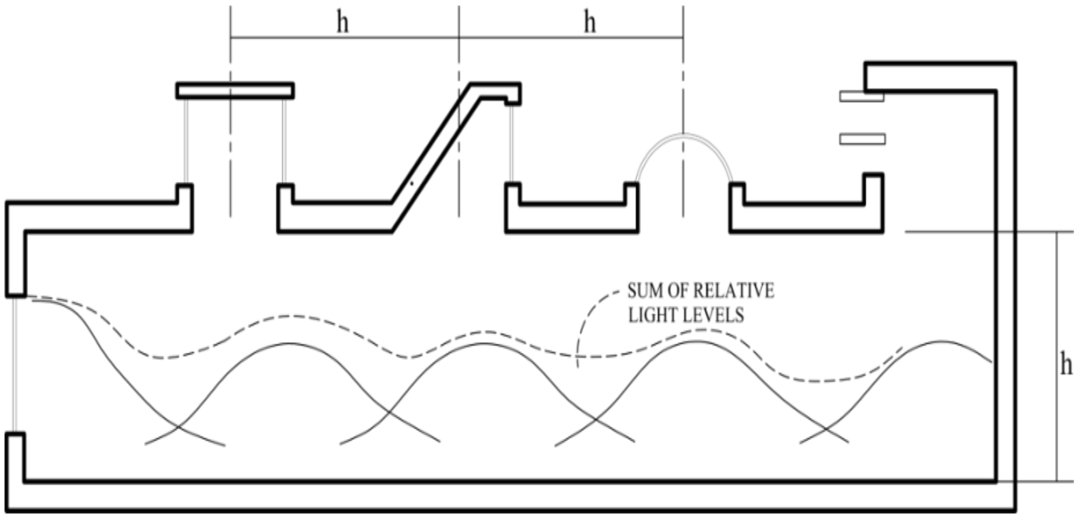


Figure 2.13: Conceptual distribution of daylight through skylights (after, AGS, 2000).

Direct sunlight from horizontal openings can be diffused by translucent glazing, (Figure 2.14) and glare can be controlled by baffle systems (AGS, 2000). A disadvantage of horizontal roof lights is that, compared to vertical windows, they collect more light and heat in summer than in winter – usually the opposite of what is desired, particularly in the tropics.

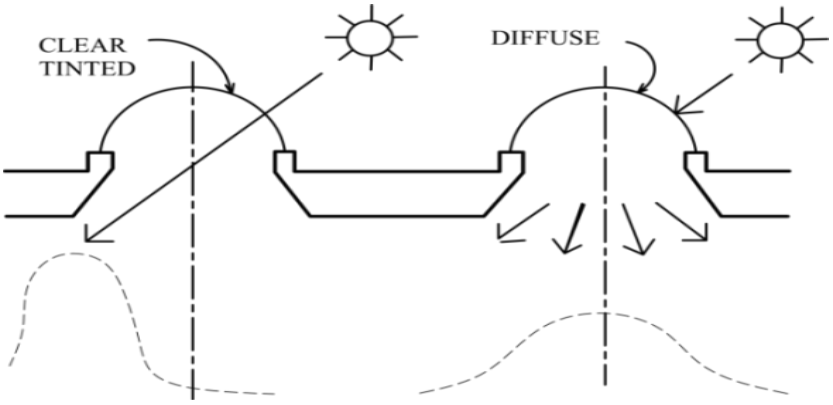


Figure 2.14: Daylight distributions under different skylight materials (AGS, 2000).

2.9 Different aspects of skylight configuration

The factors to be considered when designing the skylight configuration are following (NARM 2009):

(a) Is there sufficient general lighting outside to create a pleasant and suitable for multipurpose internal environment?
(b) Is there a requirement for increased or controlled light levels in specific areas of the building?
(c) Is the relationship between the height of the building and the diffusing quality of the skylights good enough to provide good general light at ground level or work plane level?
(d) Is there sufficient weather ability and minimizing laps, especially between dissimilar materials of the skylight configuration?
(e) Is the skylight glaze area to building floor area ratio sufficient to create suitable working environment round the year without creating glare or overheating?

2.10 Daylighting standards for multipurpose hall

The use of daylight as the principle light source is an integral part of sustainable buildings, because daylighting has been recognized as a useful source of energy savings and visual comfort in buildings (Sharmin, 2011).

In Useful Daylight Index (UDI) concept, the preferable range is from 100 lux-2000 lux. Illumination values outside 2,000 lux range are not useful in horizontal work plane. 2000 lux is the upper threshold, above which daylight is not wanted due to potential glare and/or overheating (Nabil et al., 2005).

Recent studies have shown that, daylight has a significant impact on human productivity, health and behaviour (Bakke and Nersveen, 2013). In most of the cases, buildings placed in the compact urban context of Bangladesh fail to provide adequate daylighting during daytime into the multipurpose halls (Figure 3.6). Artificial lighting becomes necessary in these rooms to run events. Without having adequate daylight, usage of artificial lighting for a longer period can create significant damage to human body and productivity. Strategies for improving luminous environment in multipurpose halls should be established for incorporation in the design process.

The importance of an appropriate visual environment for knowledge sharing tasks deserve careful consideration of appropriate daylighting to develop learners" behaviour, stimulate learning (IESNA, 2000) and thus promote 20% improvement in performance (Jackson, 2006).

The minimum maintained luminance on desks for regular work is recommended as 500 lux (CIE, 2004); however, the lower values are recommended in some countries e.g. India (300 lux), Denmark (300 lux) and Australia (320 lux) (CIE, 2004). Acceptable illumination level, mentioned in IESNA (2000) for space with both computer task and regular paper tasks is 300 lux to 500 lux. According to Bangladesh National Building Code (BNBC, 2006), the recommended illumination level for multipurpose hall in educational buildings in the context of Bangladesh are 150 lux (general) and 300 lux (lecture, examination, platforms and similar functions) respectively.

Buildings in general e.g. office, school and industry use 40% of the total consumed energy for lighting (Lechner, 2001). Bangladesh is a developing country with shortage of energy supply. As most of the educational buildings operate during the daytime and multipurpose hall in educational building is considerably an active place; daylighting can reduce high energy consumption for lighting purpose in educational buildings.

2.11 Critical Findings from Literature Review

In this section, key findings from literature review are briefly presented.

a) Nature, as stated by Janine Benyus (1997) and other researchers, has efficiently and effectively answered different questions of energy demands and usage and biomimicry can aid surreptitiously in solving energy related problems. Biomimicry has three primary levels - construction, behaviour and ecosystem - which further translates to form, function, material construction and process. These levels are not mutually exclusive and can overlap in designs.

b) It is observed from numerous studies that buildings inspired from plants, organisms and natural forms have different characteristics. Buildings inspired by plants, flowers and organisms are usually resistant to imposed forces and good for structural stability. The characteristics of buildings inspired by organisms include controlled entry for sunlight and regulation of internal temperature and can be achieved by mimicking them. Mimicking natural forms can increase thermal mass capacity and are always inspiring to create dynamic forms and achieve energy efficiency. Therefore, for daylighting solutions, mimicking organisms could be the way to follow.

c) The available daylight that can replace artificial lighting is both direct sunlight and diffuse light from the sky.

d) Direct sunlight from horizontal openings can be diffused by translucent glazing, (Figure 2.14) and glare can be controlled by baffle systems (AGS, 2000).

e) The preferred illumination level in the multipurpose hall work plane is 300 lux (BNBC, 2006) and the illumination level on work plane should not exceed 2000 lux (Nabil, et al., 2005).

2.12 Summary

This chapter has achieved the first objective to understanding the concept and philosophy of biomimicry to create a passive design that allows effective use of daylight in a tropical zone i.e. Bangladesh.

By mimicking plants, flowers, organisms or regular behaviour in nature, controlling of internal temperature can be attained. However, most importantly for this research, imitating organisms can result in daylighting solutions as features of buildings inspired by organisms comprise measured access of sunlight.

Within the scope of this thesis, possibilities of evaluating the biomimicry inspired roof configurations, factors influencing daylighting, standard illumination for multipurpose hall in an educational building have been discussed in this chapter, based on previous research and published sources. The findings of the chapter helped to select issues on which steps for the generating biomimetic roof configurations for the case hall and simulation study has been developed in Chapter 3.

3. CHAPTER THREE: METHODOLOGY

Preamble

Steps to adapt biomimicry

Organism and daylighting strategies

Generating design concept

Simulation process

Summary

CHAPTER 3 METHODOLOGY

3.1 Preamble

The first chapter of this thesis introduces the research. Chapter 2 provides the theoretical basis of this research and provides a clear understanding of biomimicry concept, how to adapt biomimicry, importance of daylighting and different national and international standards. This chapter explains the detailed steps of the methodology of biomimicry and simulation exercise done during this research. The performances of the different biomimicry inspired roof configurations with the same glaze/floor area have been evaluated from the point of view of useful daylight inclusion. It is difficult to isolate the effects of one single aspect, and its variations due to simultaneous influences of many different conditions. Simulation allows study of the effect of changes in one aspect, keeping other factors constant. By using advance lighting simulation tool, i.e. DAYSIM, the amount of daylight and its quality can be identified.

The findings of this Chapter aid to evaluate the performance of different roof configurations and experimental parametric exercise. In addition to that, this chapter includes the method of simulation tool selection, case hall selection, and selection of different parameters for the case multipurpose hall. The next chapter will compare the annual simulation results of different skylight configurations in terms of some daylight photometric(e.g. DA, UDI, and DAmax) based on the recommended methodology developed in this chapter.

3.2 Methodology of the research

Two major divisions of the methodology followed during this researchare shown in Figure 3.1. One focuses on the biomimicry process which deals how to adopt biomimicry, detail approaches of biomimicry, concept generation and application of biomimicry. The other step focuses on simulation analysiswhich deals with contextual analysis, generating 3D model, simulation data collection through software, data analysis and parametric studies.

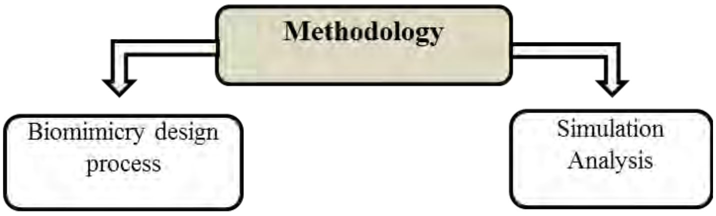


Figure 3.1: Two major divisions of the methodology.

3.3 Steps to adopt Biomimicry

The Biomimicry Institute (founded by Janine Benyus, 2006) created a Design Spiral methodology to help designers to adopt and practice biomimicry. The spiral process begins identifying a problem that has to be resolved rather than asking what to design, or what to come up with. Researchers also have to be concerned with who is involved with the problem, who will be involved in the solution, its consequences, where is the problem and where the solution will be applied. The second phase is interpreting the question so it can be approached from nature's perspectivei.e. what would nature do or not do here. This reframing of the question will yield additional key words and will involve placing the issue in broader contexts and conditions so as to better interpret life's principles into problem solving parameters. It is needed to know the climate, social, temporal and other conditions of the problem. The Biomimicry Institute refers to this as biologizing the question. Third phase is to discover for champions in nature, to observe what is available to answer or resolve the challenge already identified. In order to answer the question of what naturewould do here, the approach may be interpreted literally or figuratively. The former entails literally going outside and observing nature to find examples of organisms that offer insights. The insightful organisms are often those aspects of nature that appear unfazed by their situation, despite its challenges (e.g., tree, stream, field, an ant's nest) and may often be on the extremes of the habitat which is being observed. After scouring the literature and brainstorm solutions these third-phase strategies will move to the fourth phase, where one can discover and report repeating patterns and processes that nature has used to achieve success and chronicle these discoveries and create taxonomy of nature's genius, her life's strategies, selecting those most relevant to the problem or challenge. The next step is to develop ideas and solutions based on nature's models and apply these solutions to the problem; that emulate nature. The solutions will apply the lessons which are learned from nature, mentor and teacher (Figure 3.2).

Whatever the strategy, such as mimic a form from nature, one of nature's functions or a natural process (e.g., an ecosystem) it is important to settle upon, endeavour to apply the lesson(s) as deeply as possible. Ensuring this depth will entail resorting back to the discovery phase so one can find more patterns and processes that repeat in nature, indicating they have worked in the past to ensure survival and evolution. Final phase is evaluate how well the ideas and solutions (i.e., designed to address the challenge or problem) reflect the successful principles of nature. Future work can build upon the research here and can be developed into a project through this final step.

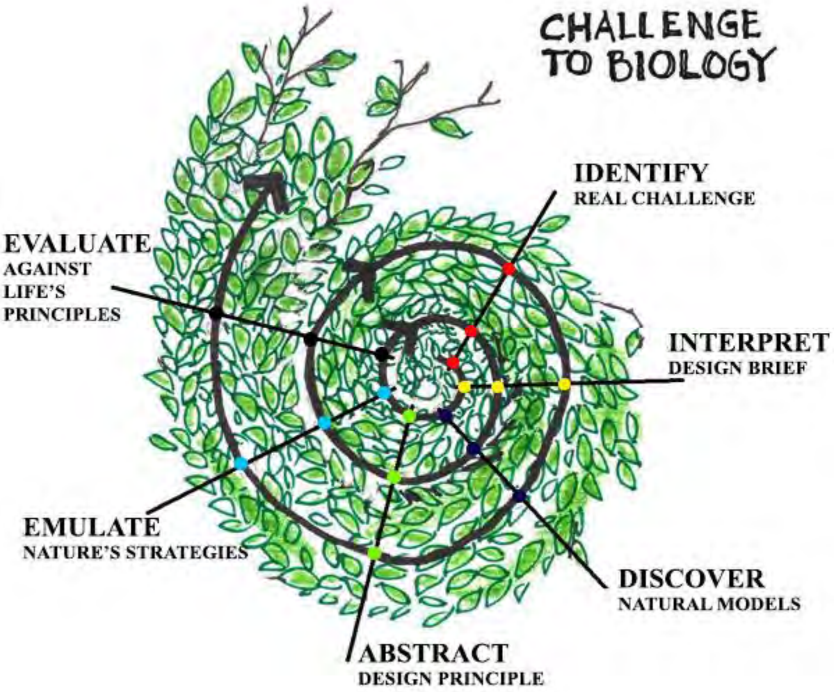


Figure 3.2: Biomimicry Institute's Design Spiral methodology (Source: after, Yowell, 2011)

From many examples, there are two main approaches in biomimicry: solution based approach; and problem based approach. The main difference is the point of view The first one considers a mechanism discovered that has to be adapted as a solution being potentially useful for different applications and the otherone is considered as a classic research where a solution is needed to fix a specific problem (Badarnah and Kadri, 2014).

3.3.1 Solution based approach

When biological knowledge influences human design, the collaborative design process is initially dependent on people having knowledge of relevant biological or ecological research rather than on determined human design problems. A popular example is the scientific analysis of the lotus flower emerging clean from swampy waters, which led to many design innovations as detailed by Baumeister (2007a), including Sto"s Lotusan paint which enables buildings to be self-cleaning. Lotus flowers have microscopic bumps and hairs on the waxy leaves which allow them to trap water as it rains. As the raindrops roll off the leaves due to gravity, they take all the dirt with them leaving the flower clean. The lotus paint creates microstructures on the facade of the buildings in a way that is similar to the microstructures on lotus leaves in addition to keeping the buildings cleaner. Lotusan paint also reduces the build-up of algae and mold. As a result, maintenance costs are lower and facades have to be repainted less frequently (Tandon G.H. 2016)

Figure 3.3:Lotus inspired Lotusan Paint (Source: Zari, 2007).

An advantage of this approach therefore is that biology may influence humans in ways that might be outside a predetermined design problem, resulting in previously unthought-of technologies or systems or even approaches to design solutions. The potential for true shifts in the way humans design and what is focused on as a solution to a problem, exists with such an approach to biomimetic design (Vincent, 2005).

A disadvantage from a design point of view with this approach is that biological research must be conducted and then identified as relevant to a design context. Biologists and ecologists must therefore be able to recognize the potential of their research in the creation of novel applications.

Research held in Georgia Institute of Technology by Michael Helms, Swaroop S. Vattam and Ashok K. Goel, at the Design Intelligence Lab in 2006, also defined this approach through 7 definite steps:

- Step 1: biological solution identification
- Step 2: define the biological solution
- Step 3: principle extraction
- Step 4: reframe the solution
- Step 5: problem search
- Step 6: problem definition
- Step 7: principle application

3.3.2 Problem based approach

In this approach, designers look to the living world for solutions and are required to identify problems and biologists then need to match these to organisms that have solved similar issues. This approach is effectively led by designers identifying initial goals and parameters for the design.

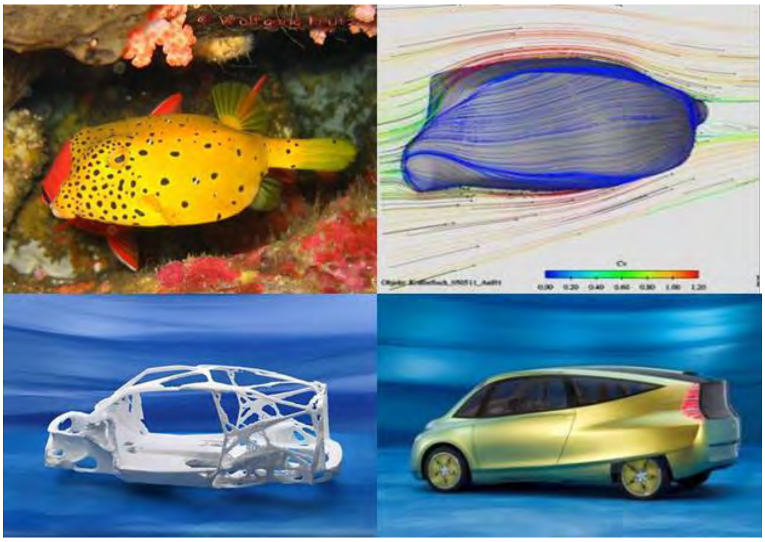


Figure 3.4: DaimleCrysler bionic car inspired by the box fish and tree growth patterns (Source: Zari, 2007)

The pattern of problem-driven biologically inspired design follows a progression of steps which, in practice, is non-linear and dynamic in the sense that output from later stages frequently influences previous stages, providing iterative feedback and refinement loops (Helms et al., 2009)

An example of such an approach is DaimlerChrysler„s prototype Bionic Car (Figure 3.4). In order to create a large volume, small wheel base car, the design for the car was based on the boxfish (ostracion meleagris), a surprisingly aerodynamic fish given its shape similar to a box. The chassis and structure of the car are also biomimetic inspired by the growth of trees, having been designed using a computer modelling method based upon how trees are able to grow in a way that minimizes stress concentrations. The resulting structure looks almost skeletal, as material is allocated only to the places where it is most needed (Vincent, 2006).

The possible implications of architectural design where biological analogues are matched with human identified design problems are that the fundamental approach to solving a given problem and the issue of how buildings relate to each other and the ecosystems they are part of is not examined (Ahmar, 2011). The underlying causes of a non-sustainable or even degenerative built environment are not therefore necessarily addressed with such an approach.

The Bionic Car illustrates the point. It is more efficient in terms of fuel use because the body is more aerodynamic due to the mimicking of the box fish. It is also more material-efficient due to the mimicking of tree growth patterns to identify the minimum amount of material needed in the structure of the car. The car itself is however is not a new approach to transport. Instead, small improvements have been made to existing technology without a re-examination of the idea of the car itself as an answer to personal transport (Zari, 2007).

Designers are able to research potential biomimetic solutions without an in-depth scientific understanding or even collaboration with a biologist or ecologist if they are able to observe organisms or ecosystems or are able to access available biological research. With a limited scientific understanding, translation of such biological knowledge to a human design setting has the potential to remain at a shallow level. It is, for example, easy to mimic forms and certain mechanical aspects of organisms but difficult to mimic other aspects such as chemical processes without scientific collaboration (Zari, 2007). Despite these disadvantages, such an approach might be a way to begin transitioning the built environment from an unsustainable to efficient and effective paradigm (McDonough, 2002). The Biomimicry Institute has referred to this design approach and explained it through the ―Challenge to Biology Design Spiral as illustrated in Figure 3.2.

Research held in Georgia Institute of Technology by Helms et al. (2009) at the Design Intelligence Lab in 2006, also defined this approach through six definite steps, which are very similar to those defined by the Biomimicry Institute as following (Helms et al. 2009).

- Step 1: problem definition
- Step 2: reframe the problem
- Step 3: biological solution search
- Step 4: define the biological solution
- Step 5: principle extraction
- Step 6: principle application

3.4 Steps of biomimicry process

Based on Helms et al. (2009) flow diagram of the biomimicry process of this research is shown in Figure 3.5.

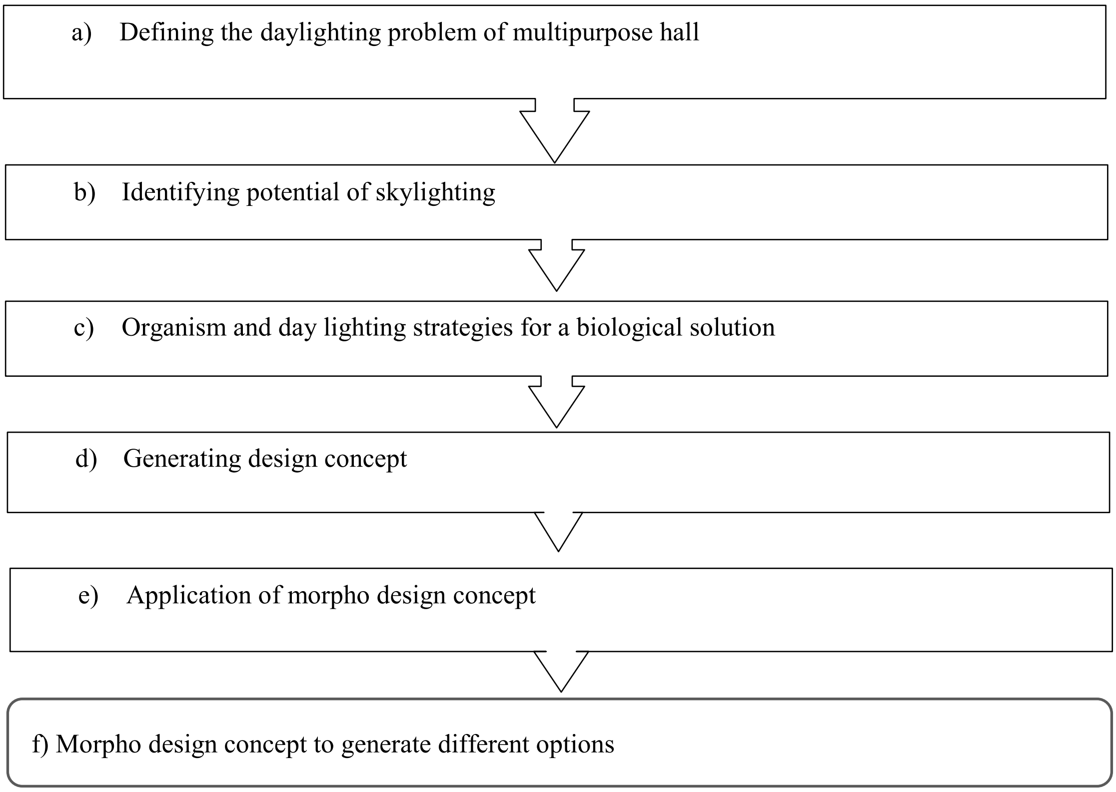


Figure 3.5: Flow diagram of the biomimicry process of the research (after, Helms et al., 2009)

3.4.1 ***Daylighting problem of multipurpose Hall in Educational Building of Bangladesh.***

Bangladesh is a developing country with shortage of energy supply. Artificial lighting consumes a great amount of total energy supply in this country. But during field survey in several multipurpose halls in Bangladesh it is found that most of them are artificially lighted during the day hours (Figure 3.6). In academic buildings multipurpose halls are used to arrange several events e.g. seminars, conferences, debate competitions, cultural programs, workshops, juries, exhibitions and similar functions. Some events, for example cultural programs may need the artificial lighting for special effect or dramatic glamor but most of the events demand simple visual clarity where individuals in the room rightfully expects to get the clear vision of the event or performance. As most of the educational buildings operate during the daytime and multipurpose hall in educational building is always an active place; therefore, daylighting can reduce high energy consumption for lighting purpose in educational buildings.

Figure 3.6: Multipurpose halls at different private Universities in Bangladesh.

3.4.2 ***Identifying Potential of skylighting***

The multipurpose halls that are usually located on the top floor of a building, to get large column free space, are highly potential for daylighting through roof. Skylights are light transmitting fenestration (elements filling building envelope openings) forming entire or a portion of the roof of a building's space for daylighting purposes (Figure 2.13). In the case of single-story building or that of the top floor of multi-stored buildings, the whole floor area can receive daylight from the roof.

The amount of light skylights can provide depends directly on how much daylight is available outside, which varies with climatic conditions, the time of day, and the season of the year. On bright, sunny days, the maximum amount of daylight is available. On very dark, rainy days there is comparatively less light available. In the winter, days are short, and the number of daylight hours may be eight hours or less. In the summer, days are long and daylight may last for 16 hours or more per day. Since light sources in sky-lighting are the sun and the sky, it is important to understand the different quantities and qualities of daylight available from each source and how they vary with diurnal and seasonal changes that depend on the climate of an area. The specifics of the local climate will affect the optimum design of skylights for that area.

3.4.3 *Organisms and daylighting strategies*

Animals have the capacity to sense other range of wavelengths different than humans due to their own evolutionary process that usually responds with the environment. Besides, the interaction with light is not limited to the visual capacity; other functions include being noticed by other organisms for protection or mating, obtaining energy (photosynthesis) or stimulating heat circulation. In the following sections some examples are presented where problem based approach and solution based approach of biomimicry design are applicable by using the potential of sunlight (or daylight) in the architectural design process.

a) Butterfly colors

The diversity of colours in butterfly wings are produced by nanostructures that scatter and refract certain type of wavelengths giving as a result different colours, the laminar structures present cavities that are repeated periodically as seen in Figure 3.7 (Potyrailo et al., 2005). A specific example is the cover scales on the Morpho butterfly wings that produce a selective pattern to refract blue colour acting as an optical diffuser; in some species two types of scales, cover and ground, interact to produce the shiny blue characteristic on the Morpho family (Yoshioka and Kinoshita, 2004)

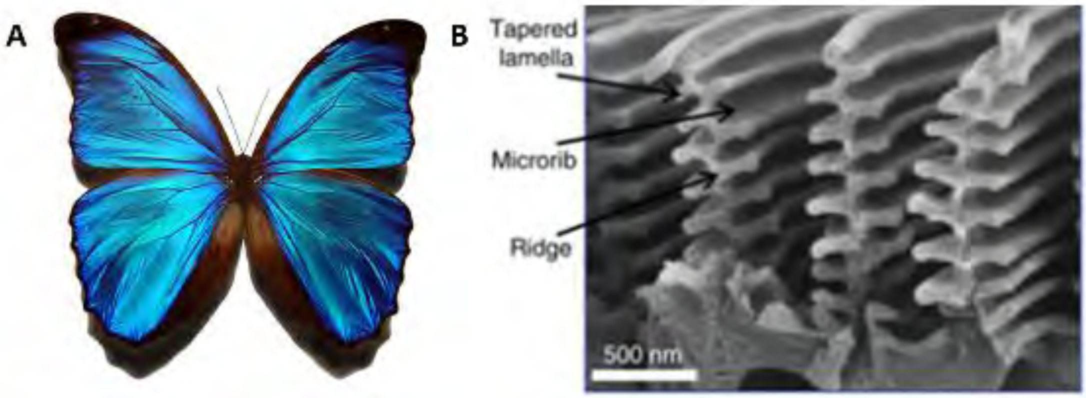


Figure 3.7: Morpho Butterfly (Potyrailo et al*, 2015)*

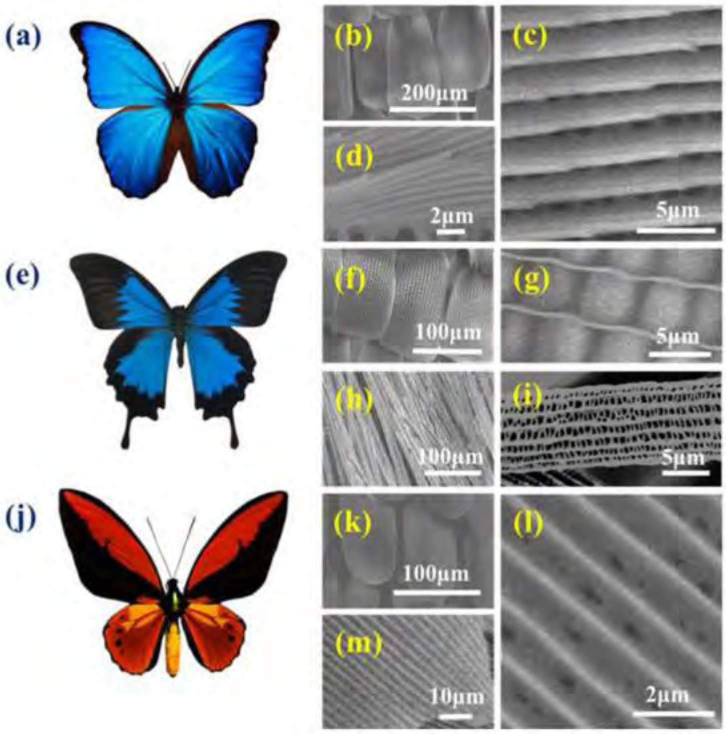


Figure 3.8: Nanopatterns in butterfly wings scales (Elbaz et al., 2018)

b) Jewel beetle

The jewel beetle has the characteristic of a high reflective coating, this light effect is produced by the scattering and reflection when the light reach the different patterns of the nano structures on the skin surface (Schenk et al., 2013).

Figure 3.9: Jewel Beetle (Land of Strange, 2015)

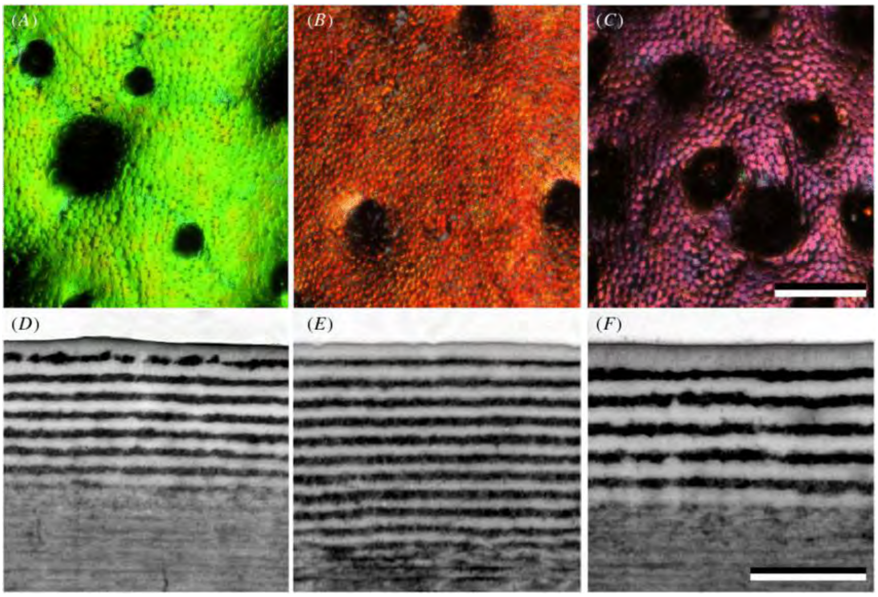


Figure 3.10: Cuticular surface of the Japanese jewel beetle (Schenk et al., 2013)

c) Sponge

Some type of sponges has an interior structure called spicules that allows them to distribute the minimal amounts of light reached on the surface into deeper tissues; these siliceous structures vary in length and size and they act as filters of some wavelengths. The transmission efficiency is 60% (Brümmer et al., 2008).

Figure 3.11:A sponge Tethya aurantium (Anne Frijsinger and Mat Vestjens, 2010)

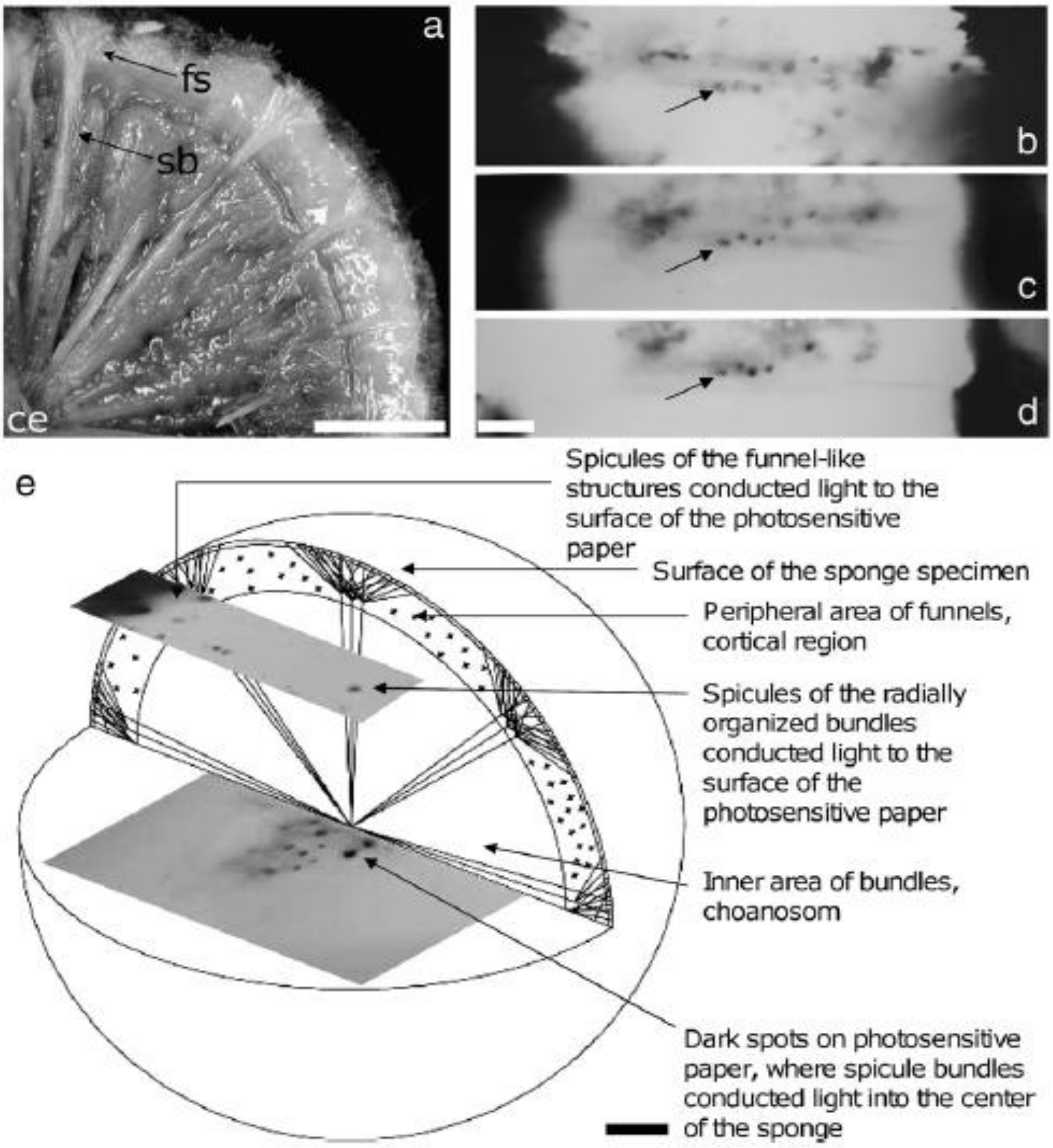


Figure 3.12:Inside structure of the sponge Tethya aurantium (Brümmer et al., 2008)

d) Firefly

The nanostructures located on the surface of the firefly enhance the light transmission (Figure 3.13). The structure of the firefly consists on a dorsal layer, a photogenic layer where the light is produced and the cuticle. The nanostructures in the cuticle have an antireflective effect, as a result more quantity of light is transmitted through the structure (Figure 3.13G) (Kim et al., 2012).

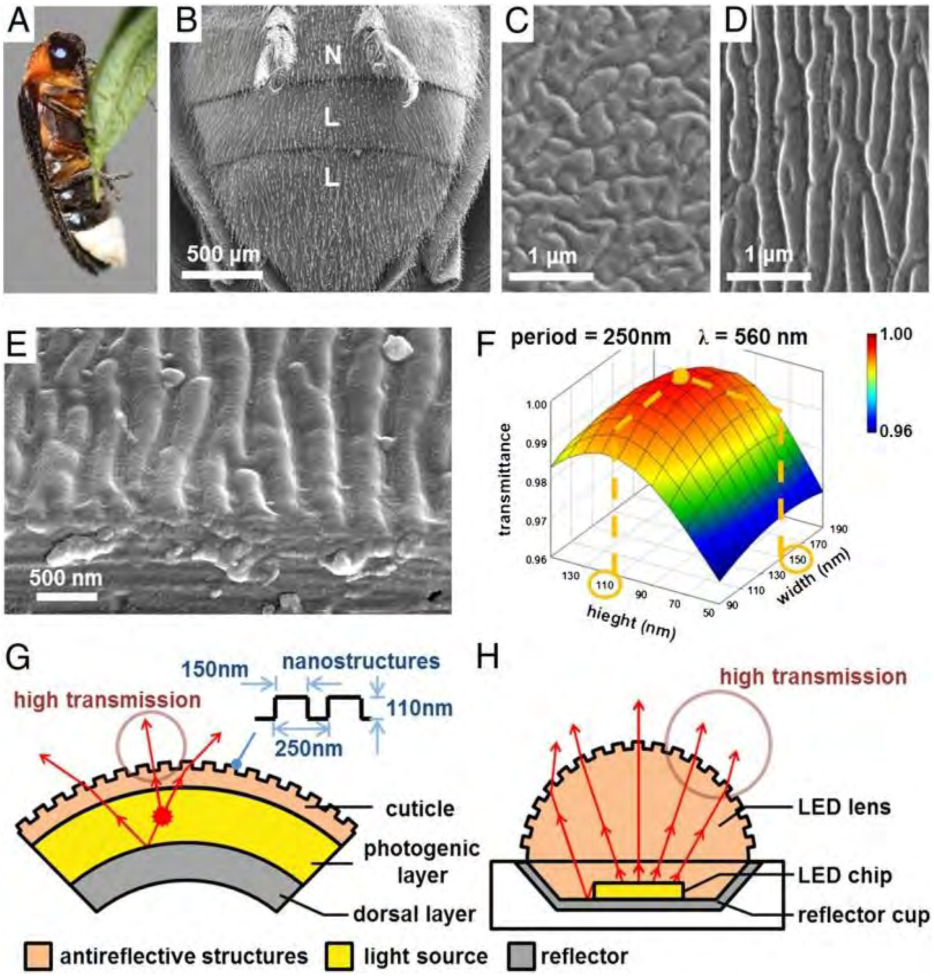


Figure 3.13:Firefly and detailed nanostrutucres (Kim et al., 2012)

e) Dolichopteryx longpipes

This fish has an interesting ocular system; the main eyes are supported by a structure called diverticulum that allows capturing light to recognize objects from horizontal and below directions, in the diverticulum (Figure 3.15), there is a cell mirror that reflects light aiming to the retina Abbreviations are as follows: a, argentea; ar, accessory retina; ce, ciliary epithelium; chg, choroid gland; dc, diverticular cornea; dr, diverticular retina; I, iris; m, mirror; mc, main cornea (partially removed for facilitating the impregnation of tissue with resin); mr, main retina; oc, outer coats of the eye, consisting of sclera, argentea, and choroid; rl, retractor lentis muscle (ventral part); s, septum between the main tubular eye and the diverticulum (Wagner et al., 2009).

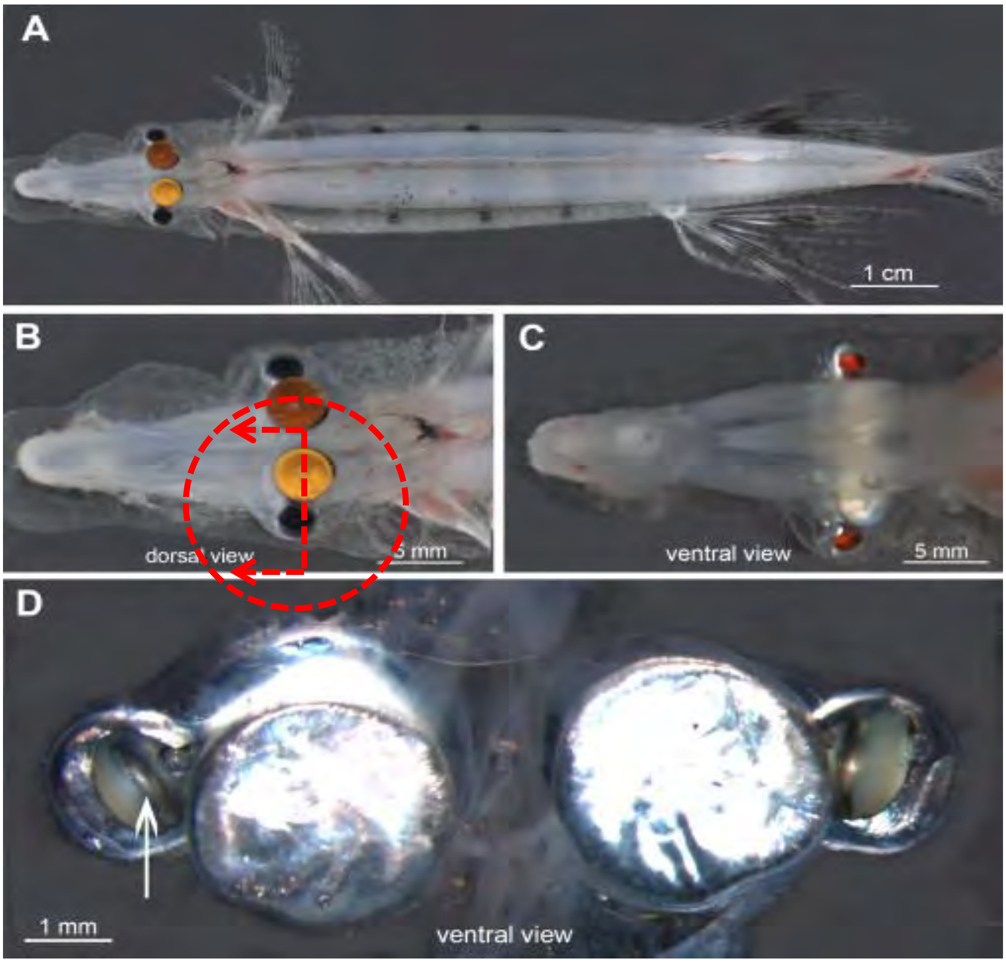


Figure 3.14:Dolichopteryx longpipes and transverse section line (B) (Wagner et al., 2009)

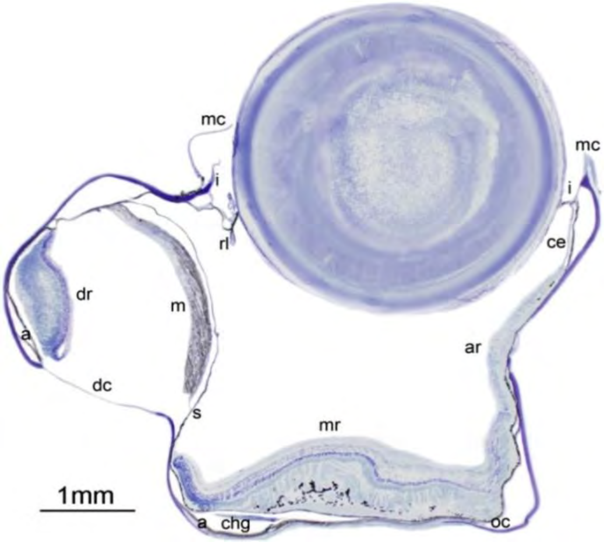


Figure 3.15:Transverse Section of the Eye of Dolichopteryx longipes, Showing Both a Main, Upwardly Directed Tubular Portion and a Lateroventrally Directed Diverticulum (after Wagner et al.,2009)

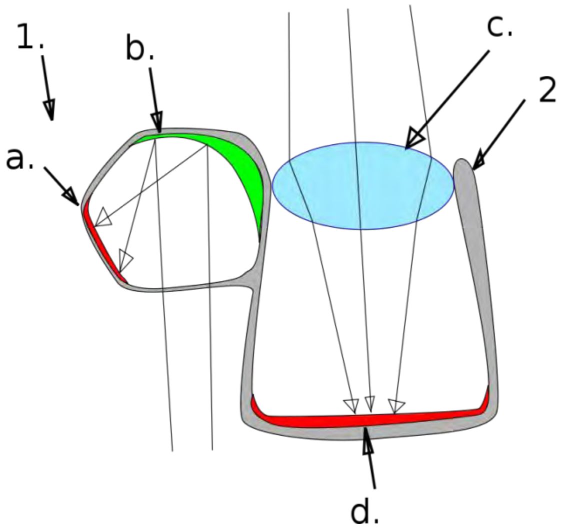


Figure 3.16:The mirror eye (as well as a lens):
(1) diverticulum (2) main eye
(a) retina (b) reflective crystals (c) lens (d) retina (after Wagner et al.,2009)

It is evident from above sections that there are several ways to use sunlight in nature. Information taken from this study on how organisms manage light has to be ordered as a first step methodology, so the exploration model could be generated from all the information obtained.

Table 3.1*: Summary of analysis pinnacles (after Yanez, 2014)*

Pinnacle´s strategy	Mechanism	Main principle	Main feature
Butterflies Diffuse and refracts light	The nanostructure of the scales interact with light, doing a filtering and creating diverse colors and textures	The layers and form of the nanostructures on the scales	Light refraction and diffusion
Jewel beetle Diffuse and refracts light	Iridescence produced by the surface	Multilayer surface	Light refraction and diffusion
Sponge The inner tubular structures transports light into inner cells	The whole structure made by the spicules distributes light to inner cells	Spicule structure plus reflective surface	Light distribution
Firefly Light emission	The nanostructures on the body enhances the transmission of light	Pattern on the surface	Light Transmission
Dolichopteryx Longpipes **Capture and reflects light**	**The cell mirror can capture as much as light possible on the downwards direction**	**The structure and curvature of the cell mirror**	**Light reflection**

3.4.4 Generating design concept

In the Table 3.1, strategies and principles of the organisms explored in Section 3.4.3 are described in a simpler form. This is useful to find the main principle to be applied afterwards and to understand the main process to achieve the required function. Two kinds of design concepts can be applied for the case hall: a morphodesign that is related with shapes and structures; and physiodesign that is related with function and materials (Yanez, 2014). Considering the significance of the volume and structure of multipurpose hall in an educational building, it is decided to approach for morphodesign.

The research approached for morphodesign, i.e. related with shapes and structures of Dolichopteryx longpipes, for the following reason. Dolichopteryx longpipes fish (Figure 3.14) has an interesting ocular system. The fish looks as it has four eyes. One half points upwards, giving the fish a view of the ocean – and potential food – above. The other half, which looks similar to a bump on the side of the fish‟s head, points downwards into the abyss below. These „diverticular‟ eyes are unique among all vertebrates in that they use a mirror to make the image.The main eyes are supported by a structure called diverticulum (Figure 3.16) that allows capturing light to recognize objects from horizontal and below directions, in the diverticulum, there is a cell mirror that reflects light aiming to the retina (Figure 3.16). Therefore, compared to a normal fish's eye, the reflective optical system of the diverticulum achieves a greater light-gathering capability for extended sources. This, of course, requires photoreceptors to efficiently capture light arriving at angles of incidence outside their light-guiding acceptance angle. (Wagner et al, 2009; Yanez, 2014).

3.4.5 Application of morpho design concept

Investigating some possibilities, the first thought is to create a replicated structure based on the cell mirror in the Dolichopteryx Longpipes fish. This structure would be able to receive the sunlight throughout the day and sunlight would be reflected in a panel that provide diffuse light for the multipurpose hall.

The basis in this design is that the curvature on the cell mirror reflects a range of light rays effectively that come from different angles. Figure 3.17 shows how the light is directed to the several points of the retina depending on the angle of incidence. Figure 3.18 is showing that the light is reflected in all directions so it can be considered as an ideal condition.

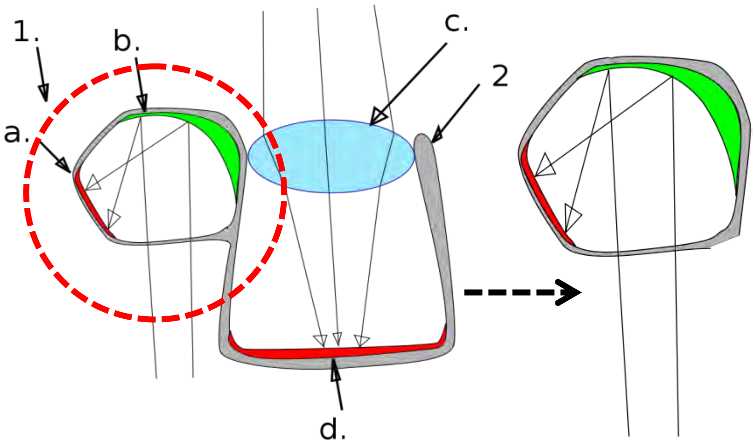


Figure 3.17: Lightreflected from different angles on the cell mirror

(1) diverticulum
(a) retina (b) reflective crystals retina (after Wagner et al.,2009)

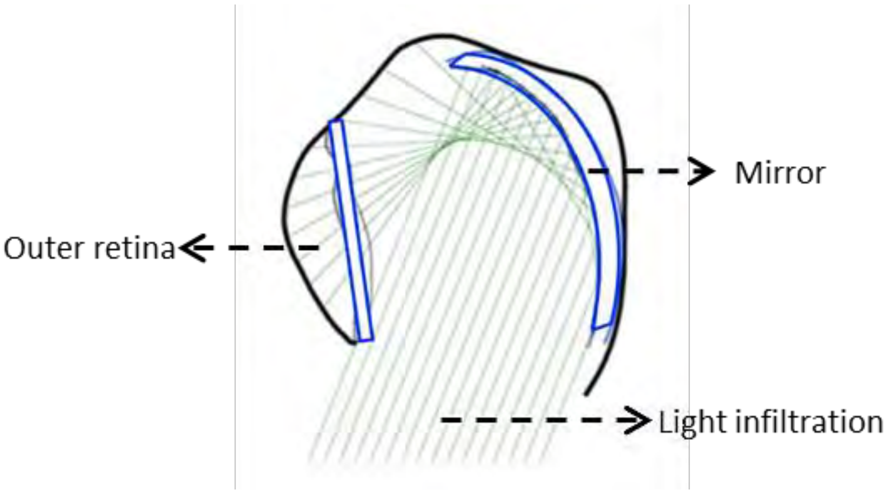


Figure 3.18: Light reflecting replica in all directionson the cell mirror (Wagner et al, 2009)

According to the geographical context, east or west facing orientation for roof light is not suitable because of the sun position; so the possibilities in this case are the structure for roof opening is facing towards north or south.

Another thought is that the roof can be designed similar to a louvered structure trying to follow the sun path daily. In that case a control system should be placed to maintain the system.A manual control system would require the users to move it within a period of time and it would require extra energy using an automatic system. So there are some disadvantages in this idea but it has been established with the design path matrix that the design is set as a passive strategy.

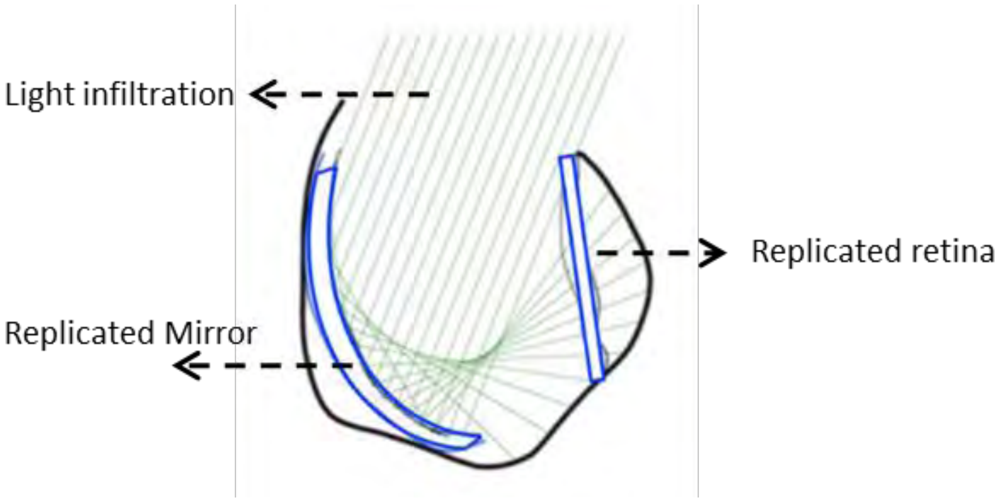


Figure 3.19: Upward facing replicated shapes (blue lines) from the cell mirror and the retina of the Dolichopteryx Longpipes (Wagner et al, 2009)

Figure 3.19shows how the structures of cell mirror could be replicated to reflect the sun light and create a daylight bulb. Here the retina acts as a light receptor but on the design the structure that represents it should be a diffuser. The diffuser that delivers light to the hall should reflect the sunlight twice in the whole process. Diffusive light without glare and heat can be achieved in that way which feels comfortable for the users.

This idea seems to be interesting but at the same time it adds challenges for building afterwards. Although biologically and geographically the range of angle is similar, the sun on the orientation north and south covers 50°(Yanez, 2014) and the mirror can receive a range of 48°(Figure 3.20);

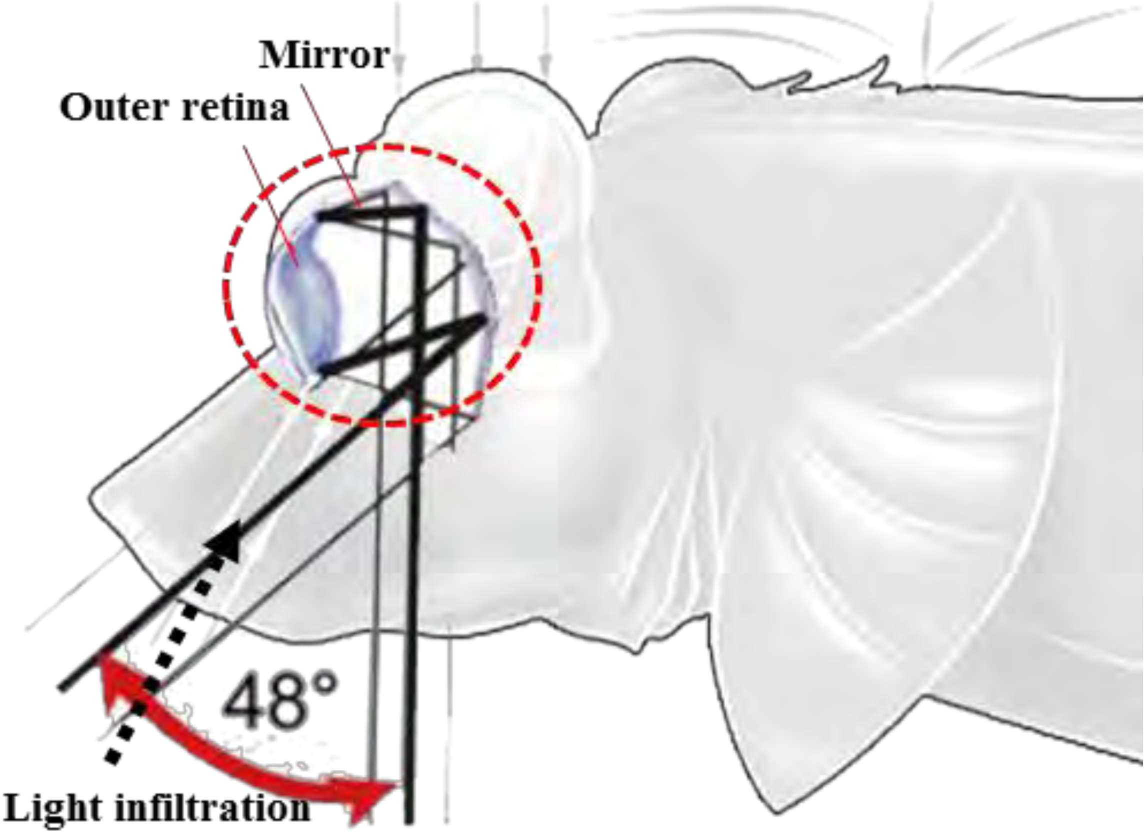


Figure 3.20: Transverse section of the diverticulum showing the light infiltration angle (after, Wagner et al, 2009)

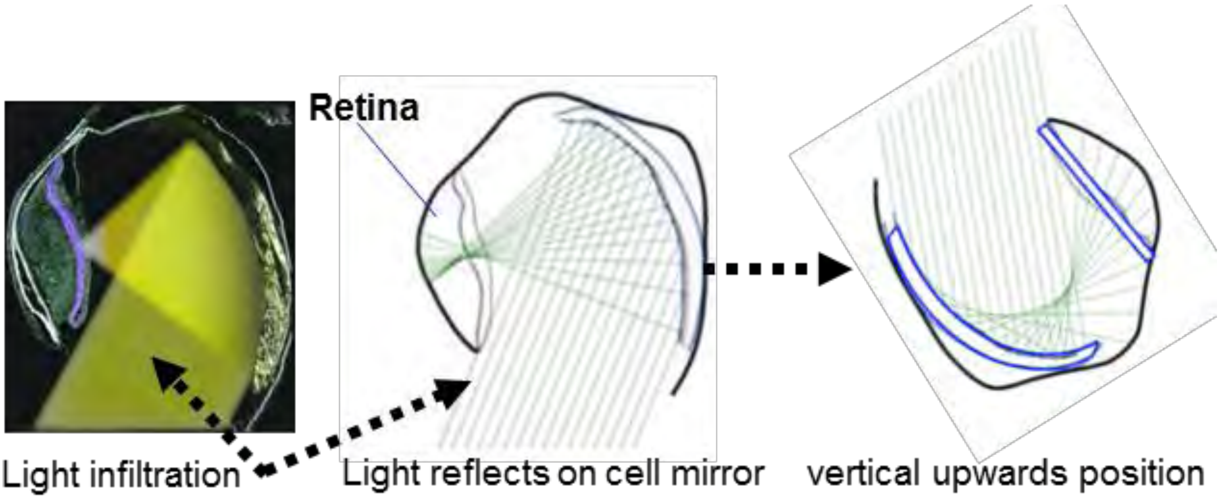


Figure 3.21: Transform to the vertical upwards position (after, Wagner et al, 2009)

The same mechanism could be used as shown in Figure 3.22. The original idea is not conceived in that way, the position of the mirror is vertical downwards so the fish can collect light from the bottom of the sea.

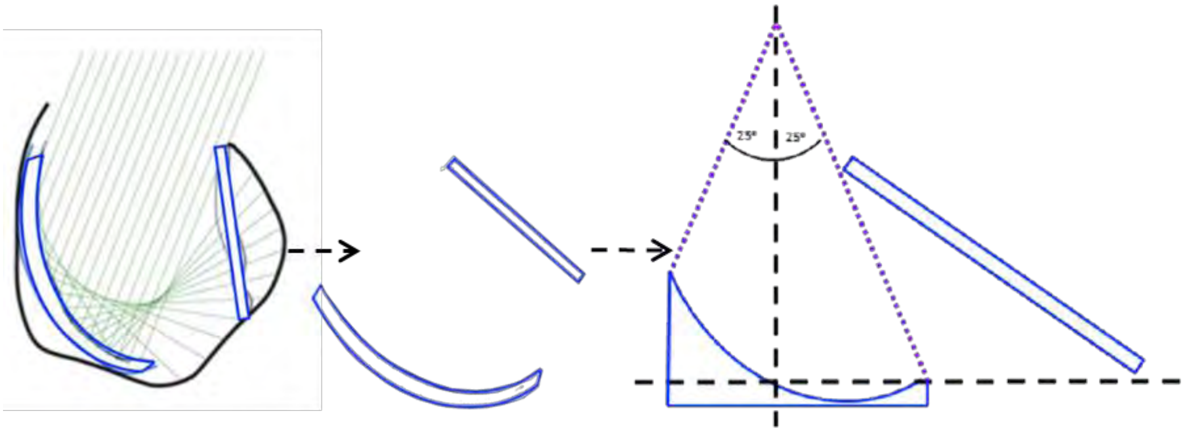


Figure 3.22: Concept of replicating the cell mirror on a rooftop (after, Wagner et al, 2009)

3.4.6 Morpho design concept to generate different options

Increasing the opening at the top as well as the inverse incline on the secondary structure to generate supplementary space to dispense the dispersed light, this dispute can be resolved by setting a platform that is able to hinder the direct light consequently, the design of the platform will serve simultaneously as a light shelf in this case (Figure 3.23). Providing as much as dispersed light possible would be the sought after result here. In the course of the modelling exercise, the dimensions of the structure would be determined.

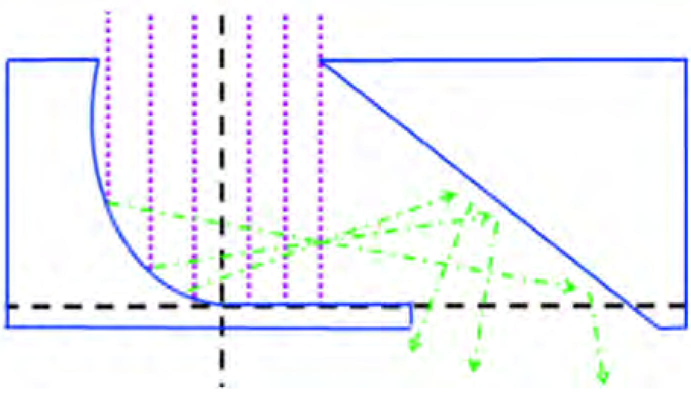


Figure 3.23: Morpho design concept 1 replicating the cell mirror structure. Sun rays are colored as purple and reflected light as green (Yanez, 2014)

The use of cell mirror horizontally (Figure 3.24), in which case the mirror would collect the same amount of sunlight for the aperture at the uppermost part and consequently the light can be redirected to secondary panels, one on each side, produces another possibility. The reflection angles in this design may aid in taking the benefit in more light redirected, although it does not necessarily replicate the exact position as that of the cell mirror.

It‟s a matter of significant concern that cell mirror acts as a convergent mirror, meaning it gathers light from multiple points and redirects it to a single point, as illustrated in Figure 3.21 congregation of the rays can be seen at one point of the retina which can be deemed as in sufficient, making this nature one of the chief disquiets.Four more configurations have been created in order to prove how effective the convergent mirror could be. Figure 3.25 shows how the convergent mirror will be replaced by an angular convergent, a divergent (Figure 3.26), an angular divergent (Figure 3.27), and a flat platform (Figure 3.28) hoping to disperse the light instead of converge.

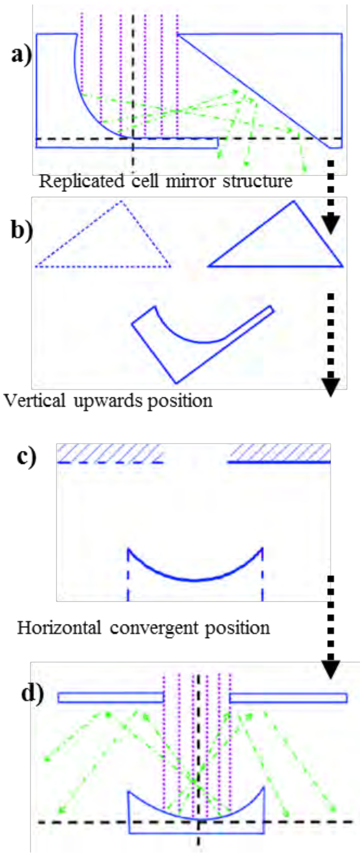


Figure 3.24: Morpho design concept 2 (d) derived from Morpho design concept 1 (a) with mirror in horizontal position, in different conditions(after Yanez, 2014)

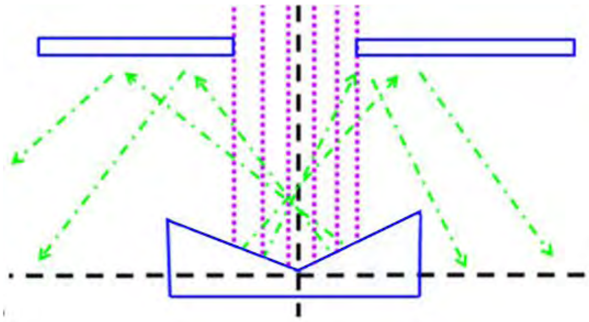


Figure 3.25: Morpho design concept 3 with angular

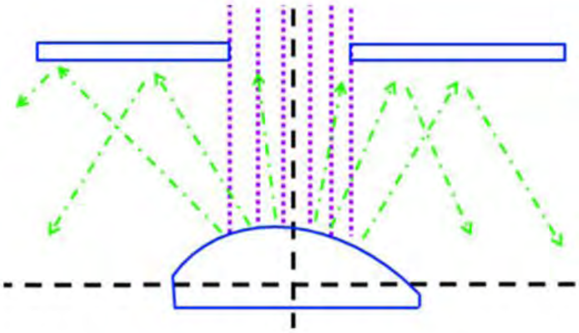


Figure 3.26: morpho design concept 4 with divergent platform (Yanez, 2014)

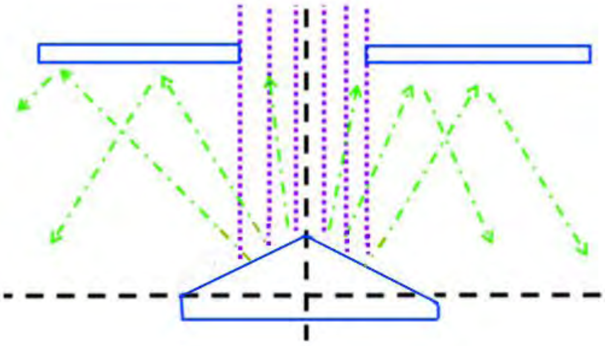


Figure 3.27: Morpho design concept 5 with angular divergent platform

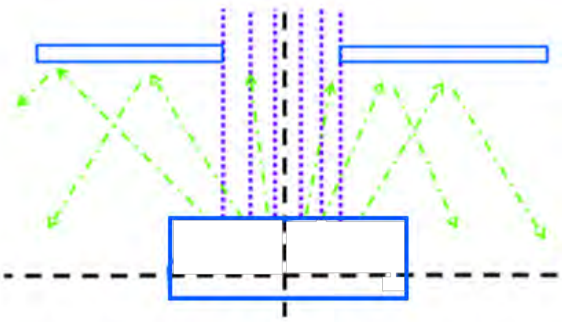
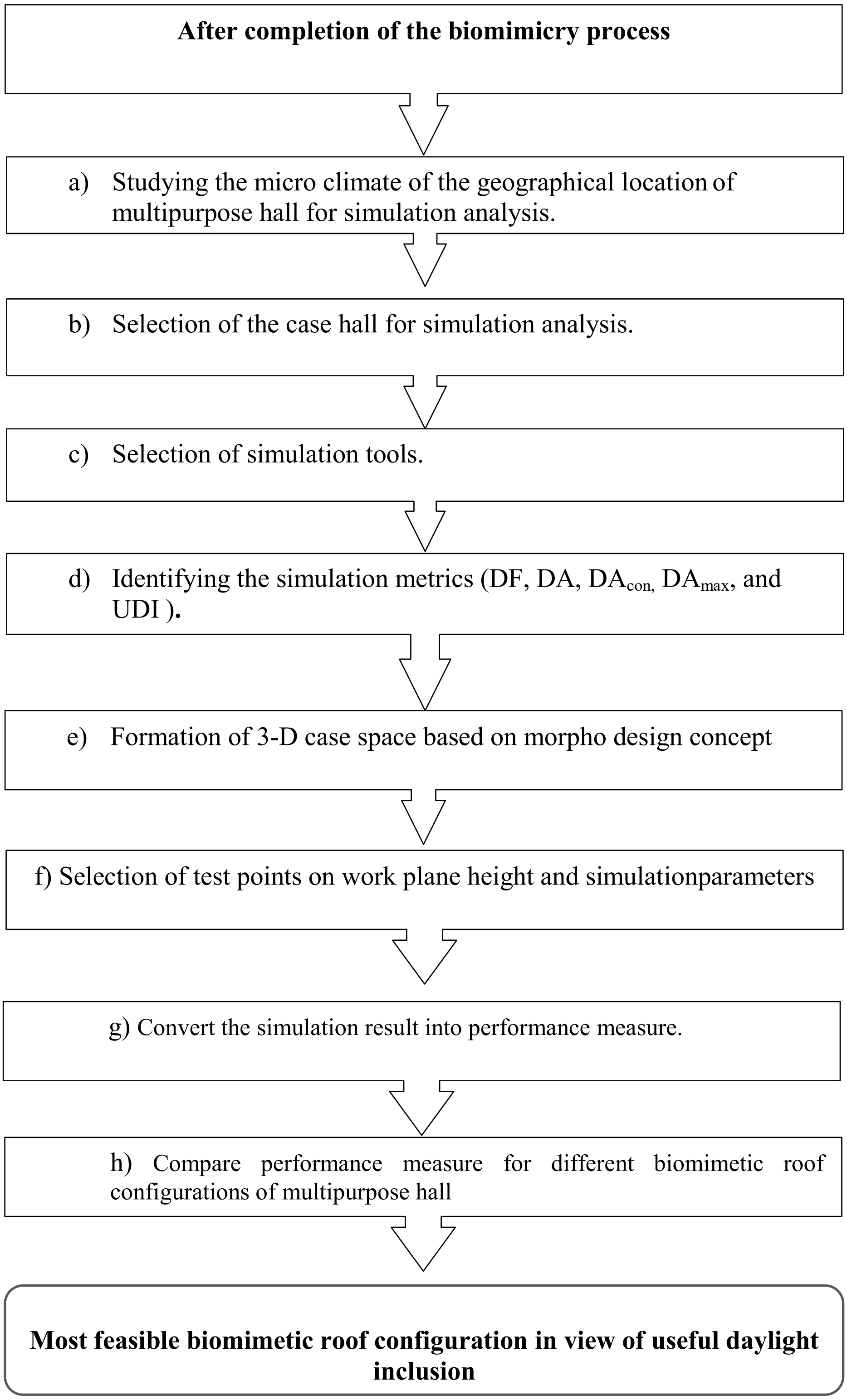


Figure 3.28: Morpho design concept 6 with flat platform (Yanez, 2014)

3.5 Steps of Simulation Study



After completion of the biomimicry process

a) Studying the micro climate of the geographical location of multipurpose hall for simulation analysis.

b) Selection of the case hall for simulation analysis.

c) Selection of simulation tools.

d) Identifying the simulation metrics (DF, DA, $DA_{con,}$ DA_{max}, and UDI).

e) Formation of 3-D case space based on morpho design concept

f) Selection of test points on work plane height and simulationparameters

g) Convert the simulation result into performance measure.

h) Compare performance measure for different biomimetic roof configurations of multipurpose hall

Most feasible biomimetic roof configuration in view of useful daylight inclusion

Figure 3.29: Flow diagram of the simulation process of the research

In this research, the prospective simulation study was chosen to identify the design parameters of biomimicry inspired roof configurations identified in Section 3.5 that can help to improve indoor luminous environment quality of a multipurpose hall. This section provides a brief overview of the simulationmethodology for the thesis. Figure 3.29shows a flow diagram of the simulation process of the research.

3.5.1 **Micro Climate of the Geographical Location of Multipurpose Hall**

Bangladesh has a subtropical monsoon climate and is regarded as one of the largest deltas in the world with a flat and low lying landscape (Ahsan, 2017). Meteorologically, the climate of Bangladesh is classified into four distinct seasons: winter, pre-monsoon, monsoon and post- monsoon (Ahmed, 1995). The winter is cool and dry; the pre-monsoon is hot and dry; the monsoon and post-monsoon seasons are hot and wet. Statistics show that, the winter months (December to February) are characterized by infrequent rains, cold northerly winds, mean temperatures of 2l°C with a mean maximum temperature below 26°C (Aman, 2017)

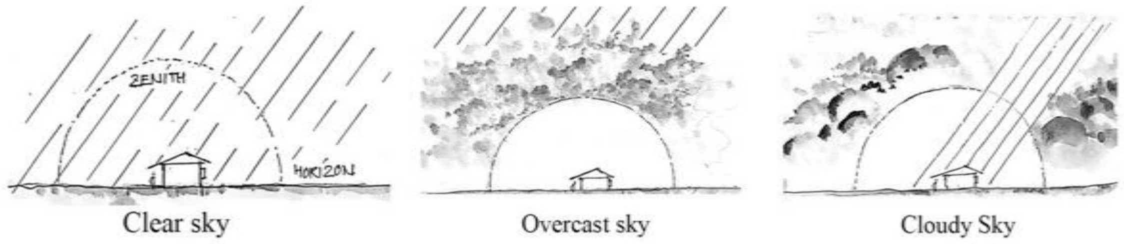
The pre-monsoon period covers the months March, April and May, and is characterized by occasional thunderstorms, and an average maximum temperature of 34°C. The monsoon is the longest season, covering the months- June to September, a period with torrential rains, with the average relative humidity above 80%, and an average temperature of 31°C. The post-monsoon season ranges between the months October and November. It is also regarded as a transitional period, with infrequent rains and average temperatures below 30°C (Trisha, 2015).

a) Microclimate **fo** *Chattogram*

Chattogram lies at 22°22′0″N and 91°48′0″E. It straddles the coastal foothills of the Chattogram Hill Tracts in south-eastern Bangladesh. The Karnaphuli River runs along the southern banks of the city, including its central business district. The river enters the Bay of Bengal in an estuary located 12 kilometres (7.5 miles) west of downtown Chattogram. Mount Sitakunda is the highest peak in Chattogram District, with an elevation of 351 metres (1,152 ft) (YC, 2011). Within the city itself, the highest peak is Batali Hill at 85.3 metres (280 ft). Chattogram has many lakes that were created under Mughal rule.

Chattogramhas a tropical monsoon climate and the city is part of the hilly regions that branch off from the Himalayas. This eastern offshoot of the Himalayas, turning south and southeast, passes through Assam and Tripura, and enters Chattogram across the river. The range loses height as it approaches Chattogram City and breaks up into small hillocks scattered over the town. This range appears again on the southern bank of the Karnaphuli river and extends from one end of Chattogramdistrict to the other. Nangarkhana to the north of Chattogram is 289 feet high. There was a light post at the top of Batali Hill for the guidance of vessels far away in the sea. The annual average temperature is 25.1°C (77.2°F) and monthly means varying between 19°C (66.2°F) in January and 28°C (82.4°F) in May.

In composite climates e.g. Chattogram, where both overcast conditions and clear blue skies during the course of each year are observed (Figure 3.30), designers face difficulties while designing considering it. The ways and means of tackling the two conditions are quite contrasting to each other (Ahmed, 1987).



Clear sky   Overcast sky   Cloudy Sky

Figure 3.30: Various Sky Conditions (Source: Hossain, 2011)

b) Sunshine hours

Daylight availability of any location is influenced by latitude and weather patterns. In the cool dry period Chattogram has almost 8.5 hours of sunshine per day. But during monsoon months (warm-humid season) this comes down to around 3.5 hours per day due to cloud cover. Month with most sunshine is March with an average sunshine: 8.9h. Month with least sunshine is July with an average sunshine: 3.4h (Weather Atlas, 2017). It is after June and July that this once again increases steadily. The atmospheric condition during the month of July to November period is cloudy. Thus, the diffused component of the daylight is considerably high. Figure 3.31shows the Monthly average daylightandmonthly average sunshine hours for Chattogram city for year 2017, while Figure 3.32 shows the sun path diagram of Chattogram.

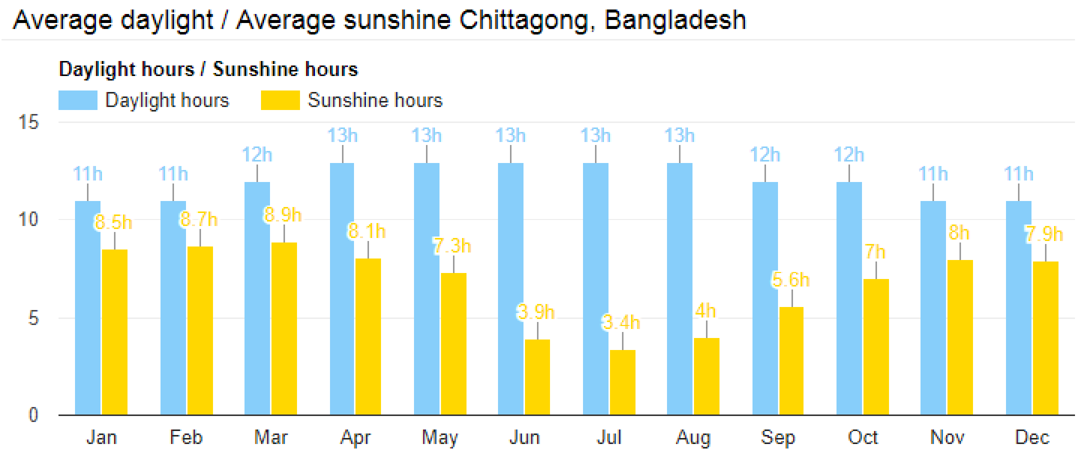


Figure 3.31: Monthly average daylight and sun shine hours in Chattogram, (Data source: Weather Atlas, Year 2017)

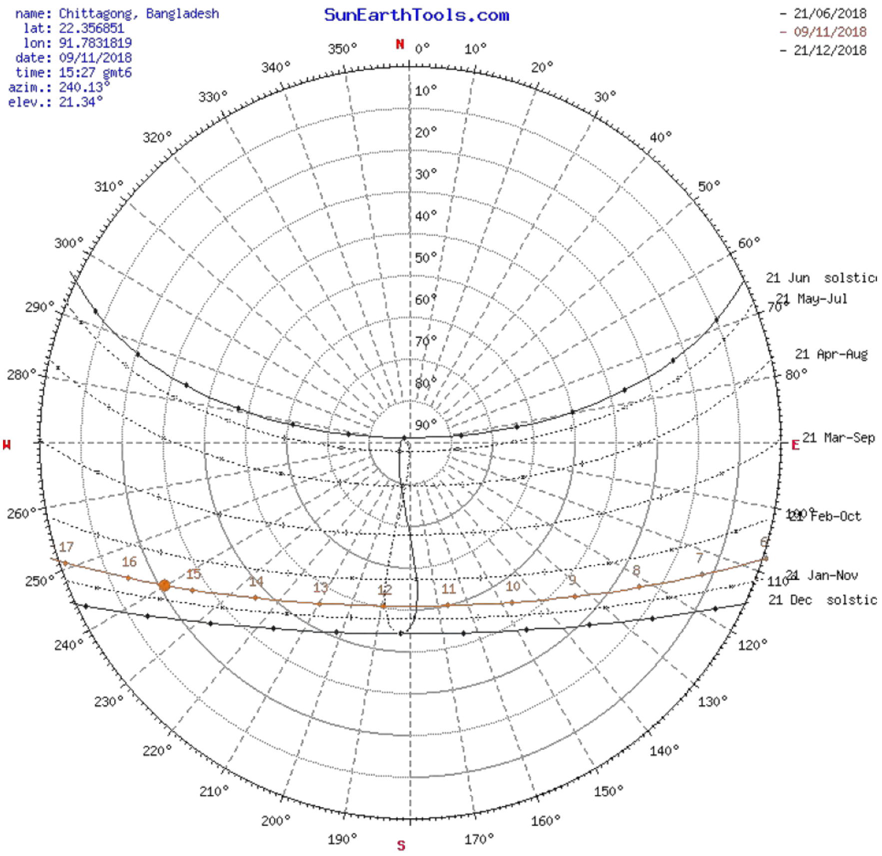


Figure 3.32: The sun path diagram of Chattogram, Bangladesh (Source: SunTools.com–Tools for consumer and designers of solar).

c) Sky condition

Direct sunlight is intense and varies substantially as the sun's position changes throughout the day (up to 1, 00,000 lux). Daylight from a clear sky can be 10% to 25% of the intensity of direct sunlight (10000-25000 lux). Daylight under partly cloudy conditions can be highly variable; daylight under full overcast conditions can be 5% to 10% of sun conditions (5000- 10000 lux) (AGS, 2000; Joarder, 2007). In context of Chattogram the sky remains clear and overcast in different parts of various seasons. During summer (Hot Dry) the sky remains both clear (sunny with sun) and overcast.

Table 3.2: Illumination from a design sky on a horizontal unobstructed surface on different latitude and solar altitude (Evans, 1980; Hossain, 2011).

Suggested values for overcast sky	lux (lumen/m^2)
Latitude 50-60^0	5,000
Latitude 40-50^0	5,000-6,000
Latitude 30-40^0	5,000- 8,000
Latitude 20-30^0	8,000-10,000
Latitude 10-20^0	10,000-15,000
Suggested values for overcast sky	
All latitude	5,000
Solar altitude 15^0	14,000
Solar altitude 30^0	36,000
Solar altitude 45^0	58,000
Solar altitude 60^0	75,000
Solar altitude 75^0	83,000
Solar altitude 90^0	94,000 to 110,000

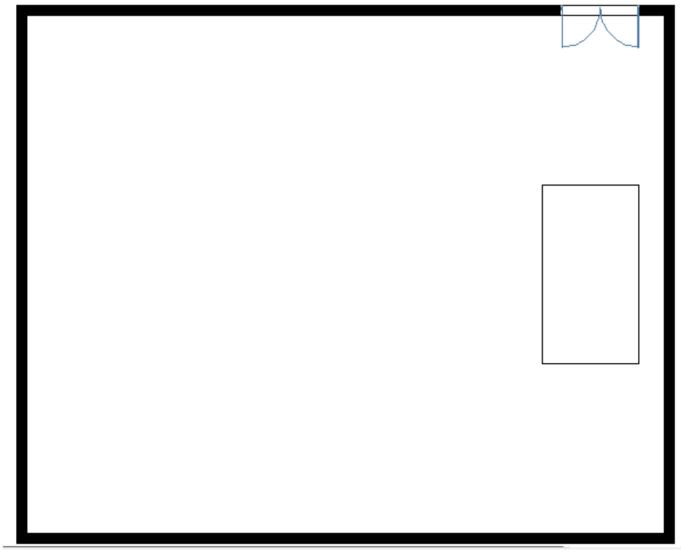
3.5.2 Selection of the case multipurpose hall for simulation analysis

A survey was conducted on 04 randomly selected multipurpose halls in educational buildings. One multipurpose hall was selected as „Case Hall“ and variables for simulation study were set, based on the physical survey. The considerations regarding the selection of the case hall were as following.

- Location would be in the urban context.
- The case hall should be designed or renovated for multipurpose hall purpose.
- The hall should be located at the top floor of the building and have the provision of allowing daylight to enter through roof.
- There should be no shadows on the roof top caused by surrounding (taller) buildings that can obstruct daylight to enter from above.
- The activity pattern and internal layout of the case hall should represent current practice of multipurpose hall design in a typical academic building of Bangladesh.

Table 3.3: Field survey data of the case 1 multipurpose hall.

Name of the University	Context	Location of the hall	Length	Width	Floor area	Daylighting source
AUST	Urban	2nd floor (Top floor)	15.50m	10.30 m	159.65 sq.m	Two glass doors and no window

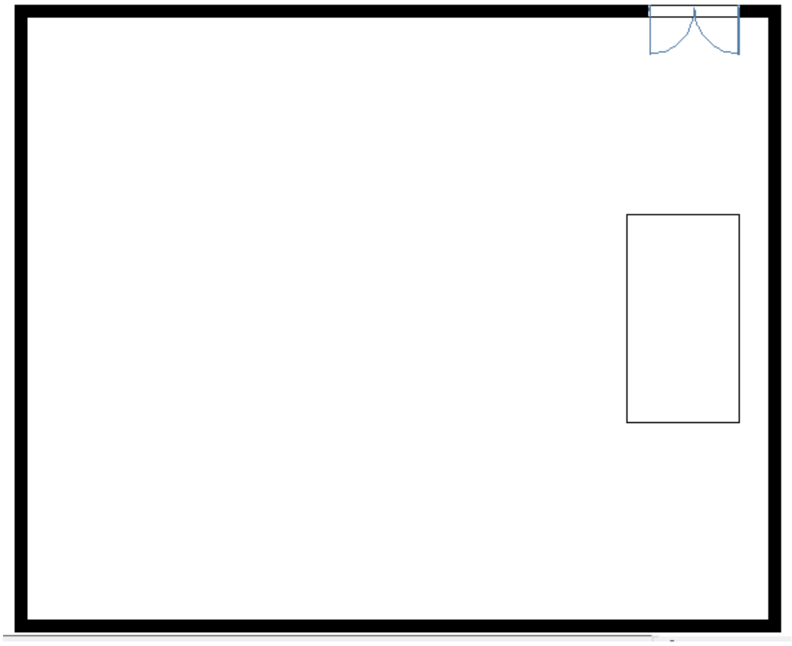


Multipurpose hall plan

Interior space photographs with existing condition

Table 3.4: Field survey data of the case 2 multipurpose hall.

Name of the University	**Context**	**Location of the hall**	**Length**	**Width**	**Floor area**	**Daylighting source**
IUB	Urban	Ground floor	16.76	13.72 m	229.95sq.m	No daylighting source

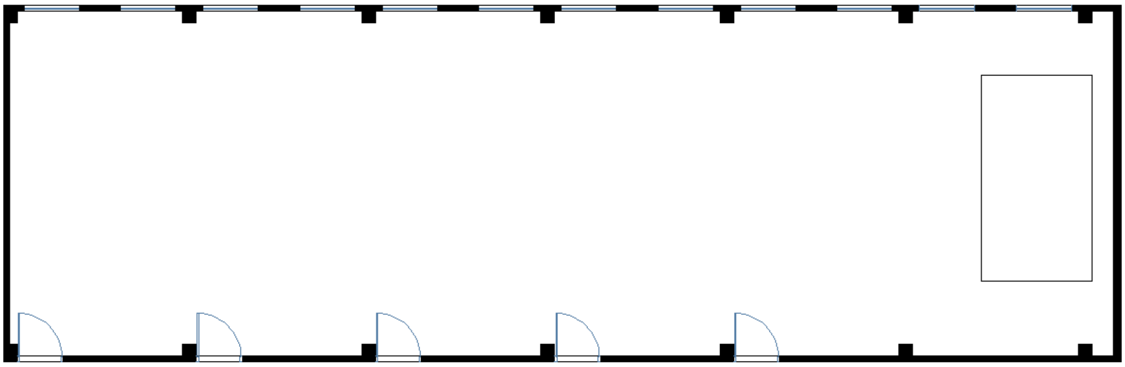


Multipurpose hall plan

Interior space photograph with existing condition

Table 3.5: Field survey data of the case 3 multipurpose hall.

Name of the University	**Context**	**Location of the hall**	**Length**	**Width**	**Floor area**	**Daylighting source**
PCIU	Urban	(Top floor)	24.40 m	7.60 m	185.44 sq.m	Side windows

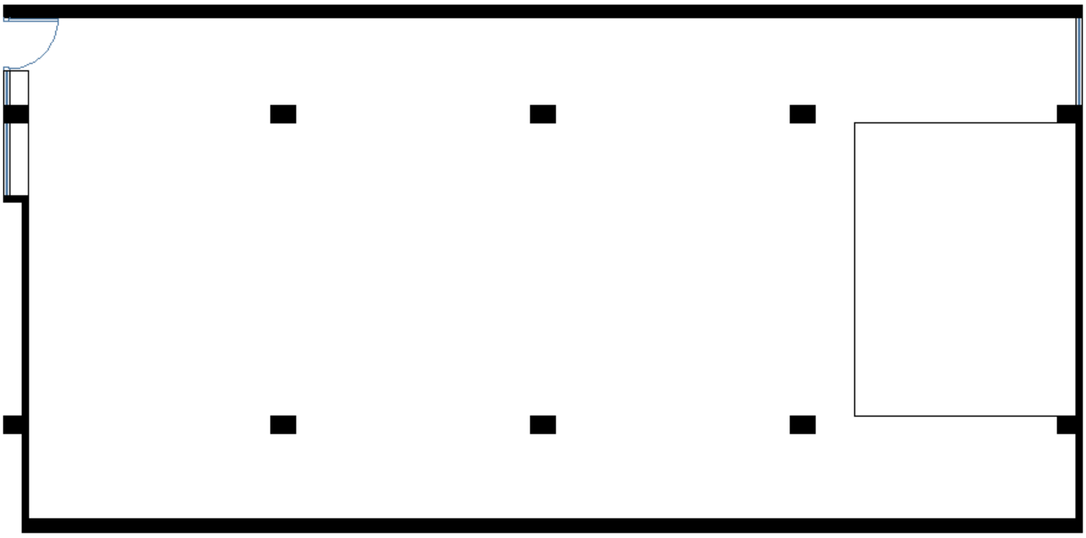


Multipurpose hall plan

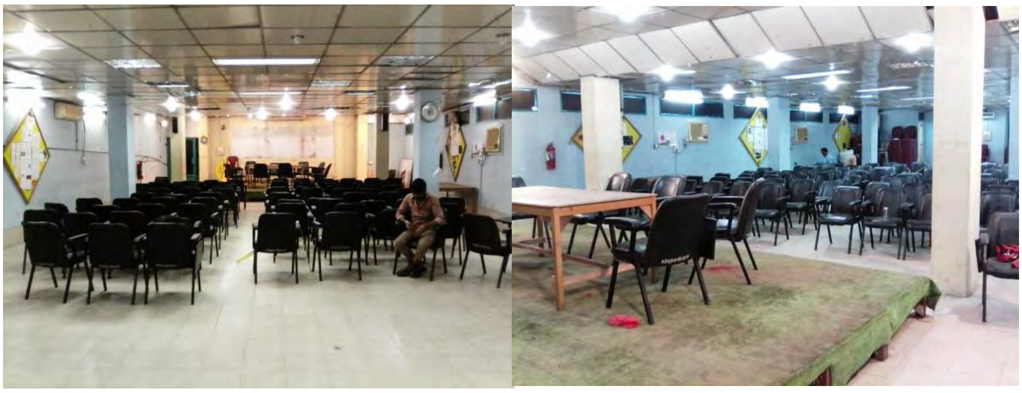
Interior space photograph with existing condition

Table 3.6: Field survey data of the case 4multipurpose hall.

Name of the University	**Context**	**Location of the hall**	**Length**	**Width**	**Floor area**	**Daylighting source**
PCIU	Urban	(Top floor)	21.30 m	9.80 m	208.70 sq.m	No daylighting source



Multipurpose hall plan



Interior space photograph with existing condition

Figure 3.33: Location of multipurpose hall at PUC

Among the four surveyed multipurpose halls it was found that the multipurpose hall of Independent University of Bangladesh (IUB) is located at ground floor, so it is not suitable for the simulation study of roof lighting. On the other hand multipurpose hall of Ahsanullah University of Science and Technology (AUST) and Port City International University(PCIU) are potential for day lighting through roof but during field survey it is observed that for the surrounding buildings and trees their roofs could be obstructed for entering daylight into the hall. Considering these issues, the multipurpose hall located on the top floor at Premier University Chattogram (PUC) (Figure 3.33) was chosen as the case hall. There is no window in this hall. Side windows were not provided even though during daytime light is often necessary for various types of programs such as seminar, workshop, conference, debate competition and teacher‟s meeting. During physical survey, following properties were recorded.

- South wall: Solid; Material: Blue painted wall.
- West wall: Solid; Material: Blue painted wall.
- East wall: Solid; Material: Off-white painted wall and a white board
- North wall: Solid; Material: Blue painted wall.
- Floor: 21,000 mm long and 10,000 mm width with Glazed tiles.
- Ceiling: Solid; Material of false ceiling: gypsum board.
- Stage (East): 5700 mm long and 4200 mm width.
- Height of the hall: 3000 mm.

Climatic parameters

- Location: Chattogram, Bangladesh (91.48 E; 22.22 N).
- Calculation settings: Full Daylight Analysis.
- Precision: High
- Local terrain: Urban.
- Window (dirt on glass): Average,
- Sky illumination model: CIE Overcast.
- Duration for dynamic simulation: Whole year.
- Illumination threshold: 300 lux (BNBC, 2006).

3.5.3 Selection of simulation tools

Through the process of applying biomimicry to technical designs, one of the most helpful and powerful tools is the modelling of designs to test them using simulation software (Yanez, 2014).There are numbers of lighting simulation tools available in the market. The Tools Directory of Building Energy Software (US-DOE, updated in August 12, 2014) listed 48 tools under the ―Lighting Systems‖ category, among them 21 were advertising daylighting as a key feature (Reinhart et al., 2007). The listed computer-based tools have different level of prediction accuracy and modelling capacities. For example LUMEN MICRO (Baty 1996) and SUPERLITE (Modest 1982) can compute daylight under strict boundary limitations, whereas, some other software can compute complex model geometry and arbitrary environments, such as LIGHTSCAPE (Khodulev et al., 1996) and RADIANCE (Ward 1998), with photorealistic rendering capacity to evaluate quality of lighting in 3D space. For the evaluation of the daylighting concept, a suitable simulation tool is required (Joarder, 2011), which

- has high prediction capability for indoor daylight distribution;
- can model simple to complex geometry with surrounding environments; and
- can provide climate based daylight metrics as output (e.g. DA and UDI).

RADIANCE, a backward ray tracing software package for lighting simulation, was validated for accurate prediction of the distribution of indoor daylight environments by many researchers, for example, Du et al., (2009), Ibarra, et al. (2009), Bryan et al. (2002) and Reinhart et al. (2001). Though RADIANCE can predict light levels for complex geometry accurately, RADIANCE does not have any built-in graphical interface to generate physical model, however, it is possible to use other software as modelling interface for RADIANCE, e.g. AUTOCAD and ECOTECT (Iqbal, 2015). Among the RADIANCE based ray tracer, a limited number of software are able to calculate climate based metrics as final output, such as 3D SOLAR, GENELUX, LIGHTSWITCH WIZARD, S.P.O.T, LIGHT SOLVE and DAYSIM.

In this research, DAYSIM was selected for daylight simulation analysis which also satisfied the above mentioned three criteria. DAYSIM uses RADIANCE (backward) raytracer combined with a daylight coefficient approach (Tregenza, 1983). DAYSIM considers Perez all weather sky luminance models (Perez et al, 1990; 1993) and can provide more than 365 x 24 = 8760 hours data for each sensor point. DAYSIM have been validated comprehensively and successfully for daylighting analysis (Reinhart et al., 2009).

3.5.4 **Metrics for simulation performance evaluation**

Studies on daylight simulations have shown that annual dynamic daylight metric methods can be used to accurately calculate time series of illuminance and luminance in buildings (Reinhart and Andersen, 2006; Reinhart, 2001; Reinhart and Walkenhorst, 2001; Mardaljevic, 2000). These time series can then be used to calculate annual dynamic daylight performance metrics such as daylight autonomies (DA) and useful daylight illuminance (UDI) to quantify the daylight quality of a given building design (Reinhart et al. 2006; Nabil and Mardaljevic, 2005), and annual energy savings from reduced electric lighting use.

The proposed dynamic daylight simulation (DDS) sky and solar division schemes distinguishes between contributions from various luminous sources, as following. Appendix A provides the brief mechanism of the contribution of the following sources under DAYSIM simulation.

- 145 diffuse sky segments
- 1 diffuse ground segment
- 145 indirect solar positions
- 2305 direct solar positions
- 3650 hours daytime illuminance

3.5.5 **Formation of 3-d case spaces**

At first, 3d- case model roof was alternatively replaced by six biomimicry inspired roof types generated by mimicking the retina study of the Dolichopteryx Longpipes (Figure 3.14) and the cell mirror study (Section 3.4.5), based on the work of previous researchers (Wagner, 2008; Yanez, 2014) . Outdoor and indoor conditions and other parameters were kept constant as found during field investigation as described. The depth of each configuration is 900 mm and the opening sizes considered for each configuration are: 750 mm upper level and 900 mm adjacent slab level. Work plane height was kept at 450mm height. Grid layout was set into the work plane height as illustrated at Figure 3.40. Dynamic metric simulation by DAYSIM was performed on that grid layout.

Six biomimetic roof configurations generated from morpho 01-06 (Section 3.4.6) were coded as R1, R2, R3, R4, R5 and R6 (Figure 3.34 – 3.39) and simulated in dynamic metrics as following.

- Dynamic metrics, which considers biomimetic models of 8760 hours of a year.
- Material properties and simulation parameters (e.g. intensity, timing and duration) were kept same as illustrated in previous chapter for dynamic metrics simulation process.
- All the skylight configuration glaze/ floor area ratios were considered as 20% (NARM, 2009) for performance evaluation of the biomimetic roof configuration in the static and dynamic metrics simulation process.
- Primarily, the upper and the lower limit of work plane illumination were fixed to 2000 lux and 300 lux. Hence, the goal of the simulation analysis was to provide minimum 300 lux daylight illumination at each sensor points at work plane height, for duration of 10 hours in a day from 8:00 AM to 6:00 PM.

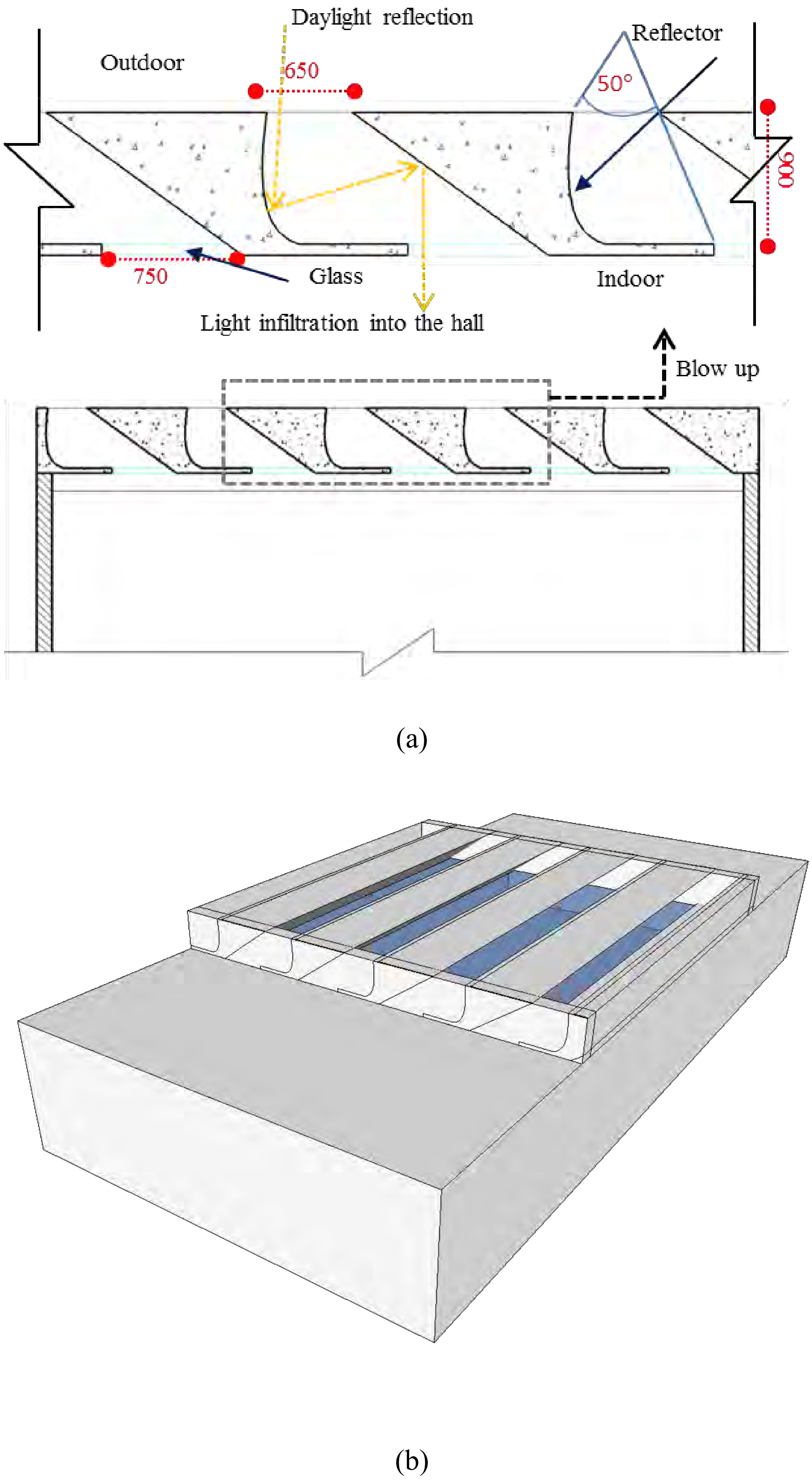
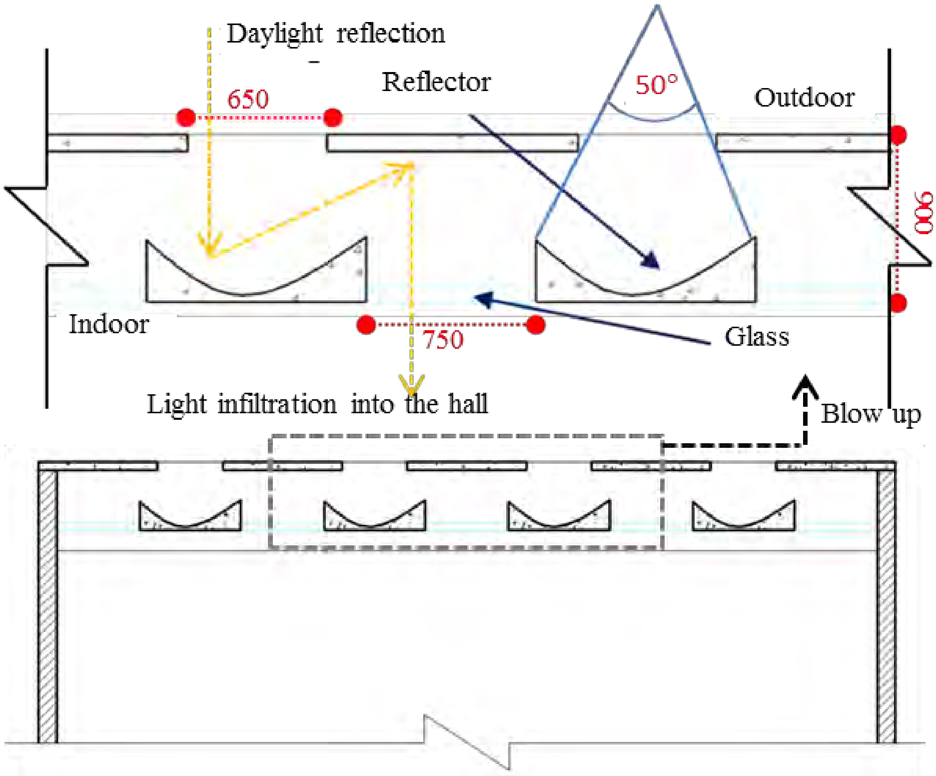
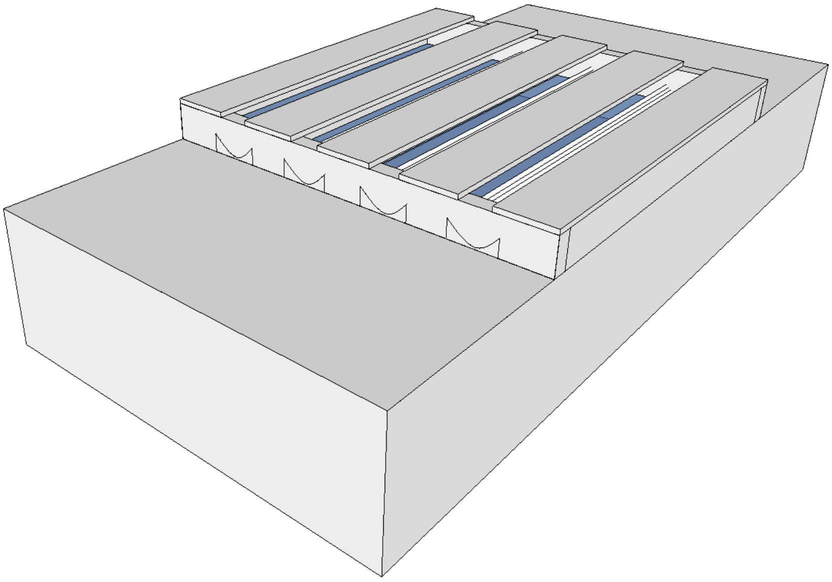


Figure 3.34: Detail section (a) and 3D view (b) of R1 roof configuration of case hall of PU for the simulation study.



(a)



(b)

Figure 3.35: Detail section (a) and 3D view (b) of R2 roof configuration of case hall of PU for the simulation study.

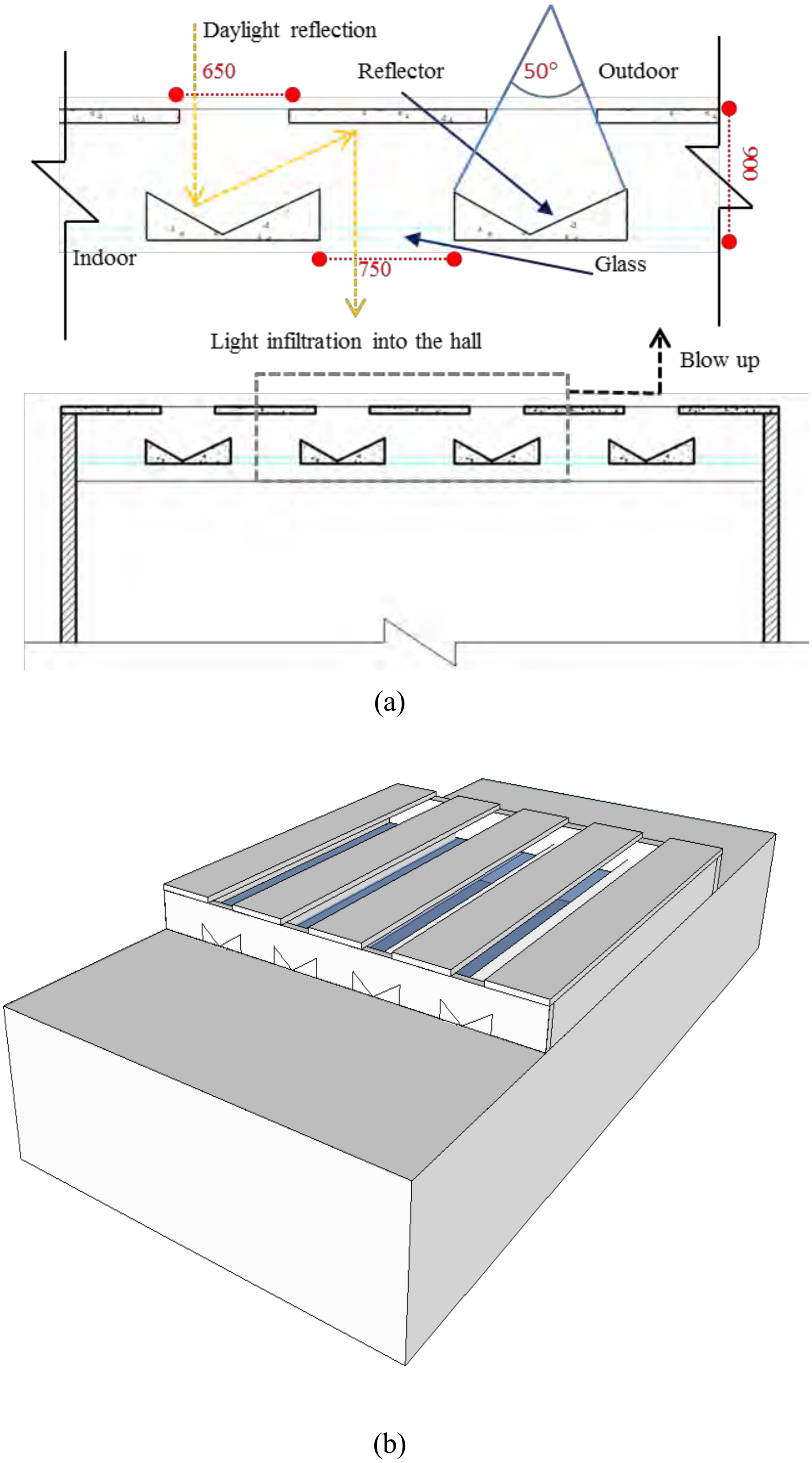
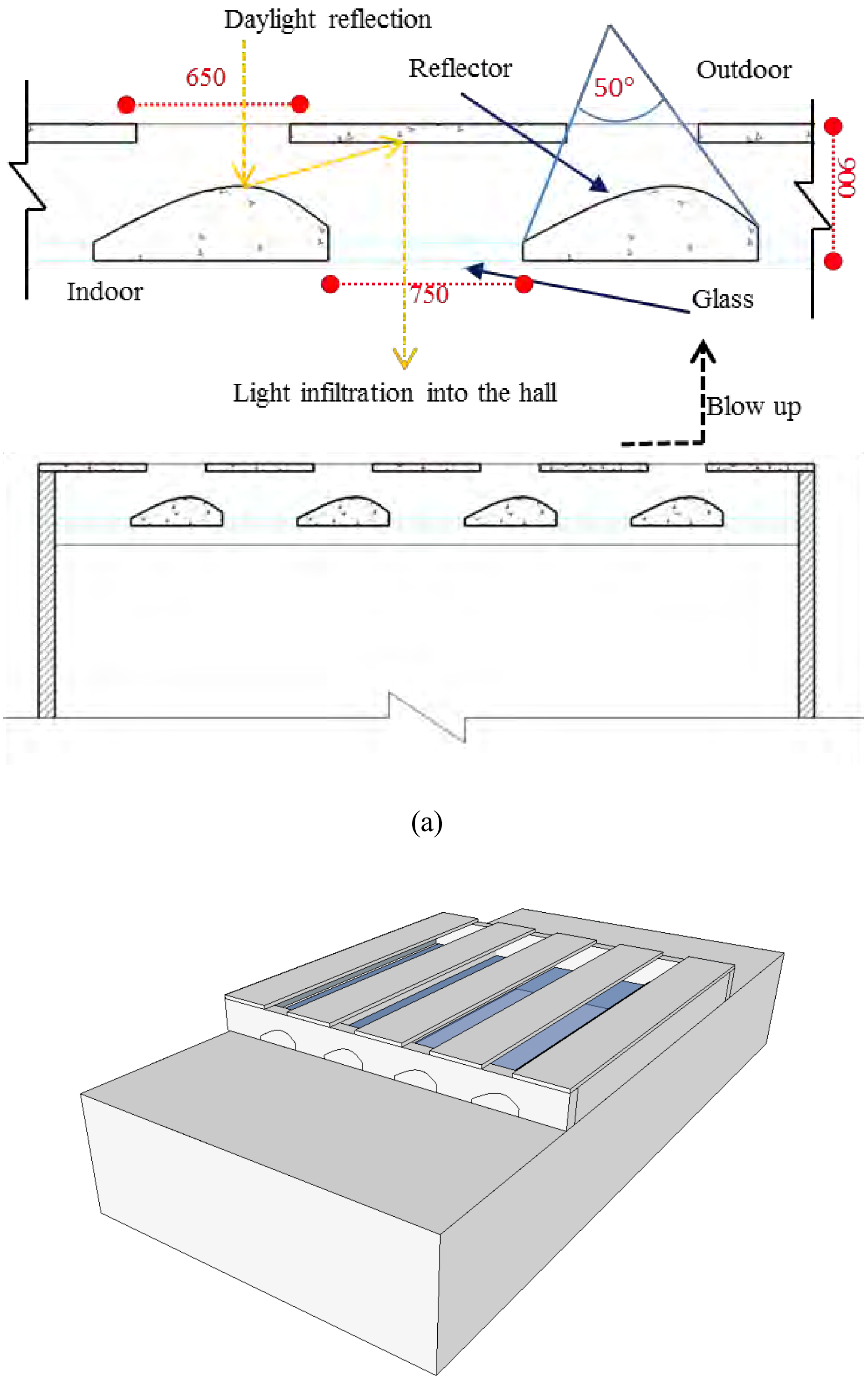


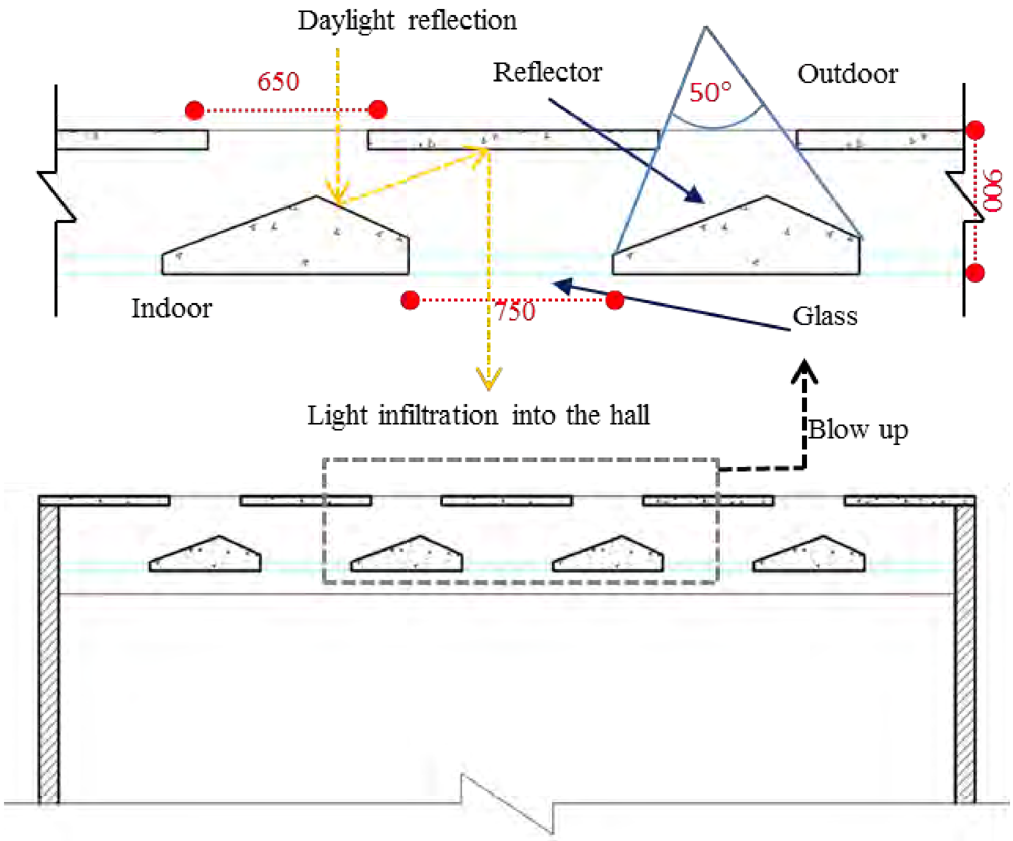
Figure 3.36: Detail section (a) and 3D view (b) of R3 roof configuration of case hall of PU for the simulation study.



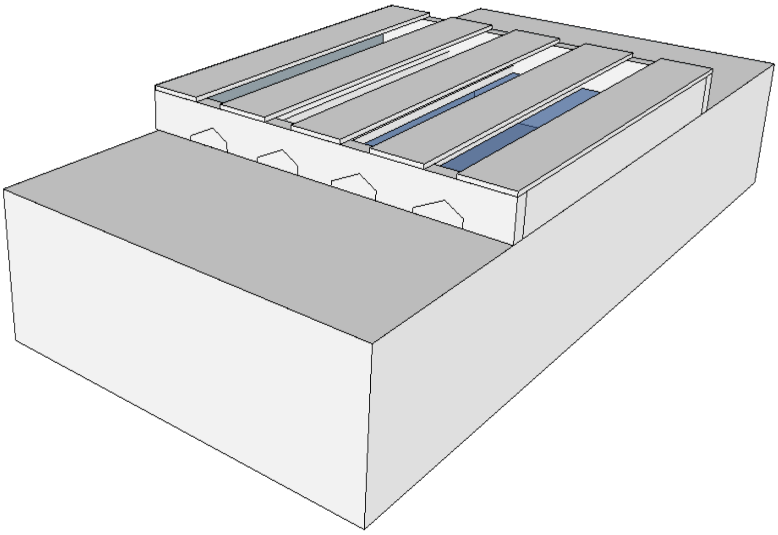
(a)

(b)

Figure 3.37: Detail section (a) and 3D view (b) of R4 roof configuration of case hall of PU for the simulation study.



(a)



(b)

Figure 3.38: Detail section (a) and 3D view (b) of R5 roof configuration of case hall of PU for the simulation study.

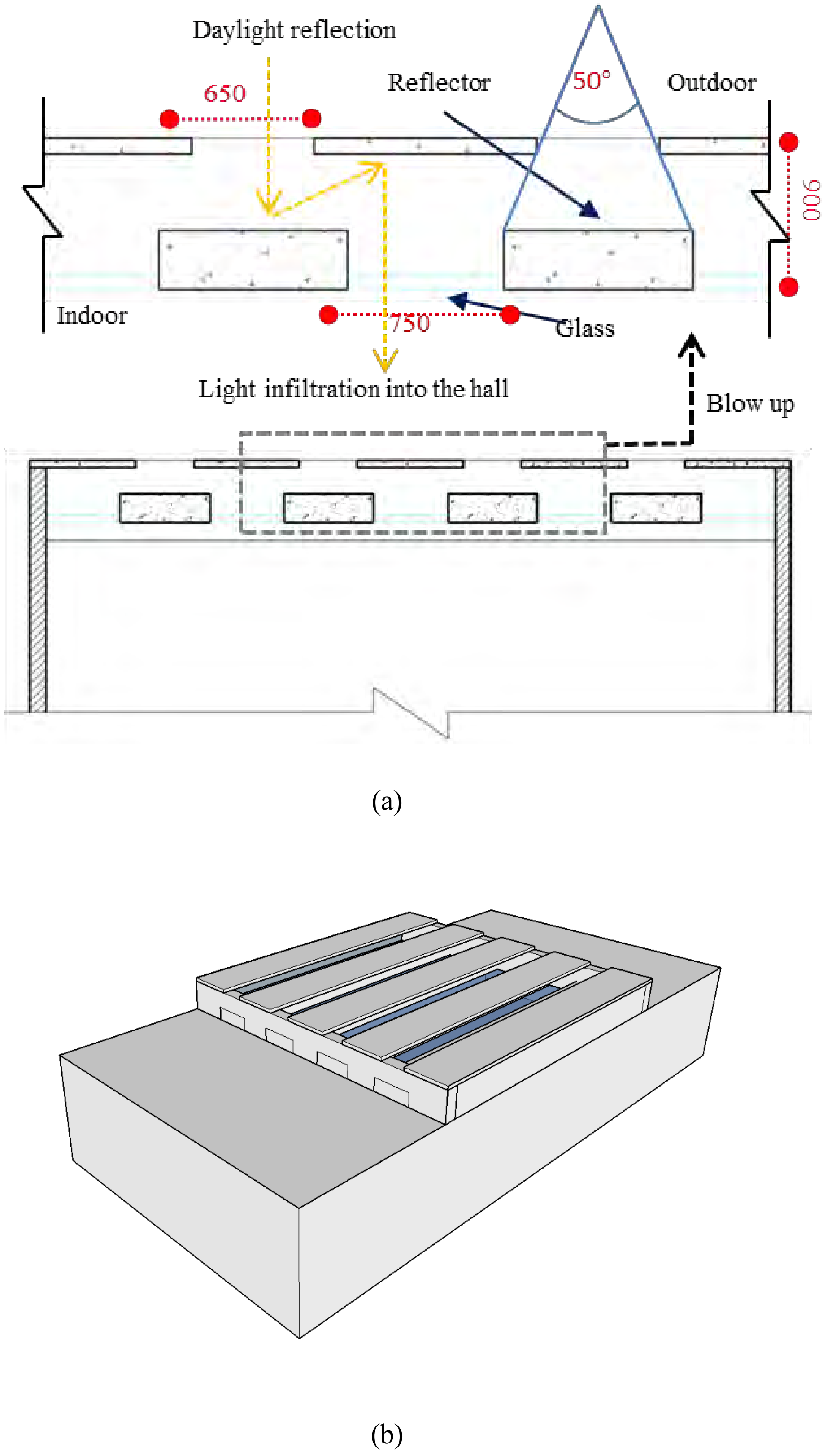


Figure 3.39: Detail section (a) and 3D view (b) of R6 roof configurations of case hall of PU for the simulation study.

3.5.6 Selection of test points on work plane height and simulation parameters

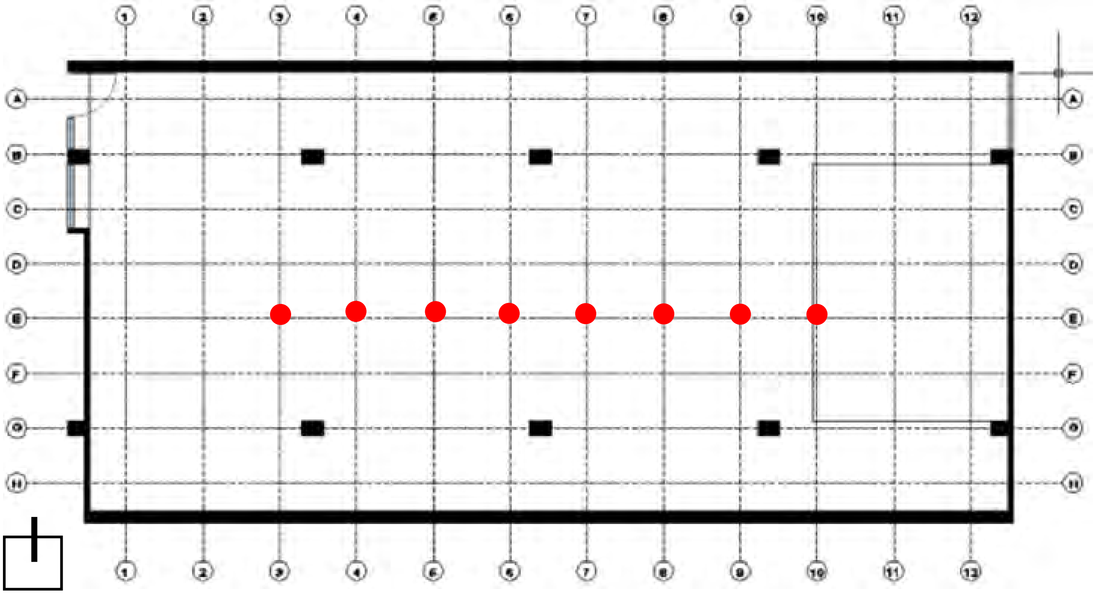


Figure 3.40: Location of the core and test sensor points in the multipurpose hall of PUC

The first step of the daylight simulation is to pick the number and location of sensor points. A common approach is to define a grid of illuminance sensors that extends throughout a lighting zone(Reinhart et al, 2006). The case hall was divided into 77 points for the simulation purpose. These 77 sensor points were set into the work plane height of 0.45m (18 inch) from the finished floor. Intersection points were coded according to the letter and number systemshown in the(Figure 3.40) and Table 3.7. There were 12 sensor axis lines on XX‟ direction and 8 on YY‟ direction and a typical grid dimension of 1.5m X 1m were maintained at the work plane height. Some of these sensor points can be specified as “core work plane sensors” (Figure 3.46) depending on the particular space, that is sensors close to where the occupants usually located (Nabil and Mardaljevic, 2005). The sensor points beside walls were not counted as core work plane sensors because these spaces are mainly used for circulation purpose and not required the same amount of light as the main occupied area. The interior space was modelled as vacant, devoid of any partitions or furniture, to avoid the effects of such surfaces, which both block and reflect daylight, and may hide the actual difference of the impact of the different roof configurations being assessed.

3.5.7 Performance evaluation criteria

Once sensor locations and a time basis have been established, the next step is to choose criteria that determine whether the daylight situation at a sensor is adequate or not. For daylight simulation performance evaluation several criteria have been suggested as following.

1. **DF** is the ratio of internal light level to external light level and is defined as follows: DF = (Ei / Eo) x 100%

Where, E_i = illuminance due to daylight at a point on the indoor working plane
E_o = simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky.

In order to calculate E_i, one must establish the amount of light received from the outside to the inside of a building. Average daylight factors are divided into the following categories.

a) Below 2% – Not adequately lit – artificial lighting will be required.
b) Between 2% and 5% – Adequately lit but artificial lighting may be in use for part of the time.
c) Above 5% – Well lit – artificial lighting generally not required except at dawn and dusk – but glare and solar gain may cause problems.

2. **DA [%],** a percentage of annual daytime hours that a given point in a space is above a specified illumination level. For this research, DA threshold was assumed as 300 lux. If daylit hours are considered from 8:00 AM to 6:00 PM, it means 10 hour of a day x 365 days = 3650 luminous hours round the year.
3. **UDI [%]** is hourly time values based upon three illumination ranges, 0-100 lux, 100-2000 lux, and over 2000 lux (Nabil, 2006). Below 100 lux is not considered as working light. It provides full credit only to values between100 lux and 2,000 lux. This range is regarded as useful daylight illumination range. Horizontal illumination values above 2,000 lux range are not useful. 2000 lux is the upper threshold, above which daylight is not wanted due to potential

glare or overheating. So, less value of UDI<2000 means good indoor luminous environment.

4. **DA $_{max}$ [%]** is an illuminance-based glare analysis metrics. The idea is to calculate DA $_{max}$ using an illuminance threshold which is 10 times the design illuminance. For example, if 300 lux is the threshold then over 3000 lux (300 x 10) will be counted as DA $_{max}$ value. DA $_{max}$ must not exceed 1%, for more than 5% of a critical working plane area (Iqbal, 2015).
5. **Continuous Daylight Autonomy [DA$_{con}$],** proposed by Rogers (2006), is another set of metrics that resulted from research on classrooms. In contrast to earlier definitions of daylight autonomy, partial credit is attributed to time steps when the daylight illuminance lies below the minimum illuminance level. For example, in the case where minimum 300 lux are required and 260 lux are provided by daylight at a given time step, a partial credit of 0.87 (260 Lux/300 Lux) is given for that time step.

3.5.8 Identifying approach for the evaluation process

Once a dynamic daylight performance metric has been calculated for multiple sensor points in a space, the result can be presented through graphical representations such as contour plots and false colour maps. Such graphical presentationsare valuable by themselves because they present how daylight is distributed throughout a space. Yet, for a rating system it is often more desirable to come up with single metric for a space.

For the dynamic performance metrics, different overall rating procedures have been proposed in the past. One approach is to concentrate on central core work plane sensors. Sensor points around the central axis towards east-west direction can be considered as central core work plane sensors. In the Table 3.7, this would be the sensors on the axis at EE (Figure 3.40) from west facade to east facade. This is the approach that has been used for the daylight autonomy calculations (Reinhart2006). In this research, core work plane sensor approach was applied. In Table 3.7 EE axis towards east west direction represents the central axis core work plane sensor point„s formula.

Table 3.7*: Intersection points for simulation study*

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	1A	2A	3A	4A	5A	6A	7A	8A	9A	10A	11A	12A
B	1B	2B	3B	4B	5B	6B	7B	8B	9B	10B	11B	12B
C	1C	2C	3C	4C	5C	6C	7C	8C	9C	10C	11C	12C
D	1D	2D	3D	4D	5D	6D	7D	8D	9D	10D	11D	12D
E	1E	2E	**3E**	**4E**	**5E**	**6E**	**7E**	**8E**	**9E**	**10E**	11E	12E
F	1F	2F	3F	4F	5F	6F	7F	8F	9F	10F	11F	12F
G	1G	2G	3G	4G	5G	6G	7G	8G	9G	10G	11G	12G
H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H
Visible node : 96												
Core sensor points: 3E, 4E, 5E, 6E, 7E, 8E, 9E, 10E.												

In order to capture the interconnection between different sensors in a lighting zone, Nabil and Mardaljevic (2005) recommend to group all work plane sensors together and consider daylight only usefull‖, if work plane sensors synchronously lie in the recommended 100 lux to 2000 lux range. For this simulation approach, DA and DAmax and continuous DA were measured with the mean value of sensor points of the entire floor. On the other hand, UDI, DA and DF were measured on the individual core sensor points on EE axis.

3.6 Summary

This chapter has achieved the second objective of this research.

To achieve the second objectiveDesign Spiral Methodology (Figure 3.2) created by the Biomimicry Institute (founded by Janine Benyus) was selected to adopt and practice biomimicry. The spiral process begins identifying a problem that has to be resolved rather than asking what to design. Dolichopteryx longpipes (Wagner et al., 2009) has an interesting ocular system; the main eyes are supported by a structure called diverticulum that allows capturing light to recognize objects from horizontal and horizon directions, in the diverticulum, there is a cell mirror that reflects light aiming to the retina which can be mimicked to generate design concept.

Six biomimetic roof configurations were generated from the replicated cell mirror. The original idea is not conceived in that way, the position of the mirror is vertically downwards so the fish can collect light from the bottom of the sea but the replicated shape is considered as vertically upwards so that it can receive lights from outside of the roof (Figure 3.24). Later the shape is considered as horizontal position and converted to divergent, convergent, and flat platform sequentially.

In the context of Bangladesh diffuse roof light is more effective in the interior space because a disadvantage of horizontal roof lights is that, compared to vertical windows, they collect more light and heat in summer than in winter – usually the opposite of what is desired, particularly in the tropics.Case hall selection, climatic analysis, simulation tool selection, performance evaluation criteria, selection of test points on work plane height and simulationparameters were set through the simulation methodology.

In some cases architects and buildings imitate the forms of living organisms by looking and following appearance as a concept without testing the inner mechanisms that cannot be considered as true biomimicry (El-Zeiny, 2012), rather named as biomorphism (Pawlyn, 2011). This research is focused on an approach for morphodesign and according to the principle of biomimicry the outcomes may not appeared to biomorphism (i.e appearance of mimicked organism) but the mechanism and process are structured by applying the principles behind biomimicry concept.

This Chapter explains the morpho design approach, day lighting strategies and methodology for the researchwith selection criteria of case multipurpose hall. The results of detail simulation analysis of case multipurpose hall for biomimicry inspired roof configurations have been presented in the next Chapter 4.

4. CHAPTER FOUR: SIMULATION STUDY AND RESULTS

Preamble

Evaluation of biomimicry inspired roof configuration performance

Dynamic daylight simulation results

Parametric study of the most feasible configuration type

Summary

CHAPTER 4 SIMULATION STUDY AND RESULTS

4.1 Preamble

The first chapter of this thesis introduces the research. Chapter 2 provides the theoretical basis of this research. The third chapter described the detail steps of the methodology applied in this thesis. This chapter contains the descriptions and outputs of simulation exercise based on the outcomes of previous two chapters. This chapter consists of three major parts. The first part describes the evaluation of biomimicry inspired roof configurations. The second part describes the outcomes of dynamic metrics which considers possible biomimetic roof models for a year. Finally, the third part elaborates the comparative analysis between the biomimetic roof configurations according to daylight simulation. The strategies based on the activities and key findings have been presented in concluding Chapter 5.

4.2 Evaluation of biomimicry inspired roof configuration performance

Performance metrics can be used for comparative studies. Performance metrics range from being rather specific, e.g. it can be used to benchmark a biomimetic roof configuration for a multipurpose hall against a pool of biomimicry inspired other roof configurations. These metrics usually combine several individual sub metrics into a single overall rating, stipulating a pass or fail criteria for each sub metric (Reinhart et al. 2006).

Dynamic Daylight Simulation (DDS) involve a pre-processing step during which a set of daylight coefficient is calculated for each sensor points and a post-processing step during which the daylight coefficients are coupled with the climate data to yield the annual time series of interior illuminance and luminance. Conversely, standing in contrast to static modelling concepts such as daylight factors, dynamic simulation processes in this perspective, meaning variable with time due to varying sky conditions and shading device settings,. Six biomimetic roof configurations generated from morpho 01 -06 (Section 3.4.6) were coded as R1, R2, R3, R4, R5 and R6 (Table 4.1) and simulated in dynamic metrics.

Table 4.1:Coding of the biomimeticroof configurations.

Biomimetic roof configuration name	Code	Glaze/floor area ratio
Roof configuration generated from morpho 01	R1	20%
Roof configuration generated from morpho 02	R2	20%
Roof configuration generated from morpho 03	R3	20%
Roof configuration generated from morpho 04	R4	20%
Roof configuration generated from morpho 05	R5	20%
Roof configuration generated from morpho 06	R6	20%

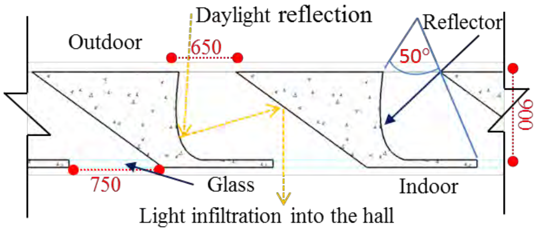
4.3 Dynamic daylight simulation results

Summary results of annual dynamic metric simulations are shown in this Section, considering core work plane sensor approach (described in Section 3.5.5), which was introduced by Reinhart (2006).

4.3.1 Dynamic daylight simulation of R1

Table 4.2 presents the summary results of dynamic daylighting performance process for R1 model in the case multipurpose hall. It was observed from the Table that core sensor point 6E yielded highest 96% DA with highest 4.8 DF. Lowest 69% DA with lowest 1.4 DF were found at 10E sensor point. 3E sensor point yielded the best UDI value with highest $UDI_{100\text{-}2000}$ metric value (95%) and 10E yielded lowest $UDI_{>2000}$ metric value (0%) than the other sensor points. On the other hand, 6E sensor point yielded the worst UDI value with lowest 58% $UDI_{100\text{-}2000}$ metric value and highest 41% $UDI_{>2000}$ metric value. R1 simulation result showed acceptable value range on different metrics performance but the UDI value is too high in several core points and have possibilities of glare and heat problem.

Table 4.2: Annual CBDM simulation result of model R1

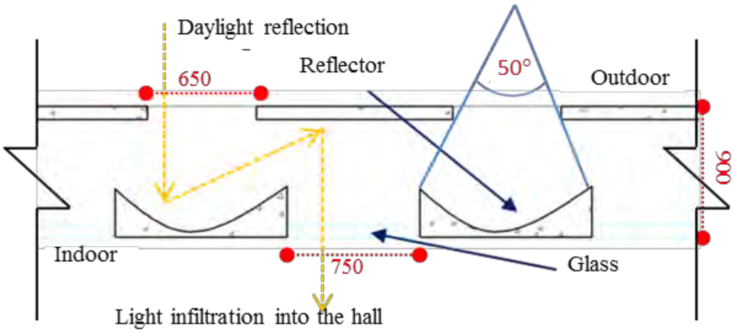
Name and code	*R1*
Cross section of the configuration	

Core points	**3E**	**4E**	**5E**	**6E**	**7E**	**8E**	**9E**	**10E**
Daylighting factor [DF] [%]	1.8	3.5	4.5	4.8	4.7	4.2	3.2	1.4
Daylight autonomy [DA] [%]	83	93	95	96	95	94	90	69
Continuous DA mean [DA $_{con}$] [%]	93	97	98	98	98	97	96	88
Maximum DA mean [DA $_{max}$] [%]	0	9	23	24	25	19	9	0
UDI<100 [%]	4	2	2	2	2	2	2	6
UDI 100-2000[%]	95	70	60	58	59	60	78	94
UDI> 2000 [%]	2	28	39	41	40	38	20	0

4.3.2 Dynamic daylight simulation of R2

Table 4.3 presents the summary results of dynamic daylighting performance process for R2 model in the case multipurpose hall. It was observed from the Table that core sensor point 5E yielded highest 95% DA. Core points 5E and 7E yielded the highest DF simultaneously i.e. 4.6%. Lowest 71% DA with lowest 1.5 DF were found at 10E sensor point. 3E sensor point yielded the best UDI value with highest UDI100-2000 metric value (96%) and 3E, 10E yielded lowest UDI>2000 metric value (0%) than the other sensor points. On the other hand, 5E and 7E both sensor point yielded the worst UDI value with lowest 65% UDI100-2000 metric value and 5E shows the highest 34% UDI>2000 metric value. R2 simulation result showed acceptable value range on different metrics performance but the UDI value is too high in several core points and have possibilities of glare and heat problem as well.

Table 4.3: Annual CBDM simulation result of model R2

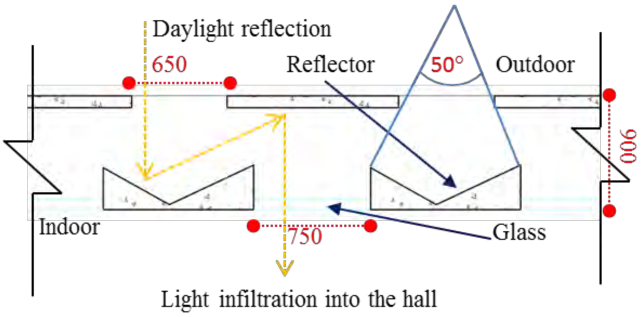
Name and code	*R2*
Cross section of the configuration	

Core points	**3E**	**4E**	**5E**	**6E**	**7E**	**8E**	**9E**	**10E**
Daylighting factor [DF] [%]	1.9	3.7	4.6	4.5	4.6	4.4	3.0	1.5
Daylight autonomy [DA] [%]	82	94	95	94	94	94	89	71
Continuous DA mean [DA_{con}] [%]	93	97	98	97	97	97	95	88
Maximum DA mean [DA_{max}] [%]	0	1	9	11	11	7	0	0
UDI<100 [%]	4	2	2	2	2	2	2	6
UDI 100-2000[%]	96	74	65	67	65	68	89	94
UDI> 2000 [%]	0	24	34	32	33	30	9	0

4.3.3 Dynamic daylight simulation of R3

Table 4.4 presents the summary results of dynamic daylighting performance process for R3 model in the case multipurpose hall. It was observed from the Table that core sensor point 4E-8E yielded highest 98% DA and 5E, 7E were found with highest 10.4 DF. Lowest 91% DA with lowest 3.2 DF were found at 10E sensor point. 10E sensor point yielded the best UDI value with highest $UDI_{100-2000}$ metric value (84%) and lowest $UDI_{>2000}$ metric value (14%) than the other points. On the other hand, 5E sensor point yielded the worst UDI value with lowest 24% $UDI_{100-2000}$ metric value and highest 74% $UDI_{>2000}$ metric value. R3 simulation result did not show acceptable value range on different metrics performance especially the $UDI_{100-2000}$ value is low and $UDI_{>2000}$ value is too high in several core points and have possibilities of glare and heat problem.

Table 4.4: Annual CBDM simulation result of model R3

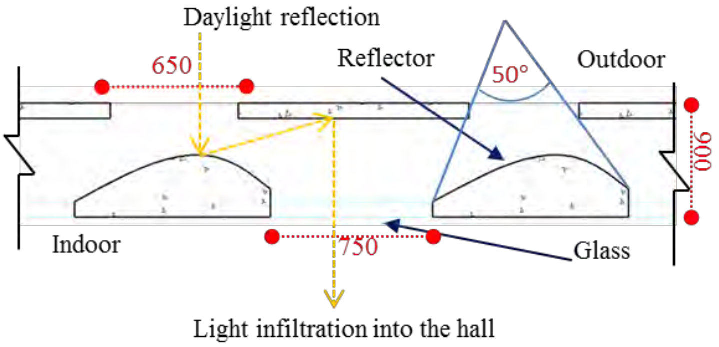
Name and code	*R3*
Cross section of the configuration	

Core points	**3E**	**4E**	**5E**	**6E**	**7E**	**8E**	**9E**	**10E**
Daylighting factor [DF] [%]	4.5	8.2	10.4	10.3	10.4	9.0	6.5	3.2
Daylight autonomy [DA] [%]	95	98	98	98	98	98	97	91
Continuous DA mean [DA_{con}] [%]	98	99	99	99	99	99	98	96
Maximum DA mean [DA_{max}] [%]	10	49	56	56	57	52	34	1
UDI<100 [%]	2	1	1	1	1	1	1	2
UDI 100-2000[%]	61	30	24	26	26	32	44	84
UDI> 2000 [%]	38	68	74	73	73	66	54	14

4.3.4 Dynamic daylight simulation of R4

Table 4.5 presents the summary results of dynamic daylighting performance process for R4 model in the case multipurpose hall. It was observed from the Table that core sensor point 5E, 6E and 7E yielded highest 96% DA and 6E were found with highest 4.8 DF. Lowest 78% DA with lowest 1.8 DF were found at 10E sensor point. 10E sensor point yielded the best UDI value with highest $UDI_{100\text{-}2000}$ metric value (93%) and lowest $UDI_{>2000}$ metric value (3%) than the other points. On the other hand, 6E sensor point yielded the worst UDI value with lowest 51% $UDI_{100\text{-}2000}$ metric value and highest 48% $UDI_{>2000}$ metric value. R4 simulation result did not show acceptable value range on different metrics performance especially the $UDI_{100\text{-}2000}$ value is low and $UDI_{>2000}$ value is too high in several core points and have possibilities of glare and heat problem.

Table 4.5: Annual CBDM simulation result of model R4

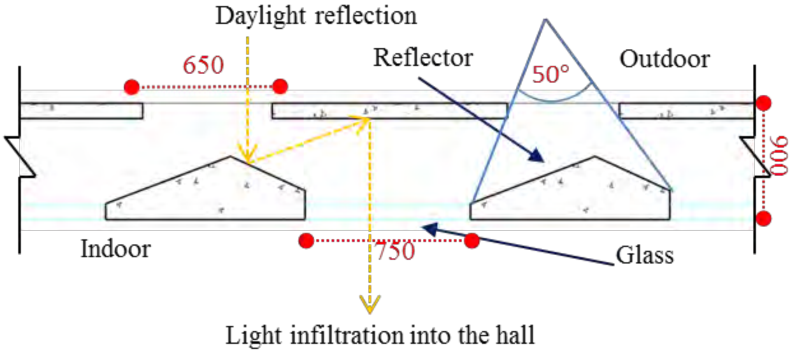
Name and code	*R4*
Cross section of the configuration	

Core points	3E	4E	5E	6E	7E	8E	9E	10E
Daylighting factor [DF] [%]	2.3	4.6	5.4	6.0	5.7	5.1	3.8	1.8
Daylight autonomy [DA] [%]	86	95	96	96	96	95	91	78
Continuous DA mean [DA $_{con}$] [%]	94	98	98	98	98	98	96	91
Maximum DA mean [DA $_{max}$] [%]	7	20	28	32	30	25	10	2
UDI<100 [%]	3	2	2	2	2	2	2	4
UDI 100-2000[%]	88	61	56	51	53	58	74	93
UDI> 2000 [%]	9	37	42	48	45	41	24	3

4.3.5 Dynamic daylight simulation of R5

Table 4.6 presents the summary results of dynamic daylighting performance process for R5 model in the case multipurpose hall. It was observed from the Table that core sensor point 4E-9E yielded highest 98% DA and 7E were found with highest 13.7 DF. Lowest 94% DA with lowest 4.5 DF were found at 10E sensor point. 10E sensor point yielded the best UDI value with highest UDI$_{100-2000}$ metric value (63%) and lowest UDI$_{>2000}$ metric value (35%) than the other sensor points which is not satisfactory. On the other hand, 7E sensor point yielded the worst UDI value with lowest only 18% UDI$_{100-2000}$ metric value and highest 81% UDI$_{>2000}$ metric value. R5 simulation result did not show acceptable value range on maximum metrics performance and have high possibilities of glare and heat problem.

Table 4.6: Annual CBDM simulation result of model R5

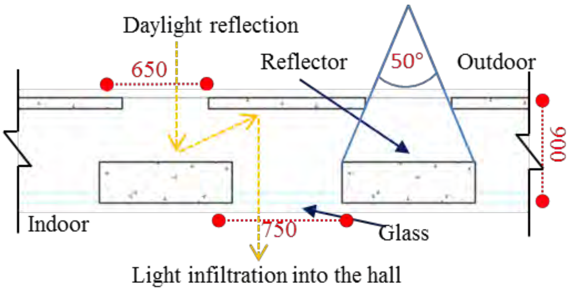
Name and code	*R5*
Cross section of the configuration	

Core points	**3E**	**4E**	**5E**	**6E**	**7E**	**8E**	**9E**	**10E**
Daylighting factor [DF] [%]	6	10.1	12.2	12.8	13.7	12.1	8.9	4.5
Daylight autonomy [DA] [%]	97	98	98	98	98	98	98	94
Continuous DA mean [DA $_{con}$] [%]	98	99	99	99	99	99	98	97
Maximum DA mean [DA $_{max}$] [%]	28	54	63	63	65	60	48	6
UDI<100 [%]	1	1	1	1	1	1	1	2
UDI 100-2000[%]	49	26	20	19	18	24	35	63
UDI> 2000 [%]	49	73	79	80	81	75	63	35

4.3.6 Dynamic daylight simulation of R6

Table 4.7 presents the summary results of dynamic daylighting performance process for R3 model in the case multipurpose hall. It was observed from the Table that core sensor point 4E-8E yielded highest 94% DA and 6E were found with highest 3.3 DF. Lowest 80% DA with lowest 1.1 DF were found at 10E sensor point. 3E sensor point yielded the best UDI value with highest UDI$_{100\text{-}2000}$ metric value (94%). 3E and 10E yielded lowest UDI$_{>2000}$ metric value (0%) than the other sensor points. On the other hand, 6E sensor point yielded the UDI value with lowest 84% UDI$_{100\text{-}2000}$ metric value and highest 14% UDI$_{>2000}$ metric value resulting much more satisfactory result compare to R1 and R2. R6 simulation result showed satisfactory value range on different metrics performance.

Table 4.7: Annual CBDM simulation result of model R6

Name and code	*R6*
Cross section of the configuration	

Core points	**3E**	**4E**	**5E**	**6E**	**7E**	**8E**	**9E**	**10E**
Daylighting factor [DF] [%]	1.4	2.6	3.1	3.3	2.9	3.0	2.2	1.1
Daylight autonomy [DA] [%]	82	94	94	94	94	94	92	80
Continuous DA mean [DA $_{con}$] [%]	88	95	96	96	96	95	93	82
Maximum DA mean [DA $_{max}$] [%]	0	3	4	4	3	3	3	0
UDI<100 [%]	6	3	2	2	2	2	4	9
UDI 100-2000[%]	94	93	87	84	88	90	92	91
UDI> 2000 [%]	0	5	11	14	9	7	4	0

4.3.7 Comparison of Dynamic Daylight Simulation Results

Table 4.8 presents the summary results of dynamic daylighting performance process for case hall provided with six biomimetic roof configurations R1-R6(Figure 4.1-4.6). According to DA and DA$_{con}$, R5 is superior to the other six roof categories. However, it scored considerably lower in DA$_{max}$, UDI$_{100\text{-}2000}$ and UDI$_{>2000}$ metrics. On the other hand, UDI$_{>2000}$ results suggest that, R1- R5 are over daylit having the rate 26%, 20.3% , 57.5%, 31.1% and 66.9% respectively. UDI$_{100\text{-}2000}$ along with other metrics shows that, model R6 generated from morpho 06 produce larger amount of useful daylight into the hall.

Table 4.8: Comparison of average dynamic daylight metrics for the studied six roof configurations (R1-R6)

Code of Roof	**DF(%)**	**DA (%)**	**DA con (%)**	**DA max (%)**	**UDI<100 (%)**	**UDI 100-2000 (%)**	**UDI>2000 (%)**
R1	3.5	89.4	95.6	13.6	2.8	71.8	26
R2	3.5	89.1	95.3	4.9	2.8	77.3	20.3
R3	7.81	96.6	98.4	39.4	1.3	40.9	57.5
R4	4.3	91.6	96.4	19.3	2.3	66.8	31.1
R5	10	97.4	98.5	48.4	1.1	31.8	66.9
R6	2.5	90.5	92.6	2.5	3.8	89.9	6.3

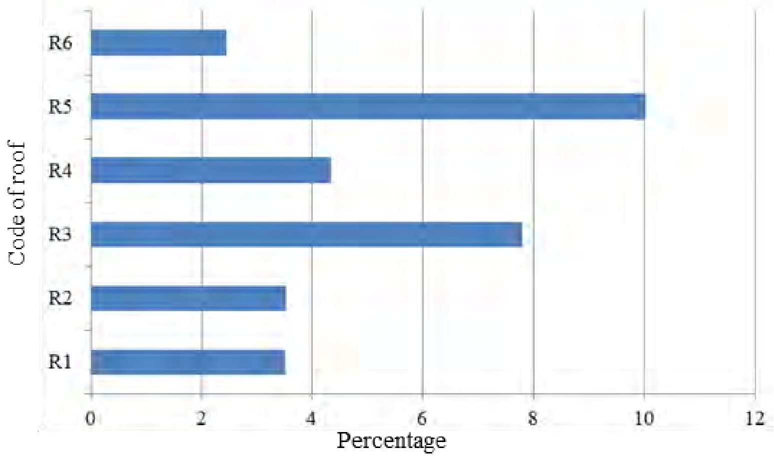


Figure 4.1: DF performance analysis of biomimicry inspired roof configurations for the case hall.

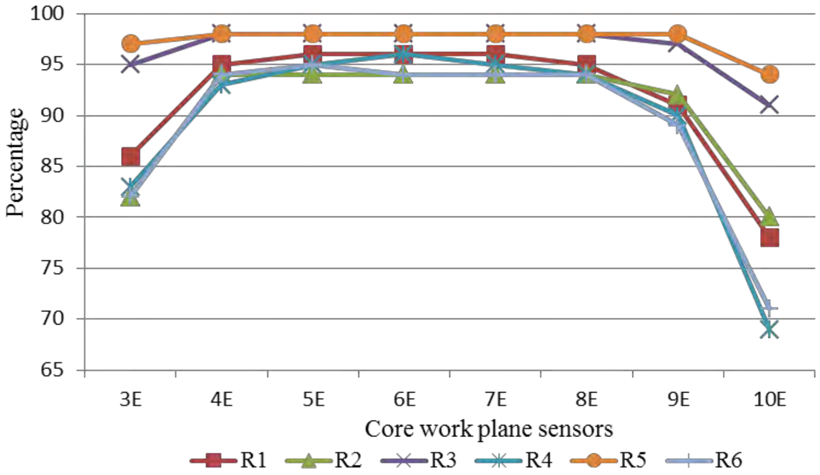


Figure 4.2: DA performance of biomimicry inspired roof configurations for the case hall.

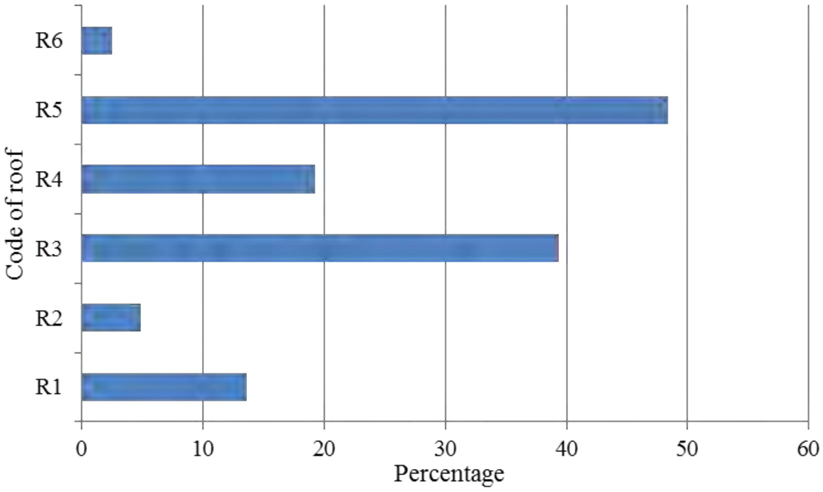


Figure 4.3: DA$_{max}$ performance of biomimicry inspired roof configurations for the case hall.

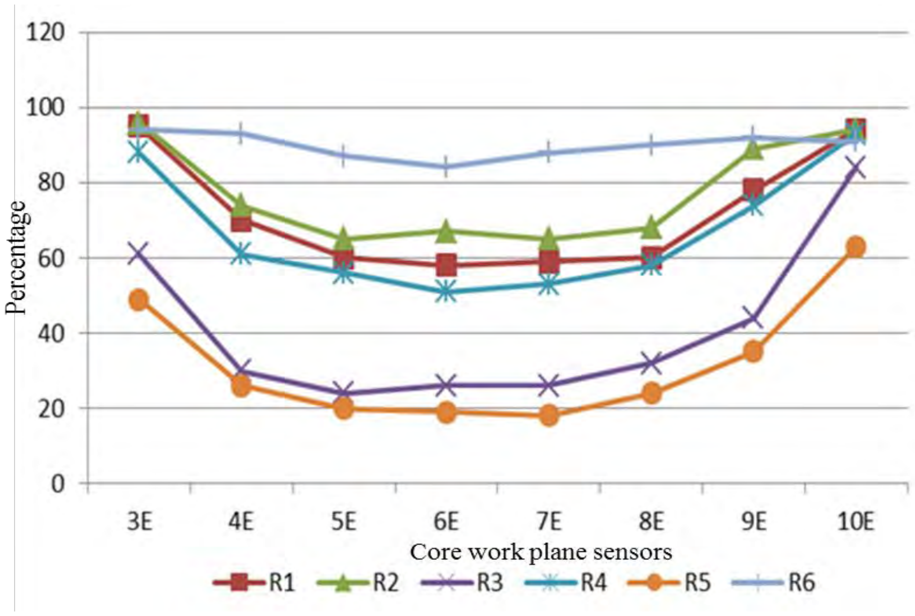


Figure 4.4: UDI $_{100\text{-}2000}$ metric performance of biomimetic roof configurations for the case hall.

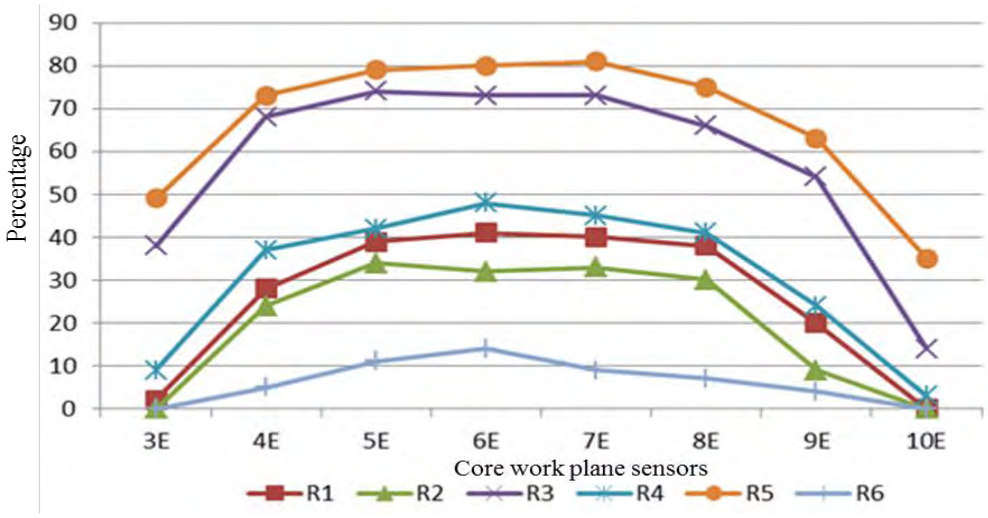


Figure 4.5: UDI$_{>2000}$ performance of biomimicry inspired roof configurations for the case hall.

4.3.8 Rating system of the simulation results

Rating between the sixbiomimetic roof configuration simulated results is easier to interpret using the dynamic metrics except DF and DA$_{con}$ metrics.DA$_{con}$ metric was identical almost for all roof configuration types and DF consider only overcast sky (Reinhart et al. 2006).

*Table 4.9**:** Rating of average dynamic daylight metrics for the studied six roof configurations (R1-R6)*

Code of Roof	DA [%]	DA max (%)	UDI<100 [%]	UDI100 -2000 [%]	UDI>2000 [%]	Rating and Ranking
R1	1	3	2	3	3	**3rd (12)**
R2	0	4	2	4	4	**2nd (14)**
R3	4	1	4	1	1	**4th (11)**
R4	3	2	3	2	2	**3rd (12)**
R5	5	0	5	0	0	**5th (10)**
R6	2	5	1	5	5	**1st (18)**

From configuration 1st to 6th place, rating points were considered as 5 point to 0 point respectively (Reinhart et al., 2006). Table 4.9 shows the rating of the six configurations (R1-R6) according to the different metrics. When a metric led to different rating for the EE axis of the space, the mean result and the minimum to maximums range for core work plane sensors were compared. After summing up the rating points achieved by the biomimetic roof configurations, R6 was found as superior with 18 points than other biomimetic roof configurations (Table 4.9). On the other hand, R5 was found as lowest as it achieved only 10 points.

4.4 Parametric study with varying roof opening angle of R6

In this section, simulation and comparison were done considering experimental light entering roof angel of R6 with 5° increment and 5° decrement (e.g.50°, 55° and 45°)

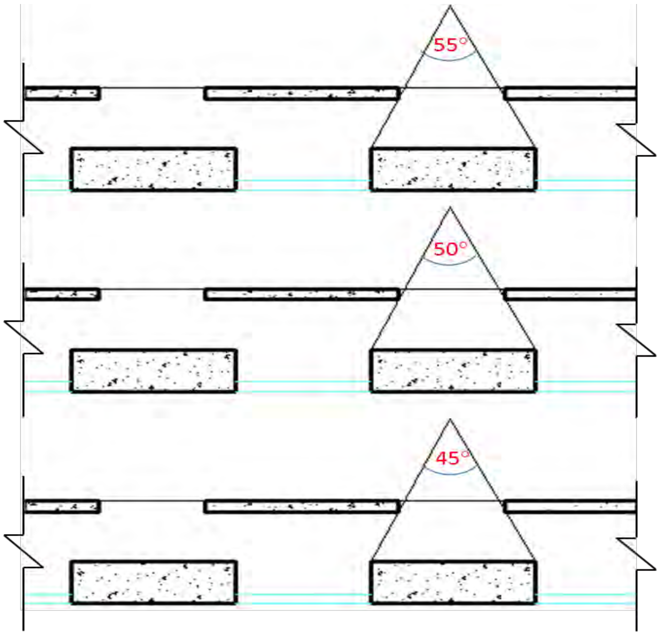


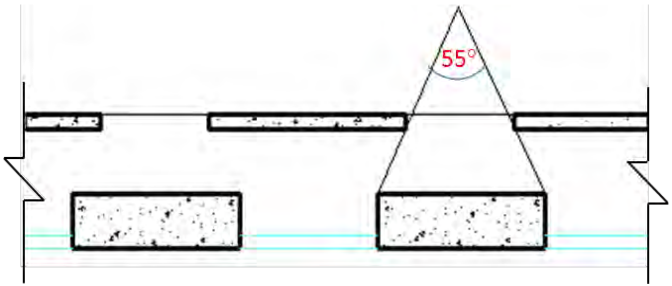
Figure 4.6: Experimental sections of different opening angel of R6 roof configuration.

a. 55° roof opening angel (coded as R6-55^{O})

Table 4.10 presents the summary results of dynamic daylighting performance process for R6-55° model in the case multipurpose hall. It was observed from Table 4.10 that core sensor point 5E-8E yielded highest 96% DA and 6E were found with highest 5.4 DF.

Lowest 72% DA with lowest 1.6 DF were found at 10E sensor point. 3E sensor point yielded the best UDI$_{100-2000}$ metric value (97%). 3E and 10E yielded lowest UDI$_{>2000}$ metric value (0%) than the other sensor points. On the other hand, 7E sensor point yielded the UDI value with lowest 59% UDI$_{100-2000}$ metric value and highest 40% UDI$_{>2000}$ metric value resulting poor result compared to 50° opening roof angel R6-50° (Table 4.7).

Table 4.10: Annual CBDM simulation result of model R6-55° opening roof angel

Name and code	*R6-55°*
Cross section of the configuration	

Core points	**3E**	**4E**	**5E**	**6E**	**7E**	**8E**	**9E**	**10E**
Daylighting factor [DF] [%]	2.2	4.1	5.3	5.4	5.4	4.6	3.4	1.6
Daylight autonomy [DA] [%]	84	94	96	96	96	94	90	72
Continuous DA mean [DA $_{con}$] [%]	94	97	98	98	98	97	96	89
Maximum DA mean [DA $_{max}$] [%]	0	2	15	16	16	9	0	0
UDI<100 [%]	3	3	2	2	2	2	2	6
UDI 100-2000[%]	97	73	60	60	59	68	82	94
UDI> 2000 [%]	0	25	38	39	40	30	15	0

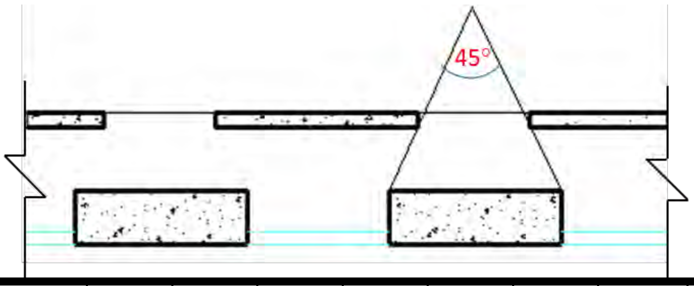
b. 50° roof opening angel (coded as R6-50^{O})

The performance of the opening roof angle 50° (e.g. R6) has been described in previous section 4.3 and Table 4.7.

c. 45° roof opening angel (coded as R6-45^{O})

Table 4.11 presents the summary results of dynamic daylighting performance process for R6-45^{O} model in the case multipurpose hall. It was observed from the table that core sensor point 5E and 6E yielded highest 91% DA and 6E were found with highest 3.1 DF. Lowest 57% DA with lowest 1.0 DF were found at 10E sensor point. 4E and 9E sensor point yielded the best UDI$_{100\text{-}2000}$ metric value (97%). 3E, 4E, 9E and10E yielded lowest UDI$_{>2000}$ metric value (0%) than the other points. On the other hand, 6E sensor point yielded the UDI value with lowest 87% UDI$_{100\text{-}2000}$ metric value and highest 11% UDI$_{>2000}$ metric value resulting good result compare to 55° opening roof angel R6-55° described earlier.

Table 4.11: Annual CBDM simulation result of model R6-45° opening roof angel

Name and code	*R6-45°*							
Cross section of the configuration								
Core points	**3E**	**4E**	**5E**	**6E**	**7E**	**8E**	**9E**	**10E**
Daylighting factor [DF] [%]	1.3	2.5	2.9	3.1	2.9	2.8	2.1	1.0
Daylight autonomy [DA] [%]	69	88	91	91	90	89	84	57
Continuous DA mean [DA $_{con}$] [%]	87	95	96	96	96	95	93	81
Maximum DA mean [DA $_{max}$] [%]	0	3	4	4	4	3	2	0
UDI<100 [%]	7	3	2	2	2	2	3	10
UDI 100-2000[%]	93	97	92	87	91	93	97	90
UDI> 2000 [%]	0	0	6	11	7	5	0	0

d. Comparison of different roof opening angle of biomimetic roof configuration R6

Table 4.12 presents the summary results of dynamic daylighting performance process for different experimental roof opening angle of R6 roof configuration. According to DA R6-50° is superior and according to DAcon and UDI$_{<100}$ R6-55° is giving the better result to the other two roof categories. R6-55°performed considerably poor in DAmax, UDI$_{100\text{-}2000}$ and UDI$_{>2000}$ metrics. On the other hand, UDI$_{>2000}$ results suggest that, R6-50° and R6-45°are giving satisfactory result, respectively 6.3% and 3.6%. UDI$_{100\text{-}2000}$ along with other metrics shows that, model R6-50° and R6- 45° (45° opening roof angel) produce larger amount of useful daylight into the hall.

*Table 4.12**:** Comparison of average dynamic daylight metrics for the studied three experimental roof configurationswith different opening angel (R6-55°, R6-50°, R6-45°)*

Code of Roof	DF(%)	DA (%)	DA con (%)	DA max (%)	UDI<100 (%)	UDI 100-2000 (%)	UDI>2000 (%)
R6-55^{O}	4	90.3	95.9	7.3	2.8	74.1	23.4
R6-50^{O}	2.5	90.5	92.6	2.5	3.8	89.9	6.3
R6-45^{O}	2.3	82.4	92.4	2.5	3.9	92.5	3.6

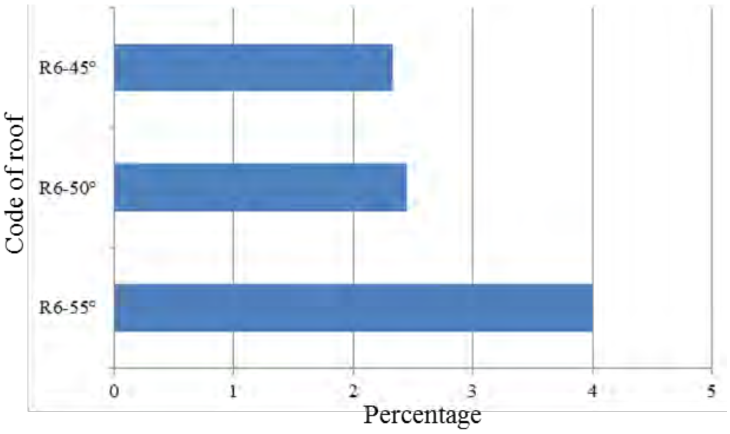


Figure 4.7: DF performance analysis of the studied experimental roof configurations with different roof opening angel of R6 configuration.

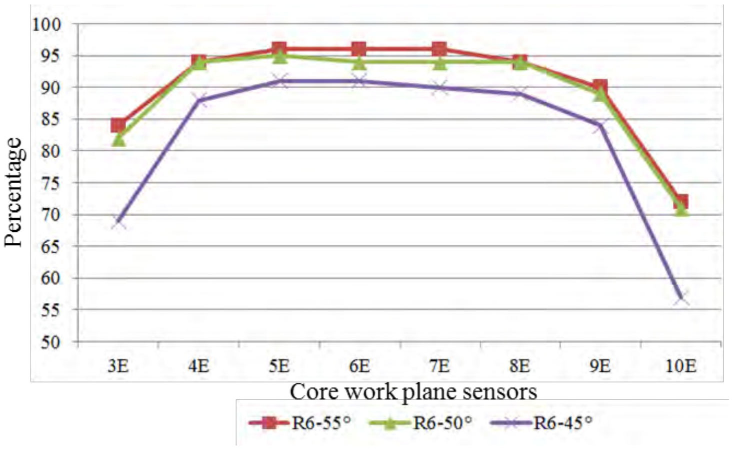


Figure 4.8: DA performance analysis of the studied experimental roof configurations with different roof opening angel of R6 configuration.

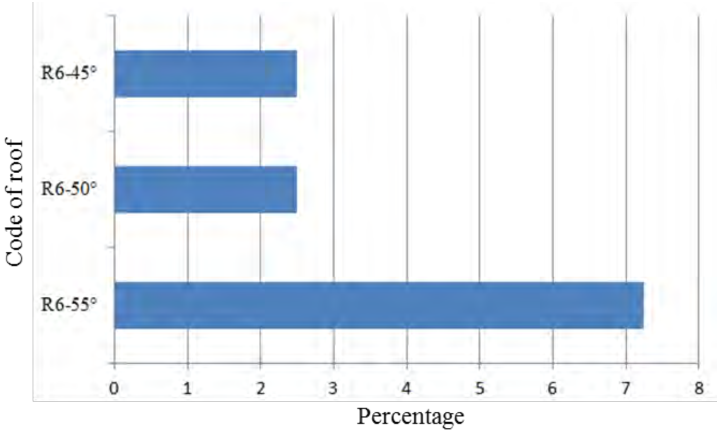


Figure 4.9: DA $_{max}$ performance analysis of the studied experimental roof configurations with different roof opening angel of R6 configuration.

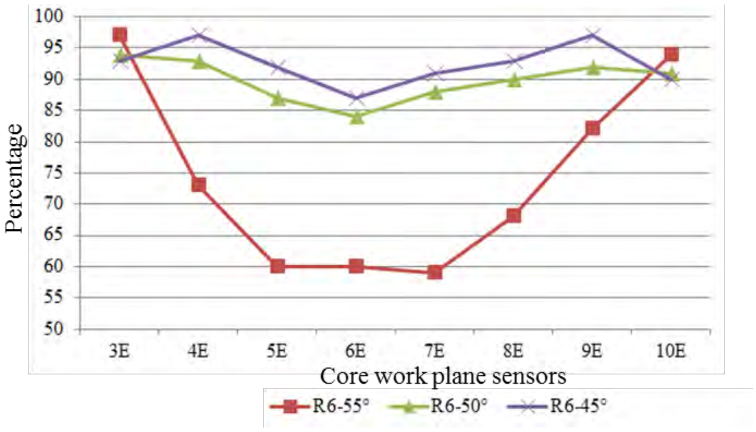


Figure 4.10: UDI $_{100\text{-}2000}$ performance analysis of the studied experimental roof configurations with different roof opening angel of R6 configuration.

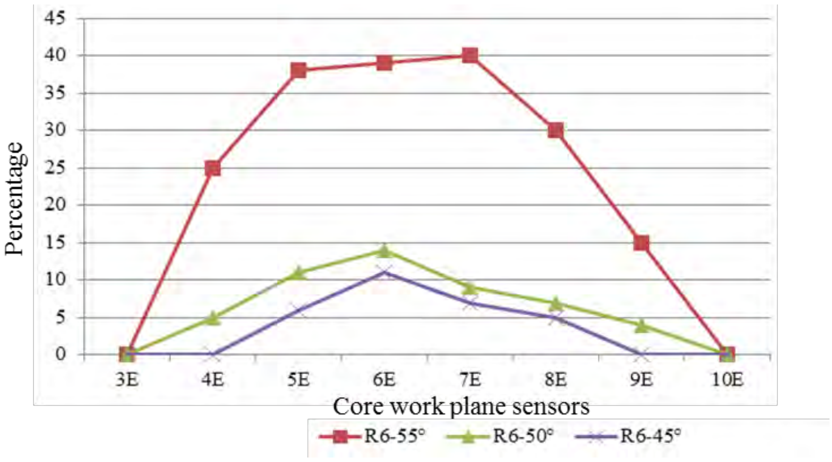


Figure 4.11: UDI$_{>2000}$performance analysis of the studied experimental roof configurations with different roof opening angel of R6 configuration.

e. Rating of different roof opening angle of biomimetic roof configuration R6

From 1st to 3rd place rating points were considered as 2 points-0 point respectively (Table 4.13). Rating was done considering the dynamic metric, e.g. DA, DA $_{con}$,UDI $_{100-2000}$, UDI$_{>2000}$ and DA$_{max}$,range values and mean value of core sensor points for experimental condition of different roof opening angle of biomimetic roof configuration R6.

Table 4.13: Rating of average dynamic daylight metrics for the studied different roof opening angle of biomimetic roof configurationof R6

Code of Roof	DA [%]	DA max (%)	UDI<100 [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	Rating and Ranking
R6-55^{O}	1	1	2	0	0	**2nd (4)**
R6-50^{O}	2	2	1	1	1	**1st (7)**
R6-45^{O}	0	2	0	2	2	**3rd (6)**

From table 4.13 it can be stated that among the studied different roof opening angle of biomimetic roof configuration R6 is still the superior biomimetic roof configuration with an opening angel of 50° which is close to the cell mirror of *Dolichopteryx longpipes* (Figure 3.14) which can receive light at a range of 48° (Wagner et al, 2009).

4.5 Parametric study with varying roof configuration depth of R6

In this section, simulation and comparison were done considering experimental roof configuration depth of R6-50^{O} with 100 mm decrement and 100mm increment (e.g.900 mm, 800 mm and 1000mm)

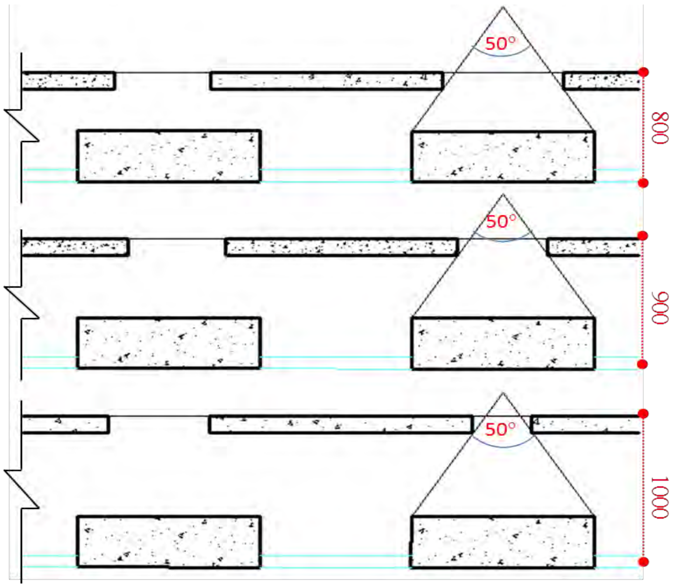
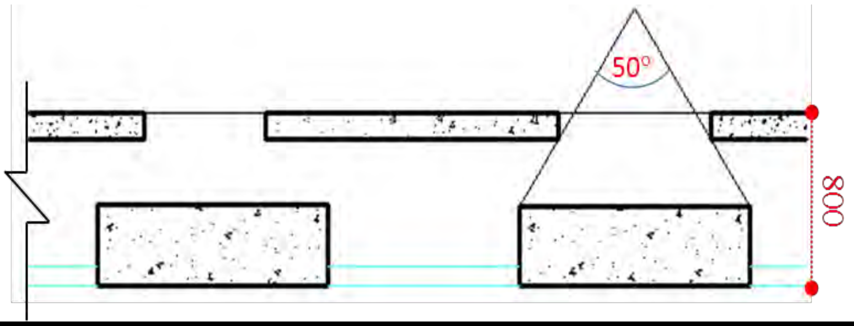


Figure 4.12: Experimental sections of different depth of R6 roof configuration.

a. 800 mm roof configuration depth (coded as R6-50^{O} [800mm])

Table 4.14 presents the summary results of dynamic daylighting performance process for R6-800 mm model in the case multipurpose hall. It was observed from Table 4.14 that core sensor point 6E and 7E yielded highest 93% DA and 7E were found with highest 3.7 DF. Lowest 59% DA with lowest 1.1 DF were found at 10E sensor point. 9E sensor point yielded the best UDI$_{100\text{-}2000}$ metric value (97%). 3E, 9E and 10E yielded lowest UDI$_{>2000}$ metric value (0%). On the other hand, 7E sensor point yielded the UDI value with lowest 77% UDI$_{100\text{-}2000}$ metric value and highest 21% UDI$_{>2000}$ metric value resulting poor result compared to 900mm roof configuration depth R6-900mm.

Table 4.14: Annual CBDM simulation result of model R6-50° [800mm]

Name and code	*R6*-50^{O} [*800mm]*
Cross section of the configuration	

Core points	3E	4E	5E	6E	7E	8E	9E	10E
Daylighting factor [DF] [%]	1.6	2.7	3.3	3.6	3.7	3.4	2.2	1.1
Daylight autonomy [DA] [%]	76	90	92	93	93	92	85	59
Continuous DA mean [DA $_{con}$] [%]	90	96	96	97	97	96	94	82
Maximum DA mean [DA $_{max}$] [%]	0	0	0	0	0	0	0	0
UDI<100 [%]	5	5	2	2	2	2	3	9
UDI 100-2000[%]	95	94	82	79	77	84	97	91
UDI> 2000 [%]	0	4	16	19	21	14	0	0

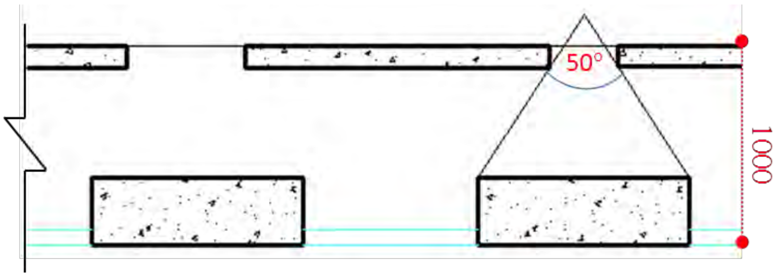
b. 900 mm roof configuration depth (coded as R6-50^{O} [900mm])

The performance of the 900 mm roof configuration depth(e.g. R6-50^{O} [900mm]) has been described in previous section 4.3.6 and Table 4.7.

c. 1000 mm roof configuration depth (coded as R6-50^{O} [1000mm])

Table 4.15 presents the summary results of dynamic daylighting performance process for R6-1000 mm model in the case multipurpose hall. It was observed from the table that core sensor point 6E yielded highest 97% DA. 6E and 7E were found with highest 6.2 DF. Lowest 78% DA with lowest 1.9 DF were found at 10E sensor point along with the best UDI$_{100-2000}$ metric value (93%) and lowest UDI$_{>2000}$ metric value (3%). On the other hand, 6E sensor point yielded the UDI value with lowest 49% UDI$_{100-2000}$ metric value and highest 50% UDI$_{>2000}$ metric value resulting in very poorperformance compared to previousexperimented roof configurations.

*Table 4.15: Annual CBDM simulation result of model R6-***50^{O}** [*1000mm]*

Name and code	*R6*-50^{O} [*1000mm]*
Cross section of the configuration	

Core points	**3E**	**4E**	**5E**	**6E**	**7E**	**8E**	**9E**	**10E**
Daylighting factor [DF] [%]	2.7	4.6	5.8	6.2	6.2	5.7	4.0	1.9
Daylight autonomy [DA] [%]	88	94	96	97	96	95	92	78
Continuous DA mean [DA $_{con}$] [%]	95	97	98	98	98	98	97	91
Maximum DA mean [DA $_{max}$] [%]	4	10	25	29	27	20	3	2
UDI<100 [%]	3	3	2	2	2	2	2	4
UDI 100-2000[%]	91	67	54	49	52	57	76	93
UDI> 2000 [%]	6	31	44	50	47	41	22	3

d. Comparison of different roof depth of biomimetic roof configuration R6

Table 4.16 presents the summary results of dynamic daylighting performance process for different experimental roof configurationdepth. According to DA, DAcon and UDI$_{<100}$ R6-1000mm is superior and according to DF R6-900mm is giving the better result to the other two roof categories.

Table 4.16: Comparison of average dynamic daylight metrics for the studied three experimental roof configurations with different ceiling to roof depth (R6-50° [800mm], R6-50° [900mm] R6-50° [900mm], and R6-50° [1000mm],

Code of Roof	DF(%)	DA (%)	DA con (%)	DA max (%)	UDI<100 (%)	UDI 100-2000 (%)	UDI>2000 (%)
R6-50^O [800mm]	2.7	85	93.5	0	3.8	87.4	9.3
R6-50^O [900mm]	2.5	90.5	92.6	2.5	3.8	89.9	6.3
R6-50^O [1000mm]	4.6	92	96.5	15	2.5	67.4	30.5

However, R6-1000mm scored considerably poor in DA$_{max}$, UDI$_{100-2000}$ and UDI$_{>2000}$ metrics. On the other hand, UDI$_{>2000}$ results suggest that, R6-900mm and R6-800mm are giving satisfactory result, respectively 6.3% and 9.3%. UDI$_{100-2000}$ along with other metrics shows that, model R6-900mm and R6-800mm (800 mm roof configuration depth) produce larger amount of useful daylight into the hall.

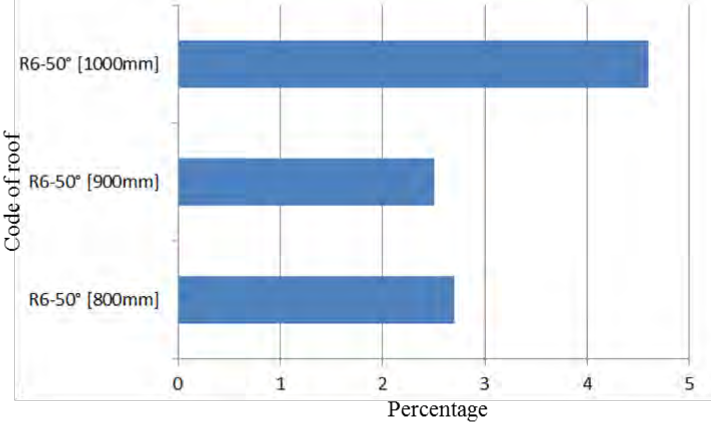


Figure 4.13: DF performance analysis of the studied experimental roof configurations with different depth of R6 configuration.

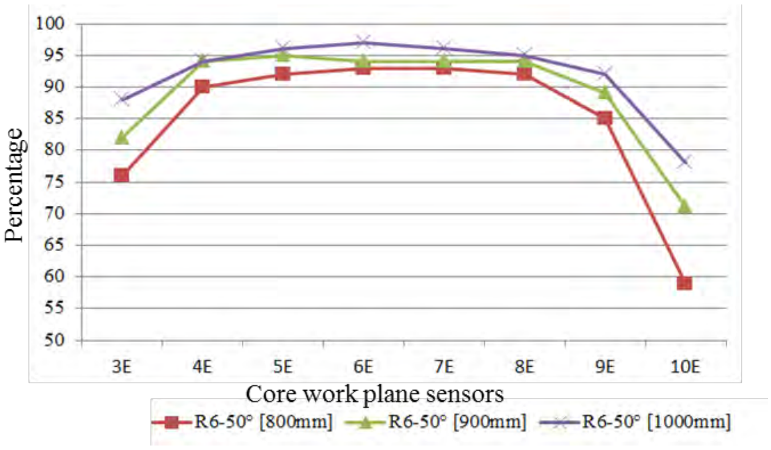


Figure 4.14: DA performance analysis of the studied experimental roof configurations with different depth of R6 configuration.

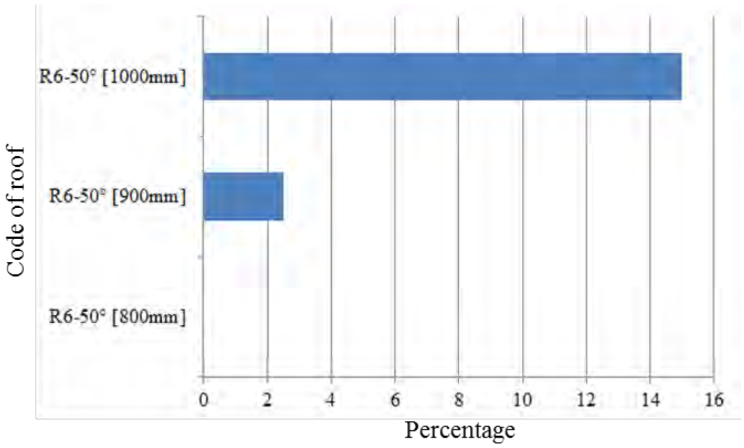


Figure 4.15: DA $_{max}$ performance analysis of the studied experimental roof configurations with different depthof R6 configuration.

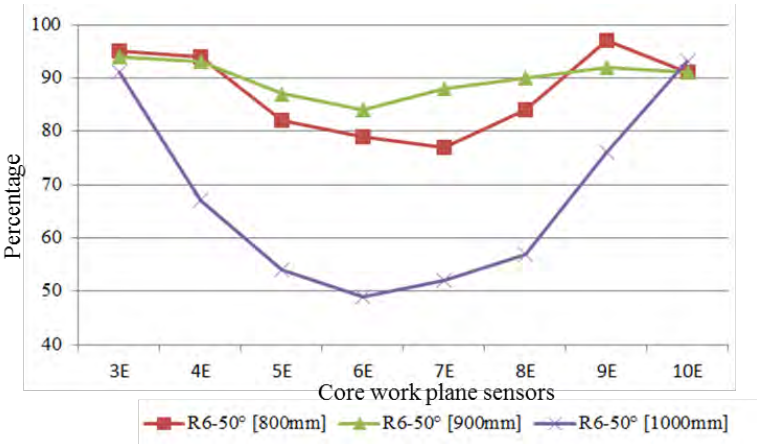


Figure 4.16: UDI $_{100\text{-}2000}$performance analysis of the studied experimental roof configurations with different depthof R6 configuration.

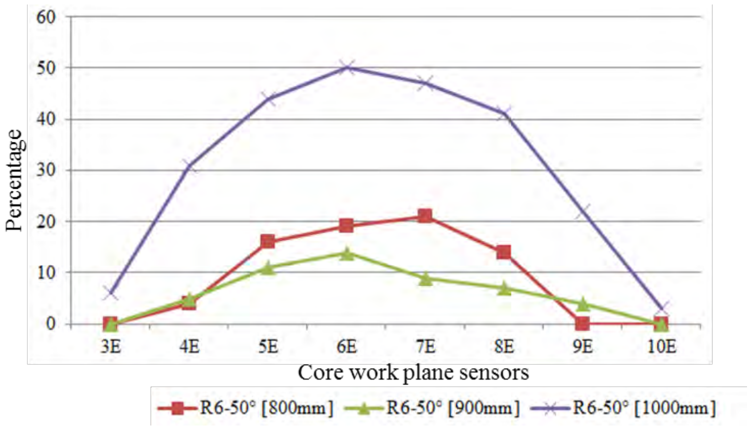


Figure 4.17: UDI$_{>2000}$ performance analysis of the studied experimental roof configurations with different depth of R6 configuration.

e. Rating of different depth of biomimetic roof configuration R6

From 1st to 3rd place rating points were considered as 2 points-0 point respectively (Table 4.17). Rating was done considering the dynamic metric, e.g. DA, DA $_{con}$,UDI $_{100\text{-}2000}$, UDI$_{>2000}$ and DA$_{max}$,range values and mean value of core sensor points for experimental condition of different depth of biomimetic roof configuration R6.

Table 4.17: Rating of average dynamic daylight metrics for the studied different height of biomimetic roof configuration of R6

Code of Roof	DA [%]	DA max (%)	UDI<100 [%]	UDI$_{100\text{-}2000}$ [%]	UDI$_{>2000}$ [%]	Rating and Ranking
R6-50^{O} [800mm]	0	2	1	1	1	**2nd (5)**
R6-50^{O} [900mm]	1	1	1	2	2	**1st (7)**
R6-50^{O} [1000mm]	2	0	2	0	0	**3rd (4)**

From table 4.17 it can be stated that among the studied depthof biomimetic roof configuration R6-50^{O} [900mm] remains the superior biomimetic roof configuration with a depth of 900 mm.

4.6 Summary

This Chapter has achieved the third and fourth objectives of the research.

To achieve the third objective six biomimetic roof configurations (Figure 3.34-3.39) were simulated.The configuration with the flat platform was found as the most feasible biomimetic roof for daylighting multipurpose hall in the climatic context of Chattogram, Bangladesh.

To achieve the fourth objective, the performance of different experimental parametric roof configurations varying the roof opening angle and the roof configuration depth (ceiling to roof) were evaluated. Flat platform with a 50° roof opening angle and 900 mm ceiling to roof depth of the biomimetic roof configuration was found as the best biomimetic roof among the studied experimental parametric configurations at the task plane throughout the year for the case multipurpose hall in educational building in context of Bangladesh.

This chapter leads to the presentation of the achievement of the research objectives in next chapter 5 with some indicative recommendations and suggestions for future work.

5. CHAPTER FIVE: CONCLUSION

Preamble

Achievement of the objectives

Recommendations

Conclusion

Suggestion for future research

CHAPTER 5 CONCLUSION

5.1 Preamble

The first chapter of this thesis introduces the research. Chapter 2 provides the theoretical basis of this research and provides a clear understanding of biomimicry concept, how to adapt biomimicry, importance of daylighting and different national and international standards. The third chapter described the detail steps of the methodology applied for the concept generation from a fish eye (Dolichopteryx longpipes) and simulation study in this thesis. In Chapter 4, six biomimetic roof configurations were evaluatedthrough dynamic daylight simulation to find out the most feasible biomimetic roof configuration for the case multipurpose hall. Parametric simulation study was also done to find out the best possible parametric configuration of the feasible biomimetic roof configuration. This chapter will summarize the research by discussing the achievements of the objectives and recommend some indicative suggestions to improve the biomimicry inspired design for daylighting through roof of multipurpose hall. It will also provide some suggestions for future research.

5.2 Achievement of the objectives

The achievements of the objectives of this research, developed in Chapter 1 (Section 1.3) are discussed in this section as following.

5.2.1 Concept and philosophy of biomimicry

The first objective was to understand the concept and philosophy of biomimicry that focus on how to create a passive design that allows effective use of daylight in a tropical zone, such as Bangladesh. At first literature review was conducted to find out the design context, bio-strategies, organisms, lighting strategies, and design creation. To apply the philosophies behind biomimicry it is essential to establish a structure to create a design from the fundamentals of biomimicry.This enables the designer or any specialist to know the idea first so as to apply the standards behind biomimicry according to the writing study. The research question intended to be answeredin this study was - "How to create a passive design based on biomimicry in order to improve the useful daylight through roof in a multipurpose hall?”. Imitating organisms can result in natural lighting solutions as features of buildings inspired by organisms comprised of regulated access of sunlight as discovered from the literature review.

Also found from studies (Chapter 2) is the fact that two kinds of design concepts can be applied for creating passive design to improve useful daylight through roof of the case multipurpose hall by imitating nature: a morphodesign that is related with shapes and structures; and physiodesign that is related with function and materials. This research is focused on an approach for morphodesign.

5.2.2 Appropriate organism for daylighting

Toidentify an appropriate organism to get inspired from in order to initiate a design concept through biomimicry for daylighting deep planned building with single large span roof e.g. multipurpose halls was second objective.An idea of replicated cell mirror is derived from morpho design concept (i.e. originated with shapes and structures of Dolichopteryx Longpipes fish eye) (Chapter 3). The sun on the north and south orientation covers 50° and the mirror can receive a range of 48°. The same mechanism is used as shown in replicated roof (Figure 5.1) as biologically and geographically the range of angle is similar (48° vs 50°). For the case hall model, six roof configurations were proposed in this study (Figure 5.1) based on the principle and work of previous researchers (Wagner et al, 2009; Yanez, 2014) by mimicking the retina study of the Dolichopteryx Longpipes and the cell mirror study (Figure 5.1).

5.2.3 Biomimetic roof configuration

The third objective was to develop a feasible biomimicry inspired roof configuration as passive design techniques for daylighting suitable for the case multipurpose hall with single large span roof. In order to achieve this objective problem based approach of biomimicry was applied. Biomimicry as a source of creativity in design has been secured a position to its application in architecture and engineering, through inspiration and innovation as two key elements for a sustainable achievement.

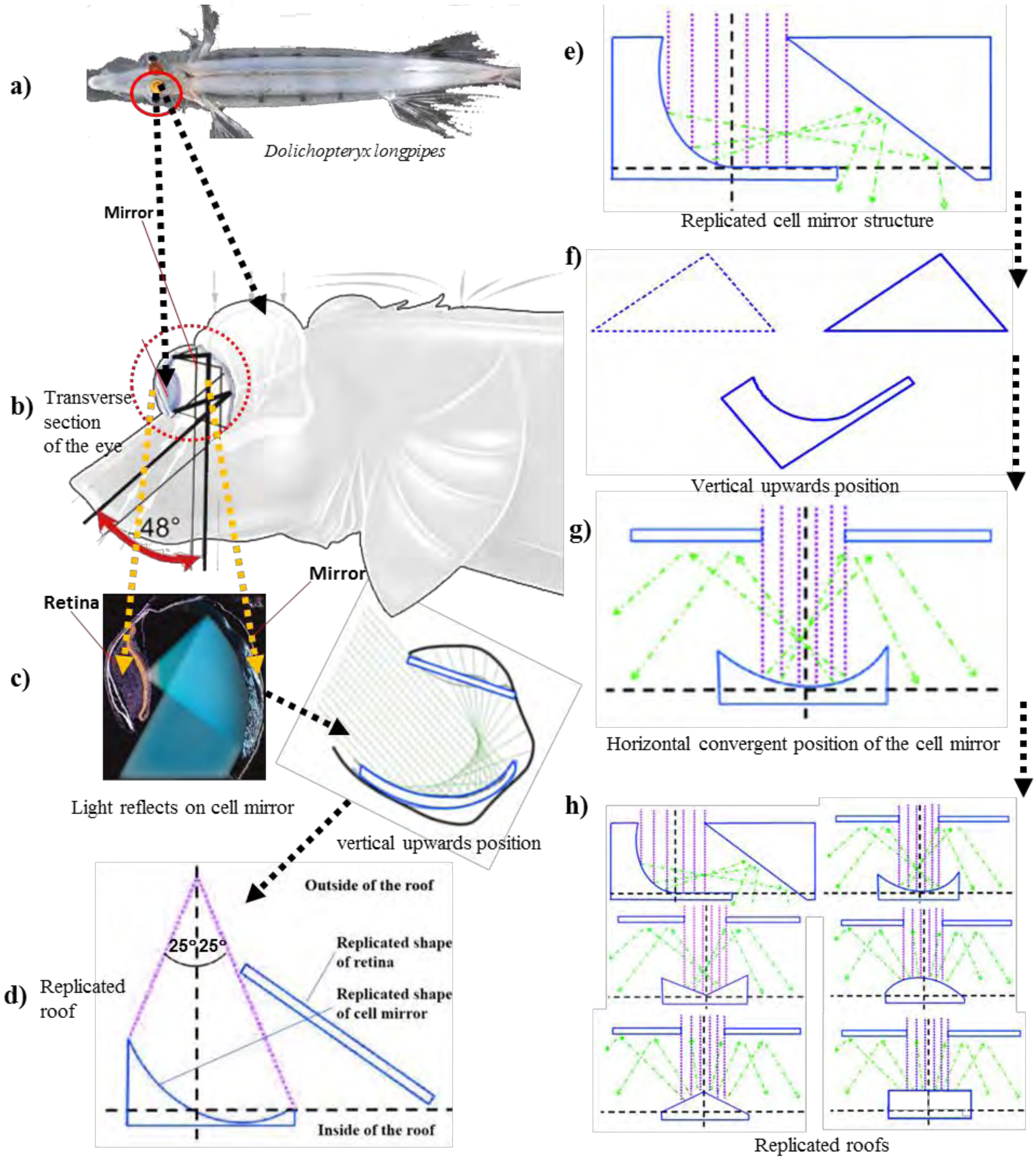


Figure 5.1: Concept of replicating the cell mirror on a rooftop used in 3.4.5 (after Wagner, 2008 and Yanez, 2014).

Dynamic daylight simulation was done based on biological principles that are applied and correlated with morphogenetic computational design. Results from dynamic simulation indicate that, roof configuration Model R6 with flat surface (Figure 5.2) based on morphodesign approach, (i.e. started with shapes and structures of Dolichopteryx Longpipes fish eye) as the most superior biomimicry inspired configuration among the six studied options for multipurpose hall.

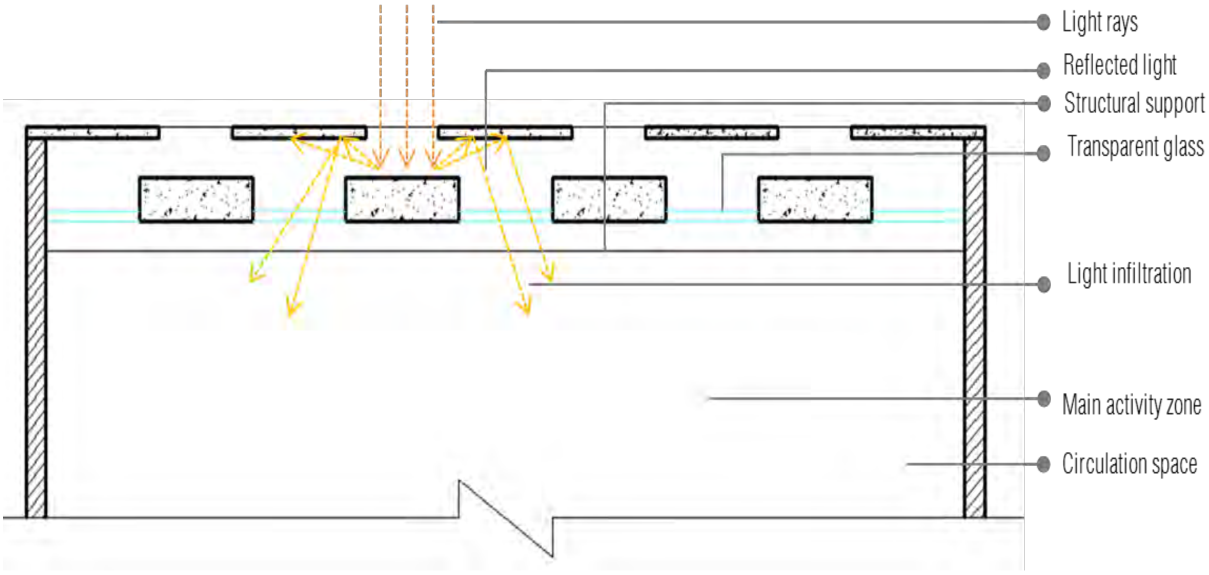


Figure 5.2:: Section of R6 roof configuration

5.2.4 Most effective parametric biomimetic roof configuration

The fourth objective was to identify an effective parametric configuration of the feasible biomimicry inspired roof design to ensure standard lighting levels according to the activities of the users in a multipurpose hall. Parametric study experimented with different roof opening angle shows that R6 (Figure 5.3) roof configuration with a 50° roof opening angle and 900 mm ceiling to roof depth of the biomimetic roof configuration remains the most superior and effective parametric biomimetic roof configuration in educational building among the studied configurations in context of Chattogram, Bangladesh (Figure 5.3).

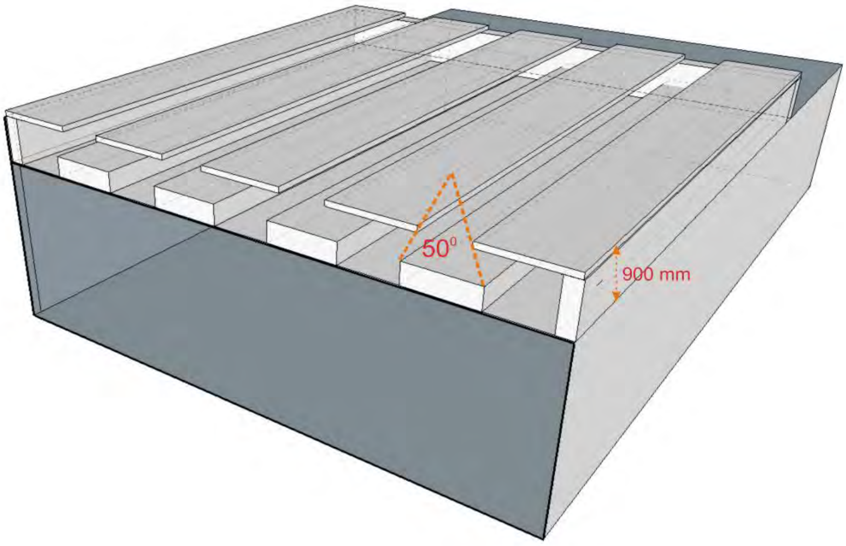


Figure 5.3: Model R6, the superior biomimicry inspired roof configuration among the studied options for the case multipurpose hall.

5.3 Recommendations

From this research the following specific as well as some general recommendations are drawn for biomimetic roof designing of multipurpose hall in educational building in order to improve the luminous environment in the climatic context of Bangladesh.

- To get a suitable biomimetic roof prefer the organism level of biomimicry.
- To start, morphodesign concept can be approached for architectural research that is related with shapes and structures.
- Use non reflective materials in morphodesign concept for avoiding unwanted light reflections as the morphodesign is related with shapes and structures and found suitable result with the existing non reflective materials.
- Use flat slab instead of concave or convex shaped slab. It controls the over reflection of light and provide more effective result along with easier construction.
- Use the roof opening angle 50°and 900 mm ceiling to roof depth as it was found more effective than the others.

Biomimicry design process is based on the natural principles but it should not be a limitation to modify the characteristics of the design if they are ineffective to meet the design aims.

5.4 Suggestions for further research

Some of the important areas that need to be explored in future with special reference to daylighting in multipurpose hall are followings.

- This study is based on the single concept among the two kinds of biomimicry concepts. „Morphodesign" concept is applied that is related with shapes and structures. Further research is needed to fix the other concept „physiodesign" that is related with function and materials.
- This study concentrates only on the daylighting of the multipurpose hall. However, thermal performance of the biomimetic roof configuration needs to be investigated.
- More research is needed to fix the acoustical condition as it"s one of the main concerns in a multipurpose hall.
- More analysis can be done to fix the slab configuration detail to protect the rainwater.
- More analysis can be done to fix the contextual comfort levels of daylighting and total visual environment for the inhabitants.
- The consequences of daylight inclusion on overall energy consumption for multipurpose halls in educational building need to be studied.
- Investigation can be done to find out influence of daylight inclusion on users physical and mental well-being.

Although the adaptation of biomimicry inspired design is structured and follows a step-by-step process, it gives the freedom to the researchers to implement their own ideas at the time of application, so the final result depends on the conjunction of the methodology plus other factors as the site condition or the researcher"s experience.Biomimicry has the capacity to be adapted and developed in conjunction with other ideas.Therefore it is suggested that the researchers should adapt the principles to their own necessities in the design goals and innovation process.It is expected that, the findings of this research will inspire architects and designers to adapt the concept of biomimicry in improving design especially for proper daylight distribution in architecture design through the roof.

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APPENDICES

Appendix A

Summary of the key findings of the research in relation to the objectives, methodologies and concerned chapters.

Appendix Bexplains the key terms and concepts relevant to this thesis in the field of architecture, and lighting. It will help the readers to distinguish between simple terms (e.g. daylight and sunlight) to technical terms (e.g. Daysim and radiance), which sometimes used synonym in daylight literature. The basic concepts to understand CBDM simulation technique (such as backward ray tracing, daylight coefficients and Perez sky model) have been discussed in this appendix.

Appendix C describes thesimulation software.

Appendix Dpresents the detail annual CBDM simulation results.

Appendix A: Summary of the key findings of the research in relation to the objectives, methodologies and concerned chapters

Objective	Methods	Chapter	Key findings
Objective 1: To understand the concept and philosophy of biomimicry that focus on how to create a passive design that allows effective use of daylight in a tropical zone i.e. Bangladesh.	Literature review	Chapter 2	The characteristics of buildings inspired by organisms under controlled entry for sunlight with regulation of internal temperature can be achieved by mimicking plants, flowers, organisms or natural behaviour. Therefore, for daylighting solutions, mimicking organisms could be the way to follow.
Objective 2: To select an appropriate organism to get inspiration to initiate a design concept through biomimicry for daylighting deep planed building/space with single large span roof e.g. multipurpose halls.	Literature study and analysis	Chapter 3	Dolichopteryx longpipes (Wagner et al., 2009) has an interesting ocular system. The main eyes are supported by a structure called diverticulum that allows capturing light to recognize objects from horizontal and below directions. In the diverticulum, there is a cell mirror that reflects light aiming to the retina which can be mimicked to generate design concept.
Objective 3: To develop a feasible biomimicry inspired roof configuration as a passive design techniques for daylighting multipurpose halls.	Dynamic daylight simulation analysis	Chapter 4	The skylight configuration with a flat platform was found as the most feasible biomimetic roof for daylighting multipurpose hall in the climatic context of Chattogram, Bangladesh.
Objective 4: To identify an effective parametric configuration of the feasible biomimicry inspired roofdesign to ensure standard lighting levels according to the activities of the users in a multipurpose hall.	Dynamic daylight simulation analysis	Chapter 4	The flat roof with a 50° roof opening angel and 900 mm ceiling to roof depth of the biomimetic roof configuration was found as the best biomimetic roof among the studied experimental parametric configurations at the task plane throughout the year for the case multipurpose hall in educational building in context of Chattogram, Bangladesh.

Appendix B: Key terms and concepts

LIGHTING TERMINOLOGY

DA (Daylight Autonomy) – is the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone.

DA_{con} (Continuous Daylight Autonomy) – is the percentage of the minimum illuminance requirement met by daylight alone at the sensor during the full occupied times of the year. The metric acknowledges that even a partial contribution of daylight to illuminate a space is still beneficial. For e.g. if the design illuminance is 300 lux on core work plane sensor, and 180 lux are provided by daylight alone at one sensor point during the whole office hours of the year; a partial credit of 180lux/300lux=0.6 (60%) is given to that sensor point.

DA_{max} (Maximum Daylight Autonomy) – is the percentage of the occupied hours when the daylight level is 10 times higher than design illumination; represents the likely appearance of glare.

Daylight factor (DF) – is the ratio of the daylight illuminance at an interior point to the unshaded, external horizontal illuminance of the building under a CIE overcast sky condition.

Diffuse radiation – is the total amount of radiation falling on a horizontal surface from all parts of the sky apart from the direct sun.

Direct radiation – is the radiation arriving at the earth's surface with the sun's beam.

Global radiation – is the total of direct solar radiation and diffuse sky radiation received by a horizontal surface of unit area.

Illuminance – is the quantitative expression for the luminous flux incident on unit area of a surface. A more familiar term would be “lighting level”. Illuminance is expressed in lux (lx). One lux equals one lumen per square meter (lm/m^2). In Imperial units the unit is the foot-candle which equals lumen per square foot (lm/ft²).Other units are – metrecandle, phot, nox.

UDI (Useful daylight illuminance) – try to find out when daylight levels are „useful" for the user and when they are not. Based on occupants" preferences in daylit RMGs, UDI results in three metrics, i.e. the percentages of the occupied times of the year when daylight is useful (100- 2000lux), too dark (<100 lux), or too bright (> 2000 lux).

LIGHTING METHODS

Ambient accuracy (aa) – value is approximately equal the error from indirect illuminance interpolation. A value of zero implies no interpolation.

Ambient bounces (ab)– is the maximum number of diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.

Ambient division (ad) – The error in the Monte Carlo calculation of indirect illuminance will be inversely proportional to the square root of the number of ambient divisions. A value of zero implies no indirect illumination.

Ambient resolution (ar) – determine the maximum density of ambient values used in interpolation. Error will start to increase on surfaces spaced closer than the scene size divided by the ambient resolution. The maximum ambient value density is the scene size times the ambient accuracy divided by the ambient resolution.

A**mbient sampling (as)** – are applied only to the ambient divisions which show a significant change.

Backward raytracing – simulates individual rays from the points of interest to light source or other objects backwardly with respect to a given viewpoint (Figure A.1). It is possible to simulate different basic surfaces (e.g. 100% specular surfaces, lambertian surfaces, transparent surfaces and translucent surfaces) and a random mixture of these basic surfaces under raytracing.

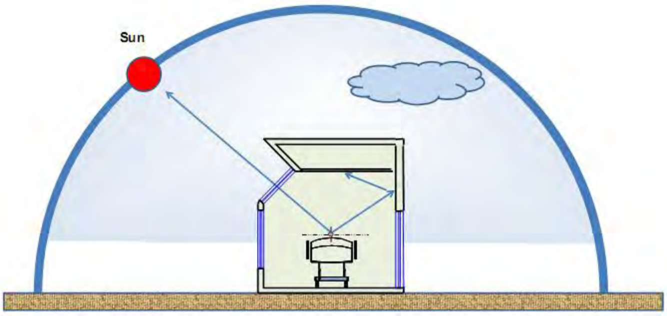

Figure A.1: Backward raytracing simulates individual rays from the points of interest to light source or other objects backwardly (after, Reinhart, 2006).

DAYSIM simulation – calculates the performance metrics considering the impact of local climate and generates a time series indoor annual illuminance profile at points of interest in a building. DAYSIM requires two steps to calculate the annual amount of daylight in a building. Daylight coefficients are calculated first considering the available daylight surrounding the building. After that, the daylight coefficients are combined with the specified climate data of building site. Based on generated illumination profile, DAYSIM derives several dynamic, climate-based daylight performance matrices, such as Daylight Autonomy (DA), Useful Daylight Index (UDI), Continuous Daylight Autonomy (DAcon) and Maximum Daylight Autonomy (DAmax). Figure A.2 shows the process of daylight simulation under DAYSIM. More details on the simulation algorithm used by DAYSIM can be found under Reinhart (2006).

DAYSIM uses **Perez all weather sky luminance model**. Perez sky model was developed in early nineties by Richard Perez et al. (1990; 1993). To investigate the performance of a building under all possible sky conditions that may occur in a year, DAYSIM first imports hourly direct and diffuse irradiances from a climate file and if required, a stochastic autocorrelation model is used to convert the time series down to five-minute time series of direct and diffuse irradiances from one hour. Then, these irradiances are converted into illuminance and a series of sky luminous distributions of the celestial hemisphere. The sky luminous distribution for a given sky condition varies with date, time, site and direct and diffuse irradiance values, and influence the relative intensity of light back-scattered from the earth surface, the width of the circumsolar region, the relative intensity of the circumsolar region, the luminance gradient near the horizon, and darkening or brightening of the horizon. Figure A.3 shows the background steps of using Perez sky model in DAYSIM.

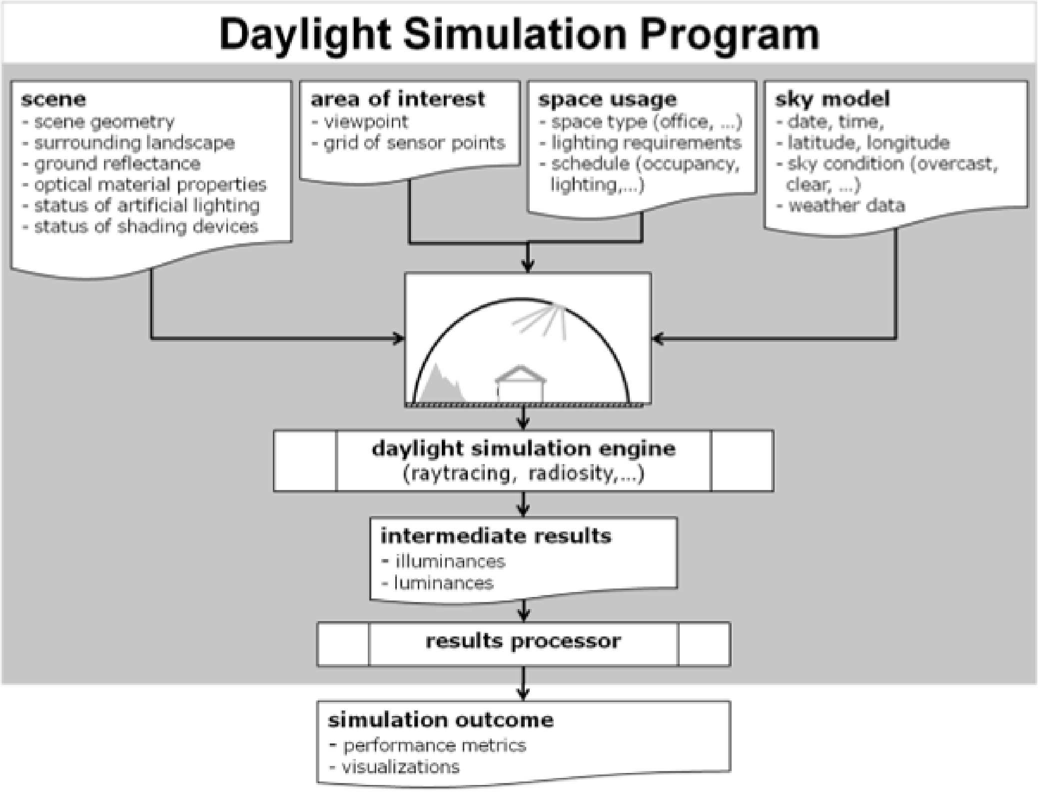

Figure A.2: The process of daylight simulation in DAYSIM (Reinhart, 2006).

DAYSIM uses **Perez all weather sky luminance model**. Perez sky model was developed in early nineties by Richard Perez et al. (1990; 1993). To investigate the performance of a building under all possible sky conditions that may occur in a year, DAYSIM first imports hourly direct and diffuse irradiances from a climate file and if required, a stochastic autocorrelation model is used to convert the time series down to five-minute time series of direct and diffuse irradiances from one hour. Then, these irradiances are converted into illuminance and a series of sky luminous distributions of the celestial hemisphere. The sky luminous distribution for a given sky condition varies with date, time, site and direct and diffuse irradiance values, and influence the relative intensity of light back-scattered from the earth surface, the width of the circumsolar region, the relative intensity of the circumsolar region, the luminance gradient near the horizon, and darkening or brightening of the horizon. Figure A.3 shows the background steps of using Perez sky model in DAYSIM.

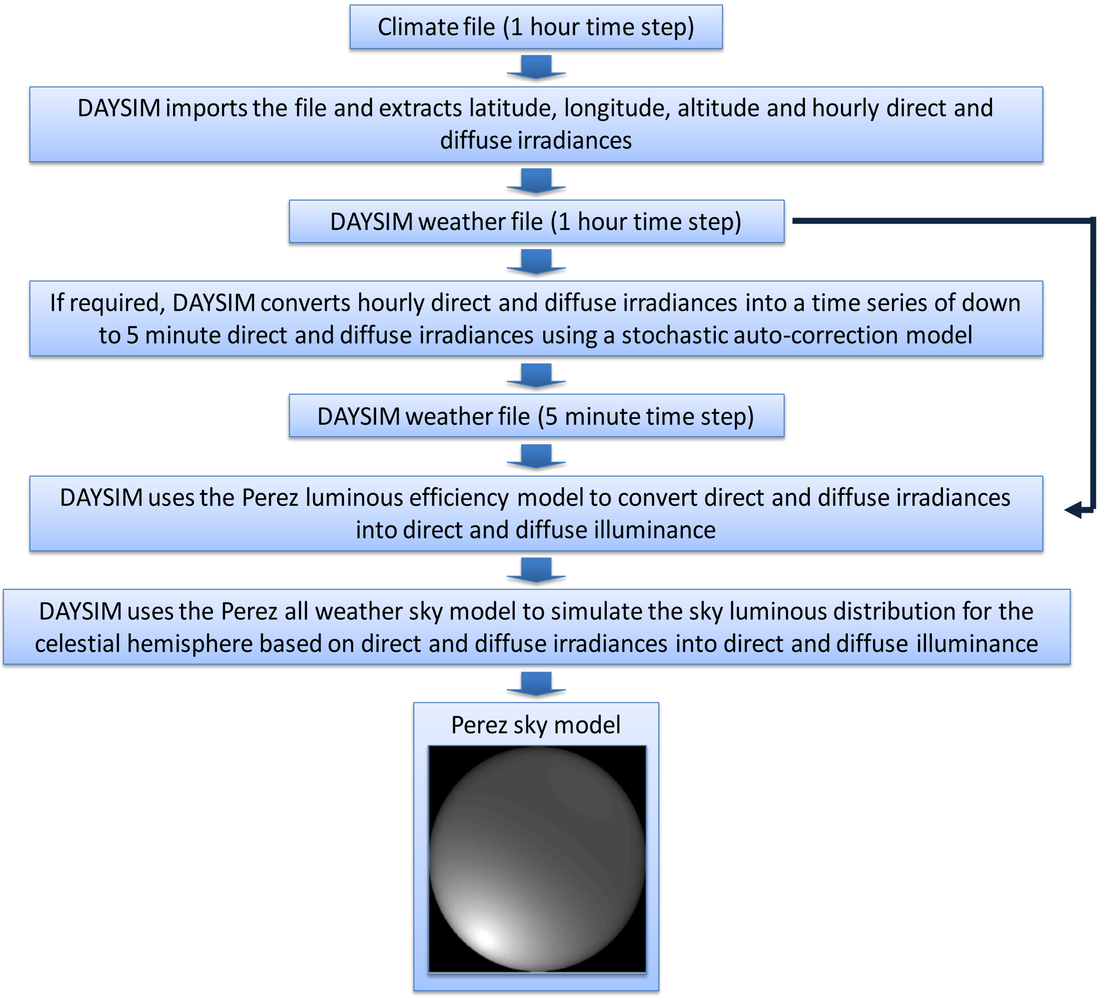

Figure A.3: The use of the Perez sky model in DAYSIM (Joarder, 2011)

Appendix C: Simulation Software

About DAYSIM software

DAYSIM version 2.1

At the most fundamental level DAYSIM offers an efficient way to calculate the annual amount of daylight available in and around buildings. To do so DAYSIM combines a daylight coefficient approach with the Perez all weather sky model and the RADIANCE backward ray-tracer. The resulting time series of illuminance, radiances or irradiances at user defined sensors points can be used for a number of purposes:

- to derive climate-based daylighting metrics
- to calculate annual electric lighting use for different lighting controls based on available daylight

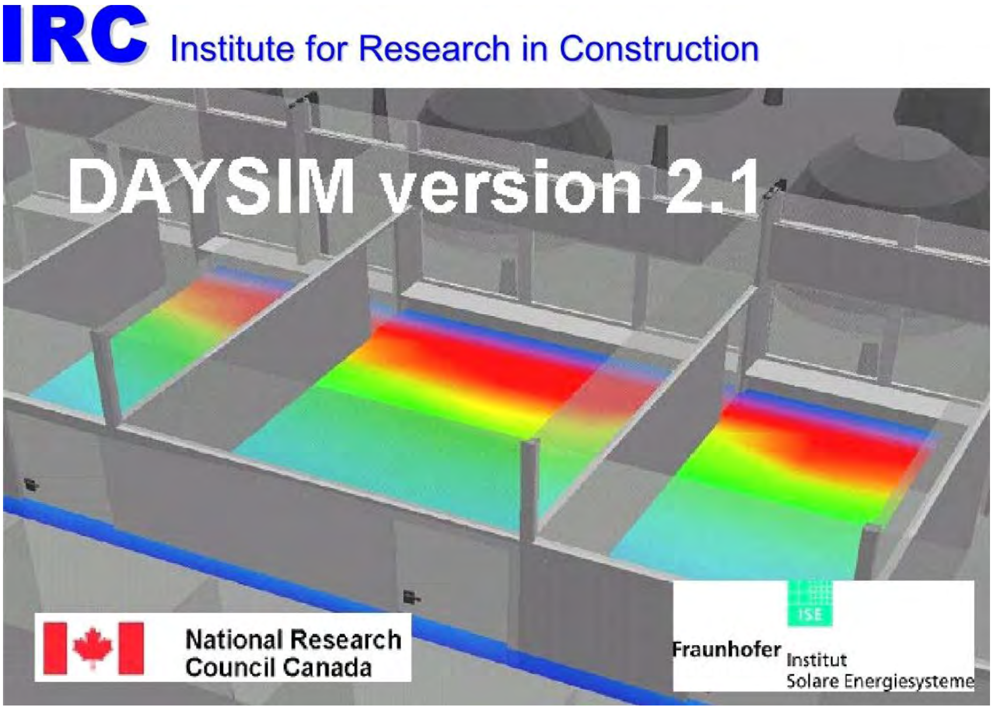

Figure E.1: Interface of DAYSIM simulation software

***Climate-based Daylighting Metrics*: Over** the past decade a new family of daylighting metrics to describe and evaluate daylight in spaces has been developed. These metrics summarize the daylight availability over the year and throughout a space. Two prominent daylighting metrics which are calculated by DAYSIM are Daylight Autonomy and Useful Daylight Illuminance. Daylight Autonomy is now being a recommend metrics by the Illuminating Engineering Society of North America (IESNA).

Electric Lighting Use: DAYSIM uses an occupant behaviour model called Lighswitch to model called Light switch to predict based on annual illuminance profiles and occupancy schedules how occupants in a spaces are going to manually operate electric lighting controls and shading systems (see below). The model thus predicts overall electric lighting energy use in a space. DAYSIM also outputs an Internal Gains schedule as can be used by energy simulation programs such as EnergyPlus^{TM} and eQuest to conduct an integrated thermal lighting analysis of a space.

Dynamic Shading: DAYSIM can also model spaces with multiple dynamic shading systems such as venetian blinds, roller shades and electro chromic glazings. In spaces with dynamic shading systems DAYSIM automatically generates multiple annual illuminance profiles each with the shading system(s) in a static position throughout the year. In a post-processing step it then uses the Light witch model to predict in which state the shading systems is going to be.

Glare Analysis: DAYSIM uses the daylight glare probability metric to predict discomfort glare from daylight for different viewpoint in a scene through the year. Similarly, as for the annual illuminance profiles DAYSIM generates annual daylight glare probability profiles for different shading device settings that in a post-process are then used to predict the setting of a dynamic shading system throughout the year.

Appendix D: Detail DAYSIM simulation results

C1: Detail DAYSIM result of R1

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	0.3	15	51	0	36	64	0	15	656725
2H	0.750	0.5	30	63	0	23	77	0	26	877888
3H	0.750	0.9	55	81	0	10	90	0	68	1459817
4H	0.750	1.5	77	91	0	5	95	0	87	2360369
5H	0.750	1.8	82	93	0	4	96	0	92	2794277
6H	0.750	1.9	84	93	0	3	97	0	92	2948637
7H	0.750	1.9	83	93	0	4	96	0	91	2870942
8H	0.750	1.8	81	92	0	4	96	0	89	2695854
9H	0.750	1.3	68	87	0	7	93	0	79	1998224
10H	0.750	0.6	42	71	0	16	84	0	45	1086684
11H	0.750	0.4	19	56	0	32	68	0	16	720008
12H	0.750	0.3	12	45	0	46	54	0	6	544646
1G	0.750	0.4	19	56	0	30	70	0	19	738767
2G	0.750	0.6	40	70	0	16	84	0	40	1051973
3G	0.750	1.1	66	86	0	7	93	0	78	1804062
4G	0.750	2.3	88	95	0	3	95	3	94	3456635
5G	0.750	2.7	91	96	0	2	87	11	95	4012692
6G	0.750	2.8	91	96	0	2	86	12	95	4092283
7G	0.750	2.8	90	96	0	2	85	13	95	4120097
8G	0.750	2.7	90	95	0	2	88	9	95	3867121
9G	0.750	2.0	84	93	0	3	96	0	90	3016744
10G	0.750	0.8	52	77	0	12	88	0	60	1364359
11G	0.750	0.5	28	61	0	27	73	0	21	813090
12G	0.750	0.3	13	48	0	41	59	0	8	593381
1F	0.750	0.4	23	61	0	24	76	0	23	825065
2F	0.750	0.7	46	75	0	13	87	0	51	1188035
3F	0.750	1.6	78	91	0	4	96	0	87	2343977
4F	0.750	3.3	93	97	0	2	79	19	96	4580026
5F	0.750	3.9	93	97	1	2	72	27	96	5293169
6F	0.750	4.2	94	97	5	2	68	30	97	5719855
7F	0.750	4.2	94	97	6	2	68	30	97	5683497
8F	0.750	4.1	93	97	3	2	70	28	97	5418465
9F	0.750	2.9	88	95	0	2	87	11	94	3995599
10F	0.750	1.0	58	81	0	10	90	0	68	1565476
11F	0.750	0.5	34	65	0	22	78	0	25	904009
12F	0.750	0.4	17	55	0	32	68	0	14	698037
1E	0.750	0.5	37	69	0	17	82	1	35	1068303
2E	0.750	0.9	57	82	0	8	91	1	67	1547946
3E	0.750	1.8	83	93	0	4	95	2	91	2845512
4E	0.750	3.5	93	97	9	2	70	28	72	6448656
5E	0.750	4.5	95	98	23	2	60	39	63	8314741
6E	0.750	4.8	96	98	24	2	58	41	71	8011932
7E	0.750	4.7	95	98	25	2	59	40	63	8482924
8E	0.750	4.2	94	97	19	2	60	38	64	7938323
9E	0.750	3.2	90	96	9	2	78	20	73	5743545
10E	0.750	1.4	69	88	0	6	94	0	79	2187226
11E	0.750	0.6	41	70	0	18	82	0	39	1108790
12E	0.750	0.4	20	58	0	29	71	0	19	761203

C1: Continued

Test points	H	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1D	0.750	0.6	40	72	0	14	86	0	38	1075984
2D	0.750	1.0	59	84	0	7	92	1	74	1829444
3D	0.750	2.6	90	96	8	2	85	13	72	5546405
4D	0.750	3.9	94	97	17	2	62	36	54	8869338
5D	0.750	5.1	96	98	29	2	54	45	42	11070617
6D	0.750	5.4	96	98	31	1	52	47	39	11456687
7D	0.750	5.6	96	98	32	1	52	47	40	11590915
8D	0.750	5.0	95	98	25	1	55	44	50	10128953
9D	0.750	3.3	91	96	10	2	76	22	67	7063167
10D	0.750	1.7	76	90	2	5	92	4	75	3242139
11D	0.750	0.8	52	76	0	14	86	0	52	1449199
12D	0.750	0.4	21	58	0	30	70	0	21	775344
1C	0.750	0.7	53	79	0	10	89	1	51	1353498
2C	0.750	1.0	65	86	1	6	92	2	74	2123734
3C	0.750	2.1	85	94	13	3	82	16	55	6089012
4C	0.750	4.3	95	98	25	1	59	39	26	11167394
5C	0.750	5.0	96	98	35	1	52	46	7	13496621
6C	0.750	5.5	96	98	38	1	49	50	5	14317068
7C	0.750	5.6	96	98	38	1	49	50	5	14253574
8C	0.750	4.8	95	98	33	1	54	45	22	12074135
9C	0.750	3.7	92	97	20	2	69	29	41	9133713
10C	0.750	1.7	76	91	8	4	85	10	71	3800871
11C	0.750	0.8	50	75	0	14	86	0	52	1341723
12C	0.750	0.5	31	66	0	21	79	0	25	1009191
1B	0.750	0.5	35	70	0	16	84	0	34	1033684
2B	0.750	1.1	66	87	1	6	92	2	71	2401063
3B	0.750	1.9	84	94	1	3	90	7	84	3568225
4B	0.750	4.4	95	98	14	1	59	39	85	6870857
5B	0.750	5.0	96	98	23	1	54	45	86	7564259
6B	0.750	5.2	96	98	29	1	49	49	74	8240696
7B	0.750	5.3	96	98	28	1	53	46	80	7785956
8B	0.750	4.9	95	98	17	2	54	44	91	7164612
9B	0.750	3.7	92	97	7	2	68	30	91	5818650
10B	0.750	1.4	69	88	1	6	91	3	76	2631235
11B	0.750	0.7	50	75	1	14	83	2	45	1650009
12B	0.750	0.4	22	60	0	27	73	0	21	810422
1A	0.750	0.5	32	68	0	17	83	0	31	988388
2A	0.750	0.7	51	78	0	11	89	0	55	1357624
3A	0.750	1.6	79	92	0	4	93	3	89	2632515
4A	0.750	4.3	95	97	13	2	65	34	75	6672322
5A	0.750	4.9	96	98	24	2	58	40	57	7953628
6A	0.750	4.9	96	98	21	2	59	40	73	7465773
7A	0.750	5.0	96	98	23	2	58	41	67	7728097
8A	0.750	4.9	95	98	19	2	58	40	70	7225995
9A	0.750	3.5	91	96	7	2	77	21	83	5464977
10A	0.750	1.2	65	85	3	8	88	5	66	2378421
11A	0.750	0.6	39	69	0	18	82	0	31	1065170
12A	0.750	0.4	20	59	0	29	71	0	18	786897

C2: Detail DAYSIM result of R2

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	0.4	3	46	0	34	66	0	0	527535
2H	0.750	0.6	28	66	0	20	80	0	13	818948
3H	0.750	1.1	65	85	0	7	93	0	72	1574115
4H	0.750	2.6	88	95	0	3	97	0	94	3297015
5H	0.750	3.1	92	96	0	2	91	7	96	3988344
6H	0.750	3.4	92	96	0	2	88	10	96	4239382
7H	0.750	3.1	91	96	0	2	88	10	96	4063560
8H	0.750	3.0	90	96	0	2	93	4	95	3762606
9H	0.750	2.3	85	94	0	3	97	0	90	2858408
10H	0.750	0.9	51	77	0	11	89	0	51	1212788
11H	0.750	0.5	14	58	0	28	72	0	0	687017
12H	0.750	0.3	0	39	0	46	54	0	0	455458
1G	0.750	0.4	6	55	0	26	74	0	1	628768
2G	0.750	0.7	37	72	0	15	85	0	29	952812
3G	0.750	1.5	74	89	0	5	95	0	81	1866484
4G	0.750	3.3	92	97	0	2	86	12	96	4269059
5G	0.750	3.9	94	97	2	2	76	22	96	5106435
6G	0.750	4.0	94	97	1	2	76	22	97	5149167
7G	0.750	3.8	93	97	1	2	77	21	97	4994860
8G	0.750	3.7	92	97	0	2	80	18	96	4757689
9G	0.750	3.1	89	95	0	2	91	7	95	3838941
10G	0.750	1.2	61	83	0	8	92	0	66	1533326
11G	0.750	0.6	26	64	0	21	79	0	5	795059
12G	0.750	0.3	0	42	0	42	58	0	0	489907
1F	0.750	0.4	8	55	0	27	73	0	2	636551
2F	0.750	0.7	40	73	0	14	86	0	34	996635
3F	0.750	1.6	77	91	0	4	96	0	86	2175498
4F	0.750	3.4	93	97	0	2	82	16	96	4495650
5F	0.750	4.1	94	97	5	2	73	26	97	5434285
6F	0.750	4.3	94	97	7	2	71	27	97	5646692
7F	0.750	4.5	94	97	8	2	69	29	97	5816431
8F	0.750	4.0	93	97	4	2	73	25	97	5393180
9F	0.750	2.7	88	95	0	3	93	5	93	3646881
10F	0.750	1.1	60	83	0	9	91	0	68	1560853
11F	0.750	0.5	19	58	0	29	71	0	2	696221
12F	0.750	0.3	1	45	0	39	61	0	0	516666
1E	0.750	0.4	22	63	0	22	78	0	10	815392
2E	0.750	0.8	56	81	0	10	89	1	55	1306819
3E	0.750	1.8	83	93	0	4	95	2	90	2638270
4E	0.750	3.5	93	97	9	2	70	28	97	5074026
5E	0.750	4.5	95	98	23	2	60	39	97	6090722
6E	0.750	4.8	96	98	24	2	58	41	97	6076216
7E	0.750	4.7	95	98	25	2	59	40	97	6104881
8E	0.750	4.2	94	97	19	2	60	38	97	5786023
9E	0.750	3.2	90	96	9	2	78	20	95	4058336
10E	0.750	1.4	69	88	0	6	94	0	80	2122252
11E	0.750	0.5	32	65	0	22	78	0	14	910347
12E	0.750	0.4	4	51	0	35	65	0	0	637896
1D	0.750	0.4	17	58	0	26	74	0	7	693150
2D	0.750	0.8	54	79	0	11	88	1	60	1456403

C2: Continued

Test points	H	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100\text{-}2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
3D	0.750	2.0	83	93	6	3	87	9	75	4557393
4D	0.750	3.4	93	97	13	2	68	30	66	7135008
5D	0.750	4.7	95	98	25	2	57	41	54	9406040
6D	0.750	4.9	96	98	27	2	55	43	52	9776475
7D	0.750	4.7	95	98	25	2	58	40	55	9479452
8D	0.750	4.3	94	97	19	2	62	36	64	8179297
9D	0.750	3.0	89	95	6	2	82	15	77	5552912
10D	0.750	1.5	72	89	1	6	91	3	74	2782441
11D	0.750	0.6	38	69	0	19	81	0	25	1068289
12D	0.750	0.4	6	52	0	33	67	0	0	611103
1C	0.750	0.4	18	60	0	24	76	0	8	720467
2C	0.750	0.9	55	81	0	9	91	0	62	1315333
3C	0.750	1.7	80	92	5	4	90	6	78	3217882
4C	0.750	3.4	93	97	8	2	71	27	74	6281749
5C	0.750	4.4	95	98	24	2	59	39	64	8341187
6C	0.750	4.6	95	98	26	2	58	40	64	8557483
7C	0.750	4.7	94	98	27	2	59	40	63	8562125
8C	0.750	3.8	93	97	16	2	63	35	66	7448950
9C	0.750	3.1	90	96	9	2	77	20	74	5607807
10C	0.750	1.3	67	87	0	7	93	0	78	1939425
11C	0.750	0.6	36	68	0	19	81	0	25	908662
12C	0.750	0.4	5	50	0	36	64	0	0	584590
1B	0.750	0.4	15	60	0	22	78	0	9	722514
2B	0.750	0.6	41	72	0	15	83	2	36	1593345
3B	0.750	1.2	66	86	0	6	92	2	75	2321646
4B	0.750	3.3	93	97	1	2	72	26	89	5378304
5B	0.750	4.0	95	97	6	2	61	37	88	6455134
6B	0.750	3.6	93	97	2	2	64	34	88	6090473
7B	0.750	3.8	93	97	2	2	64	34	95	5802049
8B	0.750	3.8	93	97	4	2	64	34	94	5890001
9B	0.750	2.9	89	95	2	2	83	15	93	4616505
10B	0.750	0.9	57	80	1	11	87	2	62	1781598
11B	0.750	0.4	23	60	1	29	69	2	11	1126792
12B	0.750	0.3	2	42	0	44	56	0	0	490754
1A	0.750	0.4	7	51	0	31	69	0	4	593628
2A	0.750	0.6	35	69	0	18	82	0	29	930899
3A	0.750	1.1	66	86	0	6	94	0	79	1782873
4A	0.750	2.8	90	96	4	2	87	10	85	4560059
5A	0.750	3.3	93	97	8	2	69	29	81	5835648
6A	0.750	3.0	91	96	4	2	75	23	90	4962621
7A	0.750	3.2	92	96	4	2	72	26	86	5304134
8A	0.750	3.2	91	96	4	2	75	23	89	5042687
9A	0.750	2.3	86	94	4	3	92	5	85	3712912
10A	0.750	0.8	52	77	2	12	84	4	56	1705453
11A	0.750	0.4	16	58	0	29	71	0	5	704214
12A	0.750	0.3	1	40	0	45	55	0	0	463614

C3: Detail DAYSIM result of R3

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	0.9	61	84	0	8	92	0	68	1393004
2H	0.750	1.4	75	90	0	5	95	0	84	1960796
3H	0.750	2.7	91	96	0	2	98	0	95	3587507
4H	0.750	5.7	96	98	18	1	55	44	95	7149778
5H	0.750	7.3	97	98	33	1	41	58	61	9127578
6H	0.750	6.9	97	98	32	1	42	57	65	8903510
7H	0.750	7.2	97	98	32	1	41	57	66	8923299
8H	0.750	7.2	97	98	31	1	42	57	70	8790192
9H	0.750	4.7	95	98	5	2	65	34	97	6055157
10H	0.750	2.0	83	93	0	3	97	0	90	2772379
11H	0.750	1.1	63	85	0	8	92	0	72	1612684
12H	0.750	0.7	45	76	0	12	88	0	49	1161597
1G	0.750	0.9	60	83	0	8	92	0	68	1419758
2G	0.750	1.6	80	92	0	4	96	0	90	2368187
3G	0.750	2.8	91	96	0	2	95	3	95	3853206
4G	0.750	7.2	97	98	34	1	40	58	52	9267369
5G	0.750	9.0	98	99	47	1	30	69	14	11361315
6G	0.750	8.7	98	99	45	1	32	66	18	11048975
7G	0.750	8.8	98	99	47	1	32	66	13	11344508
8G	0.750	8.6	98	99	45	1	35	64	21	10895143
9G	0.750	6.1	97	98	25	1	48	50	78	8013268
10G	0.750	2.3	86	94	0	3	97	0	92	3152342
11G	0.750	1.1	64	85	0	7	93	0	73	1673586
12G	0.750	1.0	59	82	0	9	91	0	66	1433797
1F	0.750	1.2	71	88	0	6	94	0	80	1713666
2F	0.750	1.7	81	92	0	4	96	0	90	2397447
3F	0.750	3.9	94	97	0	2	75	23	97	5091985
4F	0.750	7.1	97	98	37	1	40	59	40	9636901
5F	0.750	9.0	98	99	49	1	30	69	0	11967318
6F	0.750	9.3	98	99	51	1	29	70	0	12162783
7F	0.750	9.5	98	99	53	1	29	70	0	12504378
8F	0.750	9.3	98	99	50	1	33	66	0	11953518
9F	0.750	6.1	97	98	27	1	47	51	71	8218154
10F	0.750	2.6	88	95	0	3	97	1	94	3631044
11F	0.750	1.5	74	89	0	5	95	0	82	2049817
12F	0.750	0.9	57	81	0	9	91	0	64	1397364
1E	0.750	1.3	79	91	2	5	92	4	82	2308013
2E	0.750	1.9	86	94	2	3	93	4	89	3104075
3E	0.750	4.5	95	98	10	2	61	38	97	6326955
4E	0.750	8.2	98	99	49	1	30	68	8	11298714
5E	0.750	10.4	98	99	56	1	24	74	0	13544019
6E	0.750	10.3	98	99	56	1	26	73	0	13465561
7E	0.750	10.4	98	99	57	1	26	73	0	13686776
8E	0.750	9.0	98	99	52	1	32	66	0	12386155
9E	0.750	6.5	97	98	34	1	44	54	53	9050590
10E	0.750	3.2	91	96	1	2	84	14	96	4653620
11E	0.750	1.5	76	90	0	5	94	1	83	2434667
12E	0.750	1.0	60	83	0	9	91	0	68	1635837
1D	0.750	1.2	73	89	0	6	94	0	83	1882607
2D	0.750	2.0	86	94	2	3	94	3	84	3546410

C3: Continued

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100\text{-}2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
3D	0.750	4.4	95	98	19	1	58	40	57	10176554
4D	0.750	8.2	98	99	46	1	32	66	0	16270788
5D	0.750	10.1	98	99	60	1	23	76	0	20462406
6D	0.750	10.5	98	99	63	1	23	76	0	21000348
7D	0.750	10.2	98	99	59	1	23	75	0	20533478
8D	0.750	9.2	98	99	54	1	30	69	0	17627076
9D	0.750	6.4	97	98	36	1	43	56	35	11993958
10D	0.750	3.4	92	96	6	2	75	23	77	6453981
11D	0.750	1.5	76	90	0	5	93	2	79	2729458
12D	0.750	1.0	61	83	0	9	91	0	68	1546635
1C	0.750	1.2	73	89	0	6	94	0	83	1861698
2C	0.750	1.6	79	92	0	4	96	0	90	2487590
3C	0.750	4.0	95	97	10	2	66	32	78	7531159
4C	0.750	7.5	97	98	42	1	37	62	9	13664076
5C	0.750	9.4	98	99	55	1	26	73	0	17882104
6C	0.750	9.2	98	99	54	1	27	71	0	17667524
7C	0.750	9.9	98	99	56	1	26	72	0	18292108
8C	0.750	9.0	98	99	51	1	32	66	0	16938736
9C	0.750	6.4	97	98	36	1	44	55	33	12069169
10C	0.750	3.1	91	96	0	2	82	16	96	4491172
11C	0.750	1.5	77	90	0	5	95	0	84	2379194
12C	0.750	1.0	59	82	0	9	91	0	66	1489375
1B	0.750	0.9	64	85	0	7	93	0	75	1620971
2B	0.750	1.6	82	93	3	4	91	5	76	4015274
3B	0.750	2.4	89	95	4	2	86	12	78	5146599
4B	0.750	7.6	97	99	50	1	33	66	0	12697342
5B	0.750	8.5	98	99	54	1	28	71	0	13877259
6B	0.750	8.6	98	99	57	1	28	71	0	14614642
7B	0.750	8.5	98	99	53	1	29	70	0	13441443
8B	0.750	8.0	98	99	50	1	33	66	0	12697801
9B	0.750	6.0	97	98	39	1	43	56	38	9992618
10B	0.750	2.2	86	94	4	3	90	7	82	4351399
11B	0.750	1.2	69	87	3	7	89	5	69	2926829
12B	0.750	0.9	55	80	0	10	90	0	60	1407118
1A	0.750	0.9	62	85	0	7	93	0	72	1540758
2A	0.750	1.4	78	91	0	4	96	0	88	2282589
3A	0.750	2.7	91	96	2	2	87	11	95	4319091
4A	0.750	6.2	97	98	36	1	43	55	30	10604300
5A	0.750	7.2	97	98	42	1	36	63	0	13112189
6A	0.750	7.0	97	98	40	1	36	62	0	11688128
7A	0.750	6.9	97	98	40	1	39	60	3	11792677
8A	0.750	6.7	97	98	39	1	41	58	11	11060371
9A	0.750	5.0	96	98	25	1	52	46	63	8670774
10A	0.750	2.0	84	93	5	3	92	5	75	4141339
11A	0.750	1.1	66	85	0	7	93	0	74	1802492
12A	0.750	0.7	47	76	0	13	87	0	48	1190287

C4: Detail DAYSIM result of R4

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	0.5	23	63	0	22	78	0	18	806781
2H	0.750	0.8	49	78	0	11	89	0	46	1138149
3H	0.750	1.4	73	89	0	5	95	0	80	1811927
4H	0.750	3.2	90	96	0	2	97	1	95	3462391
5H	0.750	3.8	93	97	0	2	91	7	96	4183116
6H	0.750	3.8	92	97	0	2	91	7	96	4187493
7H	0.750	3.8	92	97	0	2	91	7	96	4123563
8H	0.750	3.7	92	96	0	2	92	6	96	4048181
9H	0.750	2.6	86	94	0	3	97	0	91	2976676
10H	0.750	1.1	58	81	0	9	91	0	62	1398375
11H	0.750	0.6	31	65	0	21	79	0	17	846891
12H	0.750	0.4	15	55	0	31	69	0	8	680294
1G	0.750	0.6	33	70	0	17	83	0	23	917210
2G	0.750	0.9	52	79	0	11	89	0	53	1221044
3G	0.750	1.6	76	90	0	4	96	0	83	1951998
4G	0.750	3.6	93	97	0	2	90	8	96	4146890
5G	0.750	4.7	94	97	1	2	80	19	97	5051477
6G	0.750	4.4	94	97	0	2	82	16	97	4863457
7G	0.750	4.2	93	97	0	2	83	15	97	4743564
8G	0.750	4.1	92	97	0	2	86	12	97	4506073
9G	0.750	3.2	90	96	0	2	94	4	95	3738370
10G	0.750	1.2	61	84	0	8	92	0	68	1561343
11G	0.750	0.8	45	73	0	14	86	0	39	1056560
12G	0.750	0.5	21	60	0	27	73	0	12	749971
1F	0.750	0.7	40	73	0	15	85	0	36	1021636
2F	0.750	1.0	59	82	0	9	91	0	67	1419804
3F	0.750	2.1	83	93	0	3	97	0	91	2703147
4F	0.750	3.9	94	97	0	2	80	18	97	4827135
5F	0.750	4.6	94	97	5	2	71	27	97	5578141
6F	0.750	4.7	94	98	7	2	70	29	97	5818092
7F	0.750	5.0	94	98	8	2	69	30	97	5939704
8F	0.750	4.6	94	97	4	2	73	26	97	5521251
9F	0.750	3.5	91	96	0	2	89	9	96	4158724
10F	0.750	1.4	68	87	0	6	94	0	79	1934485
11F	0.750	0.8	50	76	0	13	87	0	52	1205845
12F	0.750	0.6	32	66	0	20	80	0	19	871610
1E	0.750	0.7	45	75	0	13	87	0	44	1100147
2E	0.750	1.2	69	87	0	6	94	0	79	1737794
3E	0.750	2.3	86	94	7	3	88	9	77	4716629
4E	0.750	4.6	95	98	20	2	61	37	58	9123838
5E	0.750	5.4	96	98	28	2	56	42	52	10565036
6E	0.750	6.0	96	98	32	2	51	48	37	11398950
7E	0.750	5.7	96	98	30	2	53	45	43	11001133
8E	0.750	5.1	95	98	25	2	58	41	58	9604727
9E	0.750	3.8	91	96	10	2	74	24	70	7041196
10E	0.750	1.8	78	91	2	4	93	3	79	3027332
11E	0.750	0.9	54	79	0	11	89	0	58	1333360
12E	0.750	0.6	34	66	0	20	80	0	23	904051
1D	0.750	0.8	54	79	0	10	90	0	53	1270802
2D	0.750	1.1	67	86	0	7	93	0	76	1704804

C4: Continued

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
3D	0.750	2.7	89	95	7	2	89	9	76	4921743
4D	0.750	4.6	95	98	16	2	64	35	67	7903001
5D	0.750	5.8	96	98	33	2	51	48	44	10457454
6D	0.750	5.7	96	98	33	2	53	45	46	10361157
7D	0.750	5.8	96	98	34	1	52	47	42	10565422
8D	0.750	5.1	95	98	28	1	57	41	58	9191130
9D	0.750	3.6	91	96	10	2	72	26	69	6679175
10D	0.750	1.9	80	92	4	4	92	5	82	3195354
11D	0.750	0.9	53	78	0	12	88	0	58	1365543
12D	0.750	0.6	34	66	0	21	79	0	24	951805
1C	0.750	0.8	52	79	0	10	90	0	56	1272888
2C	0.750	1.3	76	90	0	5	93	2	78	2669860
3C	0.750	2.4	87	95	1	3	90	8	87	4124274
4C	0.750	4.0	95	97	9	2	62	36	88	6376968
5C	0.750	4.8	96	98	22	2	55	44	85	7483373
6C	0.750	5.4	96	98	31	1	46	52	65	8641660
7C	0.750	5.3	96	98	29	1	51	48	77	8002583
8C	0.750	4.8	94	98	21	2	55	43	90	7200013
9C	0.750	3.8	92	97	7	2	66	33	91	5873138
10C	0.750	1.8	77	91	1	4	93	3	83	3028921
11C	0.750	0.9	55	79	1	12	86	2	59	1781362
12C	0.750	0.5	33	65	0	22	78	0	24	892464
1B	0.750	0.7	48	77	0	12	88	0	51	1204304
2B	0.750	1.1	69	87	0	6	94	0	81	1856000
3B	0.750	2.2	86	95	4	3	90	7	84	3890645
4B	0.750	4.2	95	97	15	2	63	35	82	6782670
5B	0.750	5.1	96	98	31	2	55	43	54	8453616
6B	0.750	5.4	96	98	33	1	54	45	44	8885164
7B	0.750	5.5	96	98	33	1	53	46	42	8981343
8B	0.750	4.6	94	97	22	2	59	40	79	7200753
9B	0.750	3.5	91	96	9	2	69	29	86	5777519
10B	0.750	1.8	76	90	4	5	90	5	79	3030347
11B	0.750	0.8	51	77	0	13	87	0	55	1301553
12B	0.750	0.6	33	66	0	21	79	0	23	895970
1A	0.750	0.7	47	77	0	12	88	0	48	1175348
2A	0.750	1.0	63	85	0	7	93	0	76	1697291
3A	0.750	1.8	82	93	0	4	92	4	92	3041304
4A	0.750	3.7	94	97	13	2	66	32	90	5969040
5A	0.750	4.6	95	98	26	2	59	40	75	7279885
6A	0.750	4.5	95	98	26	2	59	39	75	7306346
7A	0.750	4.6	94	98	26	2	59	40	74	7291867
8A	0.750	4.5	94	97	23	2	58	40	77	7032248
9A	0.750	3.3	90	96	6	2	74	24	95	5087607
10A	0.750	1.2	66	85	0	8	92	0	74	2041037
11A	0.750	0.7	48	74	0	15	85	0	49	1199665
12A	0.750	0.5	23	61	0	26	74	0	15	784464

C5: Detail DAYSIM result of R5

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	1.3	74	89	0	5	95	0	85	2070926
2H	0.750	2.0	85	94	0	3	97	0	93	2836119
3H	0.750	3.7	93	97	0	2	87	11	97	4575935
4H	0.750	7.4	97	98	30	1	42	57	79	8557603
5H	0.750	9.5	98	99	45	1	32	67	38	10558861
6H	0.750	9.3	98	99	43	1	33	66	44	10433358
7H	0.750	9.5	98	99	43	1	33	66	44	10451429
8H	0.750	8.6	97	98	38	1	38	61	56	9754065
9H	0.750	6.2	96	98	16	1	52	46	94	7218004
10H	0.750	2.7	89	95	0	3	97	0	94	3536513
11H	0.750	1.6	76	90	0	5	95	0	84	2304575
12H	0.750	1.2	67	86	0	7	93	0	76	1873102
1G	0.750	1.7	81	92	0	4	96	0	90	2459504
2G	0.750	2.5	89	95	0	2	97	1	94	3441545
3G	0.750	3.5	93	97	0	2	88	10	96	4384895
4G	0.750	8.5	98	99	40	1	35	63	45	9952320
5G	0.750	10.7	98	99	51	1	28	71	11	11979435
6G	0.750	10.6	98	99	51	1	29	70	15	11675687
7G	0.750	10.5	98	99	51	1	30	69	12	11836436
8G	0.750	9.6	98	99	47	1	33	66	24	11156040
9G	0.750	7.7	97	98	34	1	42	57	67	9024071
10G	0.750	3.0	90	96	0	2	96	2	95	3890647
11G	0.750	2.0	84	93	0	3	97	0	90	2842788
12G	0.750	1.4	74	89	0	5	95	0	83	2155380
1F	0.750	1.6	81	92	0	4	96	0	90	2560516
2F	0.750	2.5	89	95	0	2	95	3	95	3658634
3F	0.750	5.0	96	98	14	2	59	39	97	6637466
4F	0.750	8.6	98	99	44	1	33	65	22	10843786
5F	0.750	10.5	98	99	55	1	25	74	0	13118611
6F	0.750	12.0	98	99	59	1	22	77	0	14507848
7F	0.750	11.6	98	99	58	1	24	75	0	13916422
8F	0.750	10.2	98	99	53	1	30	69	0	12503386
9F	0.750	8.2	97	98	39	1	39	60	41	9954931
10F	0.750	3.8	92	97	0	2	76	22	97	5077643
11F	0.750	2.1	84	93	0	3	97	0	91	3014200
12F	0.750	1.5	75	90	0	5	95	0	84	2287416
1E	0.750	1.9	85	94	0	3	96	1	93	2951552
2E	0.750	2.9	92	96	0	2	90	8	95	4183134
3E	0.750	6.0	97	98	28	1	49	49	59	9887798
4E	0.750	10.1	98	99	54	1	26	73	0	18261822
5E	0.750	12.2	98	99	63	1	20	79	0	20973260
6E	0.750	12.8	98	99	63	1	19	80	0	21824112
7E	0.750	13.7	98	99	65	1	18	81	0	22528076
8E	0.750	12.1	98	99	60	1	24	75	0	20464200
9E	0.750	8.9	98	98	48	1	35	63	4	14611529
10E	0.750	4.5	94	97	6	2	63	35	97	6019026
11E	0.750	2.3	86	94	0	3	95	2	91	3314595
12E	0.750	1.5	76	90	0	5	95	0	84	2400337
1D	0.750	2.0	87	95	3	3	90	7	89	3530974
2D	0.750	2.8	93	97	4	2	82	16	91	4747231

C5: Continued

3D	0.750	6.0	97	98	34	1	43	56	46	10427586
4D	0.750	10.4	98	99	60	1	22	77	0	17649724
5D	0.750	13.1	98	99	66	1	18	81	0	21791280
6D	0.750	13.4	98	99	68	1	17	82	0	22730338
7D	0.750	13.1	98	99	64	1	18	81	0	21982112
8D	0.750	12.2	98	99	62	1	22	77	0	20967052
9D	0.750	8.5	98	98	49	1	35	63	0	14806675
10D	0.750	4.1	93	97	8	2	63	35	97	6212960
11D	0.750	2.3	86	94	1	3	92	5	91	3768988
12D	0.750	1.5	77	90	0	5	94	1	84	2701243
1C	0.750	1.7	84	94	0	4	94	3	92	2957000
2C	0.750	2.9	92	97	6	2	79	19	78	5983869
3C	0.750	5.1	96	98	31	1	49	50	47	10750318
4C	0.750	10.0	98	99	60	1	23	76	0	17757914
5C	0.750	11.9	98	99	66	1	19	80	0	21483520
6C	0.750	12.7	98	99	70	1	16	83	0	23169540
7C	0.750	12.4	98	99	67	1	16	83	0	21895852
8C	0.750	11.6	98	99	63	1	21	78	0	19017464
9C	0.750	8.6	98	99	52	1	32	66	0	14599005
10C	0.750	4.2	94	97	16	2	58	40	74	8518491
11C	0.750	2.1	85	93	4	3	89	8	81	4393092
12C	0.750	1.5	76	90	0	6	94	0	84	2410673
1B	0.750	1.8	85	94	0	4	93	3	93	3024025
2B	0.750	2.8	93	97	2	2	83	15	95	4584730
3B	0.750	5.1	96	98	25	1	51	48	54	10686423
4B	0.750	9.9	98	99	57	1	24	75	0	17952206
5B	0.750	11.2	98	99	62	1	21	78	0	22198724
6B	0.750	11.9	98	99	64	1	18	80	0	23096242
7B	0.750	12.7	98	99	66	1	17	82	0	24078184
8B	0.750	11.5	98	99	61	1	22	77	0	20958556
9B	0.750	8.3	98	99	49	1	34	64	0	15099590
10B	0.750	3.8	92	97	10	2	65	33	78	6805457
11B	0.750	2.0	84	93	0	3	94	3	90	3273584
12B	0.750	1.5	76	90	0	5	95	0	83	2455009
1A	0.750	1.6	82	92	0	4	95	1	90	2676542
2A	0.750	2.3	89	96	2	3	88	10	95	3939763
3A	0.750	3.9	95	98	17	2	59	39	70	6994875
4A	0.750	9.1	98	99	54	1	26	72	0	14691608
5A	0.750	11.2	98	99	63	1	20	79	0	17962256
6A	0.750	10.8	98	99	62	1	21	78	0	17727396
7A	0.750	11.5	98	99	62	1	20	79	0	18349388
8A	0.750	10.9	98	99	60	1	24	75	0	17198306
9A	0.750	8.1	98	98	48	1	35	63	0	12785379
10A	0.750	3.1	90	96	6	2	74	23	95	5136777
11A	0.750	2.0	83	93	0	4	94	2	89	3155751
12A	0.750	1.3	71	88	0	6	94	0	80	2166531

C6: Detail DAYSIM result of R6-50°

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	0.3	1	38	0	46	54	0	0	427351
2H	0.750	0.4	4	52	0	27	73	0	0	597703
3H	0.750	0.9	48	78	0	11	89	0	40	1099493
4H	0.750	2.1	82	93	0	3	97	0	89	2316965
5H	0.750	2.6	86	95	0	3	97	0	93	2815548
6H	0.750	2.4	85	94	0	3	97	0	92	2663348
7H	0.750	2.4	85	94	0	3	97	0	91	2634345
8H	0.750	2.5	85	94	0	3	97	0	91	2698216
9H	0.750	1.8	75	90	0	4	96	0	82	1971221
10H	0.750	0.6	29	67	0	18	82	0	4	827408
11H	0.750	0.3	1	44	0	39	61	0	0	504581
12H	0.750	0.2	0	32	0	57	43	0	0	373776
1G	0.750	0.3	2	44	0	37	63	0	0	497195
2G	0.750	0.6	17	64	0	20	80	0	2	741143
3G	0.750	0.9	47	78	0	10	90	0	39	1085887
4G	0.750	2.2	83	94	0	3	97	0	91	2594597
5G	0.750	2.4	86	94	0	3	97	0	93	2888927
6G	0.750	2.4	86	94	0	3	97	0	93	2837809
7G	0.750	2.5	87	95	0	3	97	0	93	2962233
8G	0.750	2.5	86	94	0	3	97	0	92	2916589
9G	0.750	1.7	76	90	0	4	96	0	83	2110312
10G	0.750	0.6	31	67	0	18	82	0	7	829158
11G	0.750	0.4	2	48	0	35	65	0	0	553974
12G	0.750	0.3	0	37	0	49	51	0	0	422677
1F	0.750	0.4	5	50	0	30	70	0	0	573737
2F	0.750	0.6	28	67	0	19	81	0	11	826371
3F	0.750	1.3	70	87	0	6	94	0	77	1685977
4F	0.750	2.3	85	94	0	3	97	0	93	2882665
5F	0.750	2.8	89	95	0	2	97	0	95	3370421
6F	0.750	3.0	90	96	0	2	96	1	95	3637893
7F	0.750	2.9	90	96	0	2	96	1	95	3569295
8F	0.750	2.9	89	95	0	2	97	0	94	3359822
9F	0.750	2.0	81	92	0	4	96	0	87	2454637
10F	0.750	0.8	47	75	0	13	87	0	47	1122000
11F	0.750	0.5	13	60	0	24	76	0	0	704343
12F	0.750	0.3	0	38	0	48	52	0	0	441242
1E	0.750	0.4	8	56	0	25	75	0	3	647852
2E	0.750	0.6	33	70	0	17	83	0	23	901295
3E	0.750	1.4	82	88	0	6	94	0	80	1840758
4E	0.750	2.6	94	95	3	3	93	5	85	4173957
5E	0.750	3.1	94	96	4	2	87	11	85	4936501
6E	0.750	3.3	94	96	4	2	84	14	85	5117830
7E	0.750	2.9	94	96	3	2	88	9	84	4726405
8E	0.750	3.0	94	95	3	2	90	7	84	4673931
9E	0.750	2.2	92	93	3	4	92	4	79	3685498
10E	0.750	1.1	80	82	0	9	91	0	65	1445307
11E	0.750	0.4	9	55	0	32	68	0	1	640625
12E	0.750	0.3	1	42	0	42	58	0	0	483458
1D	0.750	0.4	10	56	0	26	74	0	6	652700
2D	0.750	0.8	48	78	0	11	89	0	46	1109197

C6: Continued

Test points	H	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
3D	0.750	1.5	76	90	5	5	89	6	73	2745934
4D	0.750	2.6	88	95	12	3	83	14	68	5548958
5D	0.750	2.8	91	96	12	2	79	18	68	6019217
6D	0.750	3.2	92	96	12	2	75	23	68	6301203
7D	0.750	3.1	91	96	12	2	76	22	68	6193216
8D	0.750	2.9	89	95	12	2	83	15	67	5768122
9D	0.750	2.0	82	92	7	4	87	9	70	4063229
10D	0.750	1.0	57	80	0	10	90	0	64	1418242
11D	0.750	0.5	16	59	0	27	73	0	3	702391
12D	0.750	0.3	2	42	0	43	57	0	0	487176
1C	0.750	0.4	10	54	0	28	72	0	7	636531
2C	0.750	0.6	40	73	0	15	85	1	35	1212715
3C	0.750	1.4	75	89	0	5	94	1	85	2230399
4C	0.750	2.5	89	95	0	3	95	2	94	3753892
5C	0.750	2.8	91	96	0	2	91	7	95	4221456
6C	0.750	2.9	91	96	0	2	88	10	95	4372566
7C	0.750	3.3	92	96	0	2	81	17	96	4714547
8C	0.750	2.9	90	96	0	2	94	3	95	4107480
9C	0.750	1.8	80	92	0	4	96	0	86	2724264
10C	0.750	1.0	61	82	0	9	91	0	66	1652837
11C	0.750	0.5	19	61	0	26	74	0	10	893246
12C	0.750	0.3	4	47	0	36	64	0	0	551901
1B	0.750	0.4	11	55	0	27	73	0	8	648726
2B	0.750	0.7	41	74	0	13	87	0	35	1036024
3B	0.750	1.2	69	88	3	6	90	4	73	2300665
4B	0.750	2.2	87	95	4	3	92	5	85	3827700
5B	0.750	2.5	89	95	7	3	86	12	81	4610959
6B	0.750	2.6	90	96	8	3	85	13	80	4750054
7B	0.750	3.0	91	96	8	2	79	19	80	5201493
8B	0.750	2.3	87	94	4	3	91	6	88	3834609
9B	0.750	1.8	81	92	4	4	91	5	83	3114322
10B	0.750	1.0	56	81	3	10	86	4	61	1865022
11B	0.750	0.4	8	52	0	34	66	0	3	620873
12B	0.750	0.3	1	41	0	44	56	0	0	476294
1A	0.750	0.4	10	53	0	26	74	0	7	622038
2A	0.750	0.5	29	66	0	19	81	0	22	876698
3A	0.750	0.9	56	82	0	8	92	0	69	1495474
4A	0.750	2.3	88	95	0	3	91	7	94	3527105
5A	0.750	2.5	90	95	0	2	89	9	95	3819668
6A	0.750	2.4	88	95	0	3	89	8	94	3714739
7A	0.750	2.5	89	95	0	3	87	10	95	3848953
8A	0.750	2.4	87	95	0	3	91	7	94	3616226
9A	0.750	1.8	79	91	0	4	95	1	86	2689785
10A	0.750	0.6	40	71	0	17	83	0	38	1050541
11A	0.750	0.4	6	49	0	36	64	0	1	582278
12A	0.750	0.3	0	36	0	51	49	0	0	417398

C7: Detail DAYSIM result of R6-45°

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	0.2	0	27	0	65	35	0	0	308201
2H	0.750	0.3	0	43	0	37	63	0	0	487469
3H	0.750	0.8	38	73	0	14	86	0	20	957764
4H	0.750	1.8	79	91	0	4	96	0	85	2151428
5H	0.750	2.2	83	93	0	3	97	0	90	2550561
6H	0.750	2.2	83	93	0	3	97	0	90	2581264
7H	0.750	2.1	83	93	0	4	96	0	89	2522519
8H	0.750	2.1	82	93	0	4	96	0	89	2483670
9H	0.750	1.4	68	87	0	6	94	0	73	1703746
10H	0.750	0.6	13	60	0	23	77	0	1	704138
11H	0.750	0.3	0	34	0	49	51	0	0	394736
12H	0.750	0.2	0	26	0	66	34	0	0	298521
1G	0.750	0.3	0	37	0	44	56	0	0	413179
2G	0.750	0.4	2	51	0	29	71	0	0	581439
3G	0.750	0.8	39	74	0	13	87	0	24	978657
4G	0.750	2.0	82	93	0	4	96	0	90	2498951
5G	0.750	2.4	86	94	0	3	97	0	93	2920207
6G	0.750	2.2	85	94	0	3	97	0	92	2704677
7G	0.750	2.4	86	94	0	3	97	0	92	2981843
8G	0.750	2.4	86	94	0	3	97	0	91	2886513
9G	0.750	1.7	76	90	0	5	95	0	84	2126768
10G	0.750	0.7	30	68	0	17	83	0	11	863688
11G	0.750	0.4	0	44	0	39	61	0	0	500826
12G	0.750	0.2	0	27	0	65	35	0	0	305696
1F	0.750	0.3	0	38	0	43	57	0	0	435185
2F	0.750	0.5	23	62	0	22	78	0	2	741077
3F	0.750	1.2	66	85	0	7	93	0	72	1570021
4F	0.750	2.2	85	94	0	3	97	0	93	3020758
5F	0.750	2.7	90	95	0	2	96	1	94	3566735
6F	0.750	3.0	91	96	0	2	93	4	95	3846607
7F	0.750	2.8	90	95	0	2	96	2	95	3673767
8F	0.750	2.5	88	95	0	3	97	0	93	3283558
9F	0.750	2.0	83	93	0	3	97	0	89	2604431
10F	0.750	0.8	45	74	0	14	86	0	41	1081412
11F	0.750	0.4	1	50	0	32	68	0	0	577926
12F	0.750	0.3	0	31	0	57	43	0	0	359485
1E	0.750	0.3	0	41	0	41	59	0	0	460885
2E	0.750	0.6	32	69	0	17	83	0	13	864410
3E	0.750	1.3	69	87	0	7	93	0	78	1757002
4E	0.750	2.5	88	95	0	3	97	0	94	3272196
5E	0.750	2.9	91	96	0	2	92	6	95	3902949
6E	0.750	3.1	91	96	0	2	87	11	96	4196045
7E	0.750	2.9	90	96	0	2	91	7	95	3961239
8E	0.750	2.8	89	95	0	2	93	5	95	3813576
9E	0.750	2.1	84	93	0	3	97	0	90	2829176
10E	0.750	1.0	57	81	0	10	90	0	61	1355579
11E	0.750	0.4	0	47	0	37	63	0	0	536143
12E	0.750	0.2	0	33	0	55	45	0	0	373233
1D	0.750	0.3	1	45	0	36	64	0	0	509076
2D	0.750	0.5	25	63	0	22	78	0	6	765944

C7: Continued

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
3D	0.750	1.3	73	89	0	5	95	0	81	1850308
4D	0.750	2.4	88	95	4	3	93	5	83	4032817
5D	0.750	2.9	91	96	4	2	85	13	82	4820995
6D	0.750	3.2	92	96	4	2	80	18	82	5161039
7D	0.750	3.1	91	96	4	2	79	19	82	5159862
8D	0.750	2.8	90	95	4	2	87	11	82	4695390
9D	0.750	2.0	83	93	4	3	92	4	79	3541828
10D	0.750	0.9	56	80	0	11	89	0	61	1338597
11D	0.750	0.4	2	52	0	31	69	0	0	596064
12D	0.750	0.2	0	32	0	56	44	0	0	370724
1C	0.750	0.3	1	44	0	39	61	0	0	489466
2C	0.750	0.5	33	67	0	20	80	0	22	1056101
3C	0.750	1.2	70	87	0	6	93	1	82	2000763
4C	0.750	2.3	88	95	0	3	96	1	94	3571906
5C	0.750	3.0	92	96	0	2	85	13	95	4469609
6C	0.750	3.0	91	96	0	2	85	13	95	4477373
7C	0.750	3.1	91	96	0	2	86	12	96	4436488
8C	0.750	2.7	89	95	0	2	94	4	95	3984007
9C	0.750	1.9	83	93	0	4	96	0	89	2835060
10C	0.750	0.9	56	80	0	11	89	0	62	1451724
11C	0.750	0.4	7	54	0	31	69	0	5	774754
12C	0.750	0.3	0	36	0	49	51	0	0	410874
1B	0.750	0.3	1	42	0	41	59	0	0	468980
2B	0.750	0.5	27	63	0	21	79	0	9	774629
3B	0.750	1.0	61	83	3	7	89	4	66	2020952
4B	0.750	2.1	86	94	3	3	93	4	85	3603463
5B	0.750	2.7	91	96	7	2	84	14	81	4884305
6B	0.750	2.6	90	96	7	3	85	13	81	4781997
7B	0.750	2.8	90	96	8	2	81	16	81	4995397
8B	0.750	2.4	87	95	4	3	93	5	89	3825284
9B	0.750	1.8	81	92	3	4	92	4	85	3074004
10B	0.750	0.9	54	80	2	10	86	4	60	1718943
11B	0.750	0.5	13	58	0	26	74	0	0	681053
12B	0.750	0.2	0	29	0	61	39	0	0	333302
1A	0.750	0.3	0	37	0	47	53	0	0	417636
2A	0.750	0.4	7	54	0	30	70	0	3	620456
3A	0.750	0.9	56	81	0	8	92	0	65	1360449
4A	0.750	1.9	84	93	0	3	97	0	92	2895763
5A	0.750	2.3	88	95	0	3	96	1	94	3495609
6A	0.750	2.3	88	95	0	3	96	1	94	3539086
7A	0.750	2.3	88	95	0	3	95	2	94	3554259
8A	0.750	2.2	86	94	0	3	97	0	93	3342759
9A	0.750	1.6	78	91	0	4	96	0	86	2453435
10A	0.750	0.6	36	69	0	17	83	0	32	942104
11A	0.750	0.3	0	39	0	46	54	0	0	447705
12A	0.750	0.2	0	29	0	60	40	0	0	330375

C8: Detail DAYSIM result of R6-55°

Test points	H	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	0.4	12	56	0	27	73	0	7	660444
2H	0.750	0.7	39	72	0	15	85	0	28	962014
3H	0.750	1.4	71	88	0	6	94	0	77	1738339
4H	0.750	3.2	91	96	0	2	95	3	95	3660459
5H	0.750	3.7	92	97	0	2	89	9	96	4258312
6H	0.750	3.6	92	96	0	2	89	9	96	4210893
7H	0.750	3.9	92	97	0	2	87	11	96	4377744
8H	0.750	3.7	92	96	0	2	89	8	96	4171571
9H	0.750	2.7	87	94	0	3	97	0	92	3109278
10H	0.750	1.0	55	80	0	10	90	0	58	1317559
11H	0.750	0.6	28	64	0	22	78	0	9	802487
12H	0.750	0.4	8	48	0	37	63	0	1	570154
1G	0.750	0.5	22	63	0	21	79	0	11	771520
2G	0.750	0.9	54	80	0	9	91	0	55	1244447
3G	0.750	1.4	70	87	0	6	94	0	77	1700311
4G	0.750	3.6	93	97	0	2	89	9	96	4204940
5G	0.750	4.0	94	97	0	2	82	16	97	4802613
6G	0.750	3.9	93	97	0	2	84	14	97	4652329
7G	0.750	4.4	93	97	1	2	80	18	97	4987638
8G	0.750	3.8	92	97	0	2	84	14	96	4603295
9G	0.750	2.8	88	95	0	2	96	2	94	3496329
10G	0.750	1.3	62	84	0	8	92	0	69	1592443
11G	0.750	0.7	39	70	0	17	83	0	23	935865
12G	0.750	0.5	14	57	0	29	71	0	4	681838
1F	0.750	0.6	30	67	0	19	81	0	19	868520
2F	0.750	0.9	57	82	0	9	91	0	62	1346416
3F	0.750	2.0	82	92	0	4	96	0	90	2568309
4F	0.750	3.7	93	97	0	2	82	16	97	4673936
5F	0.750	4.4	94	97	4	2	73	26	97	5465346
6F	0.750	4.7	94	98	7	2	70	28	97	5790045
7F	0.750	4.7	94	97	7	2	70	28	97	5773130
8F	0.750	4.3	93	97	3	2	75	23	97	5333032
9F	0.750	3.0	89	95	0	2	91	7	94	3850447
10F	0.750	1.4	67	87	0	7	93	0	78	1895023
11F	0.750	0.7	38	70	0	17	83	0	32	967497
12F	0.750	0.5	20	60	0	26	74	0	6	735144
1E	0.750	0.6	35	69	0	18	82	0	29	936910
2E	0.750	1.0	62	84	0	8	92	0	70	1472140
3E	0.750	2.2	84	94	0	3	97	0	93	2937105
4E	0.750	4.1	94	97	2	2	73	25	97	5278839
5E	0.750	5.3	96	98	15	2	60	38	97	6662538
6E	0.750	5.4	96	98	16	2	60	39	96	6724986
7E	0.750	5.4	96	98	16	2	59	40	96	6778521
8E	0.750	4.6	94	97	9	2	68	30	97	5885963
9E	0.750	3.4	90	96	0	2	82	15	96	4424347
10E	0.750	1.6	72	89	0	6	94	0	82	2140310
11E	0.750	0.8	45	74	0	14	86	0	44	1096029
12E	0.750	0.5	26	63	0	23	77	0	10	796118
1D	0.750	0.6	44	75	0	14	85	1	40	1123679
2D	0.750	1.0	61	84	0	8	91	1	70	1522101

C8: Continued

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
3D	0.750	2.3	87	95	0	3	96	2	94	3286247
4D	0.750	4.0	94	97	5	2	66	32	81	6198168
5D	0.750	4.7	95	98	16	2	61	37	81	7079344
6D	0.750	5.9	96	98	26	2	51	47	73	8265377
7D	0.750	5.3	96	98	21	2	56	42	80	7621260
8D	0.750	4.8	94	97	15	2	61	37	80	7027320
9D	0.750	3.7	91	96	4	2	74	24	81	5637590
10D	0.750	1.6	74	90	0	6	94	0	83	2358766
11D	0.750	0.8	50	76	0	13	87	0	52	1248348
12D	0.750	0.5	25	61	0	25	75	0	11	810045
1C	0.750	0.6	36	70	0	16	84	0	32	969647
2C	0.750	1.0	62	84	0	7	92	1	74	1778820
3C	0.750	2.1	84	93	4	3	90	7	82	3953131
4C	0.750	3.8	93	97	7	2	66	32	82	6349226
5C	0.750	4.8	96	98	24	2	55	43	70	8254490
6C	0.750	4.7	95	98	24	2	57	42	71	8175666
7C	0.750	4.9	95	98	25	2	57	41	72	8273255
8C	0.750	4.4	94	97	14	2	61	37	84	6948290
9C	0.750	3.3	91	96	3	2	75	23	84	5488823
10C	0.750	1.5	72	88	2	6	91	3	74	2862640
11C	0.750	0.8	51	76	0	14	86	0	51	1352840
12C	0.750	0.5	22	61	0	26	74	0	13	764414
1B	0.750	0.6	42	73	0	15	84	1	36	1091112
2B	0.750	1.0	63	85	0	7	92	1	72	1619239
3B	0.750	1.8	81	92	6	4	88	8	72	3998539
4B	0.750	3.6	94	97	11	2	66	32	65	7482785
5B	0.750	4.5	95	98	27	2	56	42	55	9249324
6B	0.750	4.4	95	98	23	2	60	38	52	9475243
7B	0.750	4.3	94	97	24	2	60	39	52	9420733
8B	0.750	4.1	93	97	21	2	60	39	58	8574552
9B	0.750	3.3	91	96	10	2	71	27	66	6765308
10B	0.750	1.4	68	87	3	7	89	5	74	2574268
11B	0.750	0.6	41	70	0	17	83	0	35	1065108
12B	0.750	0.5	22	60	0	27	73	0	10	813874
1A	0.750	0.5	27	65	0	20	80	0	19	832836
2A	0.750	0.8	53	80	0	10	90	0	57	1704006
3A	0.750	1.5	80	92	0	4	94	2	84	2946478
4A	0.750	3.3	93	97	8	2	69	29	88	5680372
5A	0.750	4.0	94	97	17	2	60	38	83	6689551
6A	0.750	3.7	93	97	14	2	60	38	88	6565427
7A	0.750	3.9	93	97	17	2	60	38	89	6473007
8A	0.750	3.7	92	97	12	2	61	37	94	6005858
9A	0.750	2.8	89	95	3	2	78	19	93	4624240
10A	0.750	1.0	62	82	1	10	89	2	70	1931047
11A	0.750	0.5	36	66	1	21	77	2	25	1135706
12A	0.750	0.4	10	51	0	35	65	0	4	616078

C9: Detail DAYSIM result of R6-50° [800 mm]

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	0.3	0	33	0	55	45	0	0	370848
2H	0.750	0.4	2	52	0	29	71	0	0	586608
3H	0.750	0.9	52	80	0	10	90	0	48	1187078
4H	0.750	2.2	83	93	0	3	97	0	91	2554892
5H	0.750	2.7	89	95	0	3	97	0	94	3116601
6H	0.750	2.5	86	95	0	3	97	0	93	2967621
7H	0.750	2.5	87	94	0	3	97	0	93	2982157
8H	0.750	2.4	86	94	0	3	97	0	91	2863482
9H	0.750	1.7	75	90	0	5	95	0	83	2063507
10H	0.750	0.6	30	67	0	18	82	0	11	842032
11H	0.750	0.3	0	41	0	43	57	0	0	466530
12H	0.750	0.2	0	27	0	65	35	0	0	313910
1G	0.750	0.3	0	40	0	41	59	0	0	452068
2G	0.750	0.5	8	56	0	26	74	0	0	641523
3G	0.750	0.8	43	76	0	12	88	0	34	1036973
4G	0.750	2.3	86	94	0	3	97	0	93	2964216
5G	0.750	2.9	90	96	0	2	96	2	95	3596953
6G	0.750	2.7	89	95	0	3	97	0	94	3321555
7G	0.750	2.9	90	96	0	2	97	1	95	3549671
8G	0.750	2.7	89	95	0	3	97	0	94	3341266
9G	0.750	2.1	83	93	0	3	97	0	89	2632247
10G	0.750	0.6	28	66	0	18	82	0	8	826637
11G	0.750	0.4	0	45	0	38	62	0	0	514302
12G	0.750	0.2	0	30	0	59	41	0	0	349824
1F	0.750	0.3	1	42	0	40	60	0	0	475048
2F	0.750	0.6	31	69	0	18	82	0	15	867369
3F	0.750	1.3	68	87	0	7	93	0	77	1723082
4F	0.750	2.7	90	95	0	2	97	1	95	3511283
5F	0.750	3.2	92	96	0	2	86	11	96	4263072
6F	0.750	3.2	92	96	0	2	87	11	96	4196345
7F	0.750	3.3	92	96	0	2	87	11	96	4243976
8F	0.750	2.9	90	96	0	2	91	7	95	3868506
9F	0.750	2.2	84	93	0	3	97	0	91	2897054
10F	0.750	0.9	51	78	0	12	88	0	53	1212001
11F	0.750	0.4	8	54	0	30	70	0	0	626292
12F	0.750	0.3	0	39	0	45	55	0	0	442962
1E	0.750	0.4	4	51	0	31	69	0	0	578740
2E	0.750	0.7	41	75	0	13	87	0	32	997930
3E	0.750	1.6	76	90	0	5	95	0	84	2080888
4E	0.750	2.7	90	96	0	2	94	4	95	3719002
5E	0.750	3.3	92	96	0	2	82	16	96	4496804
6E	0.750	3.6	93	97	0	2	79	19	97	4768983
7E	0.750	3.7	93	97	0	2	77	21	97	4893107
8E	0.750	3.4	92	96	0	2	84	14	96	4405826
9E	0.750	2.2	85	94	0	3	97	0	91	2995644
10E	0.750	1.1	59	82	0	9	91	0	67	1460258
11E	0.750	0.5	15	57	0	28	72	0	0	671428
12E	0.750	0.3	0	40	0	43	57	0	0	466526
1D	0.750	0.4	6	54	0	28	72	0	1	616862
2D	0.750	0.7	40	73	0	15	85	0	39	1024970

C9: Continued

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
3D	0.750	1.7	79	92	3	4	92	4	82	2858326
4D	0.750	2.8	90	96	3	2	88	10	86	4368994
5D	0.750	3.4	93	97	7	2	70	28	82	5622139
6D	0.750	3.7	93	97	8	2	68	31	82	5934036
7D	0.750	3.6	93	97	8	2	67	31	82	5951868
8D	0.750	3.3	92	96	4	2	79	19	91	4865779
9D	0.750	2.3	86	94	3	3	92	5	88	3552288
10D	0.750	1.1	60	83	2	9	87	4	68	1964972
11D	0.750	0.5	15	59	0	25	75	0	0	693230
12D	0.750	0.3	0	38	0	48	52	0	0	434376
1C	0.750	0.4	5	51	0	31	69	0	2	590424
2C	0.750	0.6	35	70	0	16	84	0	30	935389
3C	0.750	1.5	76	90	0	5	95	0	86	2153351
4C	0.750	2.7	90	96	4	2	89	9	81	4597734
5C	0.750	3.2	93	97	4	2	76	22	82	5328738
6C	0.750	3.3	92	96	4	2	75	23	82	5400334
7C	0.750	3.3	92	96	4	2	76	22	81	5432995
8C	0.750	2.9	90	96	4	2	82	16	82	4929050
9C	0.750	2.1	84	93	4	3	92	4	79	3745484
10C	0.750	1.0	59	82	0	9	91	0	68	1493877
11C	0.750	0.4	11	55	0	31	69	0	0	645342
12C	0.750	0.3	0	37	0	49	51	0	0	422006
1B	0.750	0.3	4	47	0	37	63	0	1	536440
2B	0.750	0.6	34	68	0	19	81	1	26	1092284
3B	0.750	1.0	62	84	0	8	92	1	77	1831082
4B	0.750	2.4	89	95	0	3	94	4	94	3826049
5B	0.750	2.8	91	96	0	2	86	11	95	4343529
6B	0.750	2.7	90	96	0	2	88	10	95	4258713
7B	0.750	2.9	91	96	0	2	83	15	96	4515228
8B	0.750	2.7	89	95	0	2	92	6	95	4108480
9B	0.750	2.0	84	93	0	4	96	0	90	3116905
10B	0.750	0.9	55	79	0	11	89	0	61	1460199
11B	0.750	0.5	15	59	0	27	73	0	5	846436
12B	0.750	0.3	0	34	0	54	46	0	0	389636
1A	0.750	0.3	2	42	0	42	58	0	0	475945
2A	0.750	0.4	10	54	0	30	70	0	5	638312
3A	0.750	0.9	56	81	0	9	91	0	67	1433353
4A	0.750	2.1	85	94	0	3	94	4	94	3334044
5A	0.750	2.6	90	95	0	3	88	10	95	3988383
6A	0.750	2.4	89	95	0	3	90	7	95	3828842
7A	0.750	2.4	88	95	0	3	93	5	94	3687484
8A	0.750	2.4	87	94	0	3	93	4	94	3637596
9A	0.750	1.8	81	92	0	4	96	0	88	2791774
10A	0.750	0.7	40	71	0	16	84	0	38	1009156
11A	0.750	0.3	1	42	0	42	58	0	0	487463
12A	0.750	0.2	0	32	0	57	43	0	0	366260

C10: Detail DAYSIM result of R6-50° [1000 mm]

Test points	H	DF [%]	DA [%]	DA_{con} [%]	DA_{max} [%]	$UDI_{<100}$ [%]	$UDI_{100-2000}$ [%]	$UDI_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
1H	0.750	0.5	19	60	0	25	75	0	14	743213
2H	0.750	0.8	48	76	0	13	87	0	46	1120175
3H	0.750	1.4	72	88	0	6	94	0	80	1828446
4H	0.750	3.4	91	96	0	2	94	4	96	3922516
5H	0.750	4.1	93	97	0	2	85	14	97	4670645
6H	0.750	4.2	93	97	0	2	84	14	97	4716019
7H	0.750	3.9	92	97	0	2	85	13	97	4611573
8H	0.750	3.6	91	96	0	2	88	9	96	4267981
9H	0.750	3.0	88	95	0	3	97	0	94	3395004
10H	0.750	1.1	59	82	0	9	91	0	64	1519388
11H	0.750	0.5	28	63	0	24	76	0	14	849607
12H	0.750	0.4	12	51	0	36	64	0	4	613205
1G	0.750	0.5	27	65	0	21	79	0	18	831270
2G	0.750	0.8	52	78	0	11	89	0	51	1195081
3G	0.750	1.4	70	88	0	6	94	0	79	1744862
4G	0.750	3.6	92	97	0	2	86	13	96	4470776
5G	0.750	4.3	94	97	2	2	75	24	97	5317379
6G	0.750	4.2	93	97	0	2	80	18	97	4991372
7G	0.750	4.2	93	97	1	2	77	21	97	5164379
8G	0.750	4.1	93	97	1	2	79	20	97	5049849
9G	0.750	3.2	90	96	0	2	91	7	95	3986454
10G	0.750	1.1	58	81	0	9	91	0	65	1447835
11G	0.750	0.7	38	69	0	18	82	0	25	935104
12G	0.750	0.4	13	54	0	33	67	0	6	660110
1F	0.750	0.6	36	70	0	17	83	0	29	955403
2F	0.750	1.0	57	81	0	10	90	0	65	1388276
3F	0.750	2.3	84	94	0	3	97	0	93	2932140
4F	0.750	4.4	94	97	2	2	74	25	97	5264619
5F	0.750	5.4	96	98	12	2	63	36	98	6411458
6F	0.750	5.2	95	98	11	2	64	35	97	6316404
7F	0.750	5.1	95	98	11	2	65	34	97	6254764
8F	0.750	4.9	94	97	8	2	68	30	97	5923711
9F	0.750	3.7	91	96	0	2	85	13	96	4477421
10F	0.750	1.5	68	87	0	7	93	0	80	1991608
11F	0.750	0.7	40	70	0	17	83	0	36	998121
12F	0.750	0.5	26	62	0	26	74	0	13	785711
1E	0.750	0.7	42	73	0	16	84	0	39	1041509
2E	0.750	1.3	71	88	0	6	94	0	79	1776861
3E	0.750	2.7	88	95	4	3	91	6	85	4182438
4E	0.750	4.6	94	97	10	2	67	31	86	6358968
5E	0.750	5.8	96	98	25	2	54	44	69	8296770
6E	0.750	6.2	97	98	29	2	49	50	59	8967780
7E	0.750	6.2	96	98	27	2	52	47	64	8632659
8E	0.750	5.7	95	98	20	2	57	41	83	7446426
9E	0.750	4.0	92	97	3	2	76	22	87	5439841
10E	0.750	1.9	78	91	2	4	93	3	80	3016482
11E	0.750	0.8	48	74	0	14	86	0	48	1142045
12E	0.750	0.6	30	64	0	23	77	0	15	825224
1D	0.750	0.7	46	75	0	14	86	0	44	1102389
2D	0.750	1.1	65	86	0	6	94	0	75	1629043

C10: Continued

Test points	H	DF [%]	DA [%]	DA$_{con}$ [%]	DA$_{max}$ [%]	UDI$_{<100}$ [%]	UDI$_{100-2000}$ [%]	UDI$_{>2000}$ [%]	DSP [%]	annual light exposure [luxh]
3D	0.750	2.8	89	96	7	2	88	10	77	4946952
4D	0.750	5.0	96	98	18	2	60	38	74	7635084
5D	0.750	6.0	96	98	34	2	50	49	38	10057560
6D	0.750	6.2	96	98	34	1	49	50	40	10043820
7D	0.750	6.3	96	98	35	1	48	50	35	10226100
8D	0.750	5.4	95	98	29	1	54	44	60	8756489
9D	0.750	3.8	92	96	7	2	73	25	79	5852644
10D	0.750	1.9	79	91	3	4	91	5	82	3044965
11D	0.750	0.9	52	77	0	12	88	0	54	1264614
12D	0.750	0.6	31	65	0	22	78	0	18	856130
1C	0.750	0.7	51	78	0	11	88	1	51	1274708
2C	0.750	1.1	69	87	0	6	92	3	75	2115688
3C	0.750	2.2	87	95	6	3	87	10	75	4921070
4C	0.750	4.3	95	98	19	2	58	40	61	9057532
5C	0.750	5.6	96	98	29	1	51	48	48	10948009
6C	0.750	5.8	96	98	33	1	46	53	45	11484751
7C	0.750	5.6	96	98	30	1	50	49	51	10934174
8C	0.750	4.6	94	97	22	2	56	42	63	9264709
9C	0.750	3.8	92	96	10	2	69	29	71	7279055
10C	0.750	1.6	74	89	4	6	89	5	76	3123445
11C	0.750	0.7	46	73	0	15	85	0	45	1177177
12C	0.750	0.5	30	63	0	24	76	0	17	865887
1B	0.750	0.6	38	70	0	16	84	0	34	995455
2B	0.750	1.0	60	83	0	8	91	0	69	1908850
3B	0.750	1.7	79	91	0	4	96	0	85	2922459
4B	0.750	4.0	94	97	10	2	63	35	91	6218098
5B	0.750	4.7	95	98	21	2	56	42	86	7204262
6B	0.750	4.7	95	98	21	2	54	44	88	7386759
7B	0.750	4.5	94	97	19	2	57	41	94	6868388
8B	0.750	4.5	94	97	17	2	57	41	95	6729557
9B	0.750	3.4	91	96	4	2	70	28	94	5277349
10B	0.750	1.4	69	87	1	6	92	2	78	2365778
11B	0.750	0.7	46	73	1	15	83	2	45	1356855
12B	0.750	0.5	19	58	0	30	70	0	12	733019
1A	0.750	0.5	27	64	0	21	79	0	22	838568
2A	0.750	0.8	52	79	0	11	89	0	59	1340852
3A	0.750	1.6	79	91	0	4	95	1	88	2551956
4A	0.750	3.4	93	97	9	2	71	27	84	5738377
5A	0.750	4.1	94	97	22	2	62	37	72	7199925
6A	0.750	3.9	93	97	16	2	63	35	86	6457139
7A	0.750	4.3	94	97	18	2	61	37	78	6871294
8A	0.750	4.0	93	97	14	2	63	35	85	6352968
9A	0.750	3.1	89	95	6	2	79	19	86	4938064
10A	0.750	1.0	59	81	3	10	85	4	66	2047257
11A	0.750	0.6	37	68	0	19	81	0	28	957077
12A	0.750	0.4	12	52	0	36	64	0	6	631148