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"Adaptive Façade: Electrochromic glazing to Enhance Energy Efficiency of Office buildings"

By:

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A THESIS

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Declaration

I hereby declare that the thesis entitled **"Adaptive Façade: Electrochromic Glazing to Enhance Energy Efficiency of Office buildings"** submitted to the Department of Architecture in partial fulfillment of the requirement for the degree of Master Science in Engineering in Energy Efficient Building, is a record of an original work done under the guidance of Assoc. Prof. Dr. Sanjaya Uprety and Ar. Shreejay Tuladhar, Institute of Engineering, Pulchowk Campus. This thesis contains only work completed by me except for the consulted material which has been duly referenced and acknowledged.

Nunaang Tumrok Limbu

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DEPARTMENT OF ARCHITECTURE

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled **"Adaptive Façade: Electrochromic Glazing to Enhance Energy Efficiency of Office buildings"** submitted by Nunaang Tumrok Limbu in partial fulfillment of the requirements for the degree of Master in Master of Science in Energy Efficient Building.

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Abstract

Fully glazed facades, particularly in office buildings, have certain benefits like transparency and a lot of daylight entering the building, but they also have some disadvantages like glare and solar heat gain in the summer. Fixed or static shade systems have limited ability to adjust to changes in the interior or outside environmental conditions over a day or season and may provide poor performance if operational needs vary over time. It optimizes access to sunshine and outside vistas, lowers energy costs, and provides architects with greater creative freedom. Electrochromic glass is a dynamic glass that can be electronically colored. The main objective of this research is to look into the potential for energy efficiency of installing electrochromic glazing on office buildings in Kathmandu valley. To study the energy, thermal, and visual features of the glazed spaces, a total of 120 questionnaire surveys were completed in three office banking offices in the Kathmandu valley. To learn more about the performance metrics of the available glazing technologies, market research and on-site surveys were also conducted. An experimental shoe box model of 12 by 8 by 3.15 inches was built to test eight glazing technologies, including electrochromic windows, using a simulation-based methodology. The basic case for energy optimization was chosen to be Prabhu Bank (Corporate building). However, the results of the shoe-box model showed that EC glazing only resulted in a 5.12% reduction in EUI. Similar to this, the shoe-box model only showed a negligible 10% reduction in the peak cooling requirement with EC glazing. Peak cooling loads decreased in the real office model by 56.79%, while the EUI decreased by 17.76% without a change in lighting. By comparing it to other static high-performance glazing systems, this study demonstrated that the EC glazing system did perform better at reducing energy.

Keywords: Electrochromic windows, Glare, EUI, Peak loads, Adaptive Façade

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List of Acronyms and Abbreviations

ACP	Aluminum Composite Panel
AEPC	Alternative Energy Promotion Centre
ANSI	American National Standards Institute
AIS	Asahi India Glass Limited
ASE	Annual Sunlight Exposure
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning
CBECS	Commercial Buildings Energy Consumption Survey
cd/m2	Candela per square meter
cDA	Continuous Daylight Autonomy
DA	Daylight Autonomy
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
EC	Electrochromic
EPD	Environmental Product Declaration
EUI	Energy Use Intensity
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
IGU	Insulated Glass Unit
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MoEWRI	Ministry of Energy, Water Resources and Irrigation
NEEAP	National Energy Efficiency Action Plan

NEEP	Nepal Energy Efficiency Program
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
SC	Solar control
sDA	Spatial daylight autonomy
SHGC	Solar Heat Gain Coefficient
SP	Sun patch
TCs	Transparent conductors
TI	Thermally Insulated
Tvis	Visual Transmittance
UDI	Useful Daylight Illuminance
VLT	Visible Light Transmittance
WWR	Window Wall Ratio

1 Chapter 1: Introduction

1.1 Background

1.1.1 Overview of building facades

In passive building technology, the usage of fossil fuels is reduced to a minimum while still maintaining a comfortable indoor environment. This is accomplished by using buildings, features, materials, and other factors for gathering, storing, and spreading solar and wind energy. A passive construction component that isolates the interior space from the exterior and makes the interior environment less susceptible to the multiple environmental changes taking place outside is the structure's envelope. Greater building envelope performance and functionality are now more in demand due to the current focus on increasing energy efficiency and reducing the usage of fossil fuels (Lee, Young-Hum, & Jo, 2021).

In the construction business, sustainable and green technologies are rapidly evolving. Critical analysis is required to integrate these technologies into the current system because they are primarily designed for manufacturing and practical application. However, in the name of efficiency, architects and engineers put people at risk with futuristic structures (Thobaiti, 2014). The question is, how do we include the variety of contemporary objects that successfully preserve both engineering goals and aesthetically pleasing elements in a building's systems? To create structures that offer a secure and comfortable environment for their human occupants, the fundamental strategy in building design typically starts with the identification of a wide variety of criteria. These criteria are then combined to develop multifunctional features. Every new technology development has as one of its main objectives to enhance the living and working conditions of its consumers. Furthermore, we don't want to feel as though we are entering a machine. A properly-designed environment that considers all of our human senses is necessary to humanize and comprehend this technology, as well as construction solutions. Finally, when technology is used in a structure, it should be scrutinized to verify that it meets its goals while also providing human comfort (Thobaiti, 2014).

Improved building energy efficiency creates environments that are more environmentally friendly (ANSI/ASHRAE Standard-55, 2017). Any choice made during the building process will affect the building's overall energy efficiency and the satisfaction of its occupants. To find the finest solutions for a better environment, it is vital to take into account building processes at all stages, from design to construction. These skins' design optimization allows them to improve visual and thermal comfort while also lowering total building energy consumption (Rizi & Eltaweel, 2020).

One of the most important and concerning topics in contemporary architecture is that study entails dealing with surfaces (Picon, 2010). Therefore, for creating a sustainable and adaptable architecture's primary goal is to create parts that can be combined to create skin geometry, which is attached to the building's façade and sensitive to certain climatic conditions. The surface generation scheme includes adaptive systems, sometimes known as "kinetic systems," which are unquestionably closely related to computational fabrication design and digital architecture. Three-dimensional layers are used to control the two-dimensional skin elements in these systems. These operating components are coupled to the material system and incorporated into the skin (Thobaiti, 2014). On the other hand, the conventional design combines skin systems, common materials, and standard operating processes; the material selection is limited to the response condition, and its features are fixed (Maragkoudaki, 2013).

Recent data indicates that 90% of people's time indoors is spent in wealthy nations. This trend reflects the various needs of the indoor environment, where structures are crucial to ensuring people's well-being. According to statistics, buildings consume more than 40% of primary energy in the majority of IEA countries. In this context, it is essential to create building stock policies to achieve the objectives set by various nations in terms of energy efficiency and climate change (Aelenei, Aelenei, & Vieira, 2016).

Given that a building's façade has the greatest impact on its energy efficiency, façade elements must be created to provide the structure the flexibility it needs for energy flow and thermal comfort. According to current standards, building envelopes must behave like energy-efficient mechanical systems that can adjust to non-constant, changing external conditions. In practice, this means that the façade must change or adapt to meet the required standards of efficiency and utility. The use of adaptive façades permits significant reductions in building energy consumption and CO2 emissions while maintaining occupant thermal and visual comfort as a result. There are already a few adaptive façade concepts (materials, systems, and components) under development, and more cutting-edge concepts are shortly to follow (Aelenei, Aelenei, & Vieira, 2016).

1.1.2 Office building overview

The consumption of energy in office buildings (commercial buildings) is beginning to have an impact on regional and national energy demand patterns. The business sector currently accounts for 13% of global energy demand, according to the United Nations. Because the energy consumption of office buildings is influenced by a variety of factors (including working hours and weather conditions), it follows some predictable annual, monthly, and daily patterns (Mikulik, 2018). In office buildings, heating, ventilation, and air conditioning (HVAC) use up half of the energy, with lighting (15%), appliances (10%), and other activities like food preparation, water heating, and refrigeration accounting for the remaining 25%. These percentages may differ based on the local climate, which has a big impact on energy use and occupant behavior (Mikulik, 2018).

Commercial buildings require more energy and have higher occupant densities than other types of structures. Enormous office buildings are being built all over the world, and buildings with substantial windows account for a large share of them. By using fewer fossil fuels, minimizing energy use benefits the environment while simultaneously improving occupant comfort (Lu, 2022). Fully glazed facades, particularly in office buildings, have some advantages such as transparency and a large amount of daylight entering the building, but they also have some drawbacks such as glare and solar heat gain in the summer. The exterior shade system is the most frequent adaptive technology used to overcome these difficulties, but it has the disadvantage of lowering vision, decreasing sunshine, and thus increasing energy usage for artificial lighting when in use (Masoudi, 2018). Simultaneously, the same solution serves as a thermal regulator, allowing it to act as a solar radiation barrier while also controlling the level of illumination. As a result, one of the major drawbacks is that just one solution is typically used to govern two aspects that, on the contrary, should be addressed separately. Once you've grasped the challenge, look into design ideas, technologies, and materials that can better respond to outdoor stimuli and operate autonomously to meet a specific need (Masoudi, 2018).

The need for a more effective method of regulating the inside atmosphere has increased as a result of the use of massive glass facades on office buildings. Early in the 20th century, curtain wall technology was initially applied in America to enable non-structural facades on commercial structures. In addition to changing the way these structures looked, this led to a rise in the requirement for artificial methods of assuring user comfort. Office buildings today house a lot of people, a lot of lighting, and a lot of technology, such as servers, copy rooms, and other things that are getting bigger and bigger. The structure's overall energy consumption rises due to the combination of possibly inefficient glass facades (as opposed to opaque walls) and heavier equipment loads, making it a significant contributor to the global warming brought on by human activity (Hansanuwat, 2010).

All-glass facades are said to be inefficient due to their poor insulation qualities. When a building's skin is entirely formed of curtain wall glass, it can lead to situations where unnecessary solar radiation enters the building or where the heat that has already entered the space is permitted to depart rather than be preserved. Although the introduction of insulated glass units has aided in efficiency improvement, it still does not take into consideration blocking the sun's rays before they reach the building's skin, which results in lower final U values (Hansanuwat, 2010). A new method of building facades has become necessary due to increased building loads and the use of all-glass facades. Building loads from equipment are not anticipated to decrease in the future but are more likely to increase, therefore a more efficient building façade might be one solution. Increased glazing insulation has been used to address this, but another solution is to incorporate sun shading, daylighting, and ventilation systems into the façade (Hansanuwat, 2010).

1.1.3 From Static to Adaptive

Fixed or static shade systems have limited ability to adjust to changes in the interior or outside environmental conditions over a day or season and may provide poor performance if operational needs vary over time. As a result, non-flexible facades that maximize façade transparency to promote daylight penetration frequently result in occupant changes owing to glare or overheating concerns over the building's life cycle, lowering the expected indoor comfort and energy savings in the long run (Tabadkani, Banihashemi, & Hosseini, 2018). To get additional natural light into the depths of the space, more sophisticated design solutions are required, even though a normal window may be adequate to let sunlight into the area.

On the other hand, a building's facade is the part that is most obvious and contributes to its aesthetic appeal. Additionally, it is in charge of acting as a physical partition and boundary between the inside and the outside. As a result, it is constantly subject to uncontrollable weather changes like solar radiation, precipitation, wind, and extreme temperatures, all of which have an impact on the comfort of the building's occupants inside.

The adaptive façade is a building envelope that can adjust and change sections of itself to respond to changing exterior environmental conditions. The adaptive facade has the potential to be a viable passive solution for addressing tenant needs. Movable shade devices, which can be used as moving elements of an altered façade, allow for non-standard forms and erratic movements. Depending on their designs, components, and constructions, movable shading devices are available in a wide range of sizes and shapes. Depending on the type of driving force—biomimicry, mechanical forces, shape memory alloys, smart materials, or anything else—the movements can also alter (Lee, Young-Hum, & Jo, 2021).

1.2 Need of the study

Façades serve a variety of purposes and are made up of a variety of parts and materials. The outside climate varies with the passing of time and season, supplying and removing energy from the building skin. Most modern façades have no means of buffering between the two, other than storing air in a double-skin façade to use as a warm blanket in the winter. Even though some buildings use thermal mass in their floors, ceilings, and aquifers to store heat or cold between day and night and seasons, these technologies operate independently of the building's exterior and aid in the building (Tabadkani, Roetzel, Li, & Tsangrassoulis, 2021).

Adaptive facades should differ from "traditional" façades in that they can alter their characteristics to changing surroundings and mediate between them. Views vs. privacy, views vs. solar gain, solar gain vs. overheating, and daylight vs. glare are some examples of design scenarios and functional performances that may conflict with each other (Tabadkani, Roetzel, Li, & Tsangrassoulis, 2021). As a result, numerous environmental factors must be taken into account during the general design phase of a building façade. A sizeable portion of the energy used throughout a building's life cycle is consumed during the operational period (such as lighting, heating, and cooling). Therefore, it is crucial to keep buildings' operational energy requirements as low as possible (Bui, Nguyen, Ghazlan, Ngo, & Ngo, 2020).

The issue is not completely resolved by conventional façade design methods, which concentrate on a single design solution (i.e., static façade systems that are insensitive to climate variations). As a result, to improve energy efficiency, an adaptive façade system that responds to changing climatic conditions is required (Bui, Nguyen, Ghazlan, Ngo, & Ngo, 2020). Electrochromic (EC) windows offer a considerable opportunity to lower building energy use. Using dynamic windows is the key to achieving this goal while preserving the view and increasing the comfort and productivity of professional workers. Therefore, it is essential to research the effects of using electrochromic glasses to improve the energy efficiency of office buildings.

1.3 Importance of the study

This study aims to assess the efficiency of office buildings using electrochromic glazing which is one of the typologies of adaptive façade systems. As a result, this study is critical to encouraging the reduction of energy consumption significantly. The adaptive façade can change its properties to adapt to variable climatic conditions. Using flexible control states, rather than a single solution for all operational conditions, individual building components (such as a single window) can also respond to climatic change. Additionally, it's crucial to promote the usage of dynamic electrochromic windows, which in developing nations like Nepal hasn't received the attention it warrants. Numerous EC window typologies, which are intelligent, dynamic, responsive, advanced, and more, are still unknown to engineers, architects, planners, and researchers. Without sacrificing views, daylighting, or aesthetics, it would open the door for better energy conservation across a variety of sectors, including residential, commercial, institutional, etc.

1.4 Problem Statement

In OECD member countries and emerging countries, respectively, it is anticipated that the energy needed by the building sector will increase by 1.5 percent and 2.1 percent per year between 2012 and 2040. (Bui, Nguyen, Ghazlan, Ngo, & Ngo, 2020). With the recent emphasis on boosting energy efficiency and minimizing the use of fossil fuels, there has been an increase in demand for greater building envelope performance and functionality (Lee, Young-Hum, & Jo, 2021). Studies have selected solar radiation, illuminance, temperature, discomfort, glare, etc., as major driving parameters configured for controlling shading.

Designing an efficient shading system that can balance daylighting and view-out maximization while lowering discomfort risks and the building's energy burden is the most challenging issue for architects and designers (Tabadkani, Roetzel, Li, & Tsangrassoulis, 2021). Regarding the evident limits on the natural environment caused by the built environment, the construction industry has been following the global ‘energy-efficient movement’. Because heating, cooling, and hot water use account for 60% of a building's energy use, energy efficiency strategies should concentrate on these concerns. Optimizing the building envelope as a significant influence on a building's heating and cooling energy demand might help to reduce total energy loads in this situation (Hande & Müjde, 2021).

Despite a lack of precise awareness of such trends in terms of various critical elements of structures, such as energy use, demand, and desired comfort level, the widespread use of glazing in building facades has expanded in Kathmandu Valley in recent years. Numerous studies have shown that energy consumption in commercial buildings is increasing as a result of increased use of glazing for fashionable reasons in various amounts, as well as a lack of empirical knowledge of heat loss and benefit and their effects on overall comfort levels and operational costs (Shrestha & Uprety, 2019).

Existing office building facades are inefficient and unable to meet the needs of rising interior heat gains and equipment loads, as well as a lack of natural daylighting and ventilation. The vast amounts of glass do not successfully give thermal comfort to the residents in an energy-efficient manner, and they do not match the contemporary needs for decreased energy usage. The inefficiencies of the façade will become even more obvious when interior loads rise, as the facades will be less effective at maintaining ambient conditions, necessitating additional high-energy mechanical systems for comfort (Hansanuwat, 2010).

To provide interior rooms with a particular amount of natural light and a view of the outside, structures often use windows. They typically perform less thermally than the adjacent wall, and the potential solar heat gain and thermal conduction via the window limit their maximum size (Reynisson, 2015). Kathmandu Valley, with a population of 2.54 million, is one of South Asia's fastest-growing urban areas, with a 6.5 percent annual growth rate. The valley is home to a multitude of commercial and financial companies that employ both formal and informal workers. In urban locations, all commercial and commerce facilities are constructed and they are mostly single-glazed units (Awale, 2021).

1.5 Objectives of the study

The main objective of this study is to investigate the energy efficiency potential of implementing electrochromic glazing on office buildings in Kathmandu valley. The sub-objectives are as follows:

- ✓ To compare the use of electrochromic glazing with other traditional glazing solutions taking into account annual and diurnal climate variations.
- ✓ To comprehend the distinct usage and find the most effective design approach to enhance an office's energy efficiency.
- ✓ To look into the visual comfort aspects of electrochromic glazings.

1.6 Boundary Conditions

Location: Kathmandu Metropolitan City

Climate: Temperate

Dates for analysis: 21st of September

Time spectrum: 08:00-18:00

Building: Office building

1.7 Validity of the study

Adaptive facades like smart windows Electrochromic (EC) smart windows are the next generation of glass with dynamic transparency modification to appropriately modulate lighting and solar energy entering buildings. Because they aim to increase a building's comfort and energy efficiency by using the energy present in the surroundings as a trigger for a change or alteration in the exterior configuration to work more effectively under those particular circumstances, they are significant in the future of environmentally friendly locations (Rizi & Eltaweel, 2020).

The literature review is done to indicate the validity of the above-mentioned research purpose. There has been a lot of research on this topic all around the world, but none of it has been done in our setting. This study will introduce EC windows to cities and aid in the adoption of the new state-of-the-art smart windows. Given the urban trends of random glazing in buildings around the country, smart windows are now a must in the future. It will keep repeating itself if we do not consider counteracting the outmoded practice of using excessive glazings without taking appropriate steps. Although the use of electrochromic glasses cannot guarantee that they will meet all energy conservation criteria on their own, it is one of the key smart solutions that has begun to be embraced all over the world. As a result, studying energy efficiency through the use of electrochromic glasses in the Kathmandu valley, where the central region is made up of congested high-rise structures with considerable glazing in varying proportions for trendy reasons, could be an effective topic.

1.8 Limitations of the study

1) Different forms of dynamic adaptive façade systems which are advanced, and have been deployed in industrialized countries, are not practical in Nepal.
2) It will be challenging to translate the appropriate functional concepts of smart windows design because it is frequently influenced by themes outside of construction.
3) The change from the traditional “static” mindset to a dynamic perspective is new and challenging.
4) There is a scarcity of data on electrochromic glazing performance and appropriate software for evaluation, making a quantitative comparison of different designs difficult.

5) It is necessary but difficult, to examine the building's entire performance rather than simply specific factors like visual or thermal performance.

1.9 Expected Outputs

1. The research's expected outcomes are to meet the research's main goal, which is to investigate the energy-efficient potential of implementing electrochromic glazing on office buildings.
2. A comparative study analysis between static facades and electrochromic glasses with quantitative results of energy conservation.
3. The simulation results should demonstrate that the use of electrochromic glasses will efficiently minimize the building’s energy consumption.
4. The research findings can show how the use of electrochromic glazings can create an effective shading system.
5. To figure out what existing solutions for adaptive facades might be accessible and feasible that are not currently being utilized.

2 Chapter 2: Literature review

2.1 Glazing Facades in Office Buildings

In recent years, architects have noticed a trend for office buildings with glass facades. It has become a regular feature in commercial construction, similar to various buildings that have a mission to improve the thermal performance of the building envelope (Mobasher A., Khodeir M., & Nessim A., 2021). In comparison to previous materials technology, modern technologies have facilitated the fabrication of a wide range of distinct styles of substances that may be efficiently utilized in building construction, resulting in superior performance. Glass is a key material in architecture, and it is effectively used to create interiors, walls, and panels in desired designs, as well as doorways, staircases, eaves, flooring, and ceilings, all with light effects, making it an excellent visual technique for architects (Gavrilović J. & Stojic, 2011). These days, glass is tinted, polished, laminated, sealed, rubbed, perforated, stitched, wired, tempered, adjusted, and in lots of forms. Glass materials on construction sites are quite exceptional from the conventional wall curtain schemes (Mobasher A., Khodeir M., & Nessim A., 2021).

Figure 2-1: Office building facade clad in "EC" glazing.
Source: (Gavrilović J. & Stojic, 2011)

Glass panels are commonly used in architectural layouts for external cladding as a "glass facade" and for glazing a variety of sizes of windows. Because glazing plays such an important role in a building's overall power balance, it is specifically addressed by the European Union's Energy Savings Code of 2002, which states that if the floor area of glazing exceeds 30% of the façade, the heating system must be designed to consider the electricity balance of the facility (Gavrilović J. & Stojic, 2011).

2.1.1 Advantages

"Glazed façades give the arrangement a refreshing feel, as well as providing the inhabitant with a view out" (Flodberg, 2012). Places with glazed façades are viewed as being more open, with the distinction between inside and outside virtually dissolving, according to Bülow-Hübe (2008). According to some authors (Pedersen, 2020), transparency is a significant factor in selecting glazed façades since they have a direct touch with the environment. Furthermore, they claim that, from the client's perspective, a change in structure has the effect of a transparent corporation painting, which can also indicate the organization's openness.

2.1.2 Disadvantages

Glazing facades are also used in office buildings to allow for daylight hours, however visual communication is typically advised. Glazing curtain partitions in buildings may increase the threats of overheating and visual discomfort at the same time as limiting solar ray penetration. Due to the glass's high thermal conductivity, overheating occurs. Glare, a negative element of light, occurs as a result of the excessive evaluation, either directly or through a mirrored picture, and it causes discomfort and incapacity (Mobasher A., Khodeir M., & Nessim A., 2021). Poirazis and Blomsterberg (2005) assert that offices with glass envelopes use more energy because they require more cooling than conventional building façades do. "Thermal comfort issues will surface when windows are huge, both in the summer and the winter. In these situations, a low U-value is required to address the winter issue, while a low g-value in conjunction with shade devices addresses the summer issue (Bülow, 2001).

2.1.3 Energy use in office buildings

Office buildings (commercial buildings) are beginning to have an impact on regional and national power demand trends. Currently, according to (Conti, et al., 2016), the demand for strength in this economic region represents 13% of global demand. Because the strength intake of office buildings is influenced by several factors (including working hours and weather conditions), there are a few common annual, weekly, and day-to-day demand patterns. According to (Pe´rez-Lombard, Ortiz, & Pout, 2008), 50% of the energy used in office buildings is used for heating, ventilation, and air conditioning (HVAC), with the remaining 25% going to lighting (15%), office equipment (10%), and other uses including food preparation, water heating, and refrigeration. The odds may also vary depending on the local climate, which has a significant impact on both electricity demand and occupant behavior (Mikulik, 2007).In addition to the industrial and transportation industries, the construction of energy intake has become one of the three most important power-consuming businesses. Offices are a symbol of today's global information economy and publish-commercial technologies. One of the most significant architectural trends of the twenty-first century, office buildings currently accommodate more than half of the metropolitan population after more than a century of expansion (Ding, Zhu, Wang, & Ge, 2017).

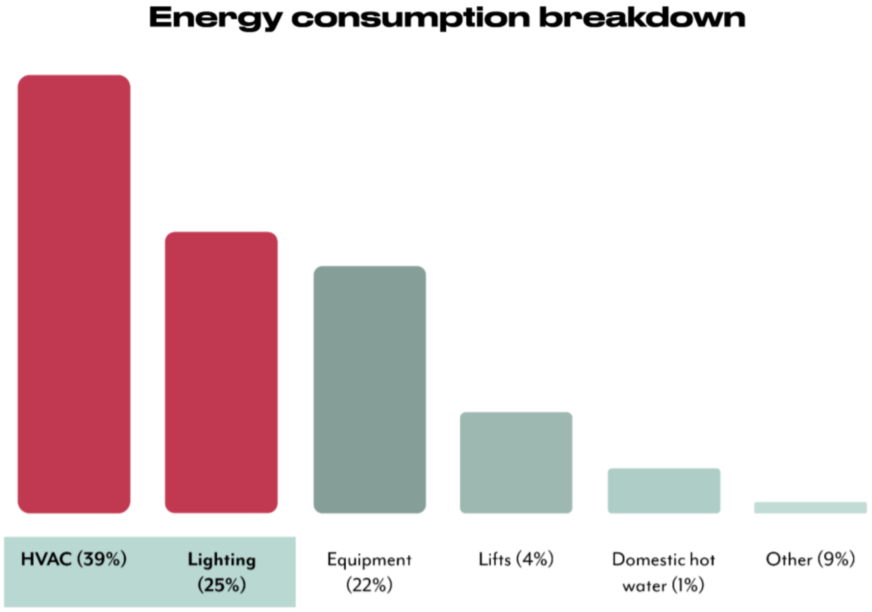


Figure 2-2: Typical Energy Consumption Breakdown
Source: (Department of the Environment and Energy, 2012)

Thanks to current manufacturing techniques and materials, as well as generation breakthroughs, builders were able to control the interior structure of buildings and adjust them to meet an expansion of capabilities. In today's workplace designs, some areas can be used as halls, receptions, atria, server rooms, gadget regions, garages, offices, conference rooms, restaurants, stores, and service units. Nowadays, the general performance-primarily based completely building idea is used in office building design and improvement, which evaluates the degree of comfort enjoyed utilizing a building's clients to confirm the high quality of its architectural and structural functions. To provide the user with the best walking environment, developers seek to deliver appealing designs, advanced spatial solutions, and a variety of creative materials (Go4Energy; Skanska; Cushman and Wakefield, 2017).

2.1.4 Motivation For Increased Flexibility And Adaptability

The smart or adaptive envelope has been added to the traditional three typologies of building envelopes described by Banham in 1969: conservative, selective, and regenerative. Energy fluxes between indoors and outdoors can be actively controlled via adaptive envelopes. They can also modify their features to increase indoor comfort while lowering energy use. Moreover, several distinct types of adaptive envelope concepts have already been established, with more developing, unique solutions expected shortly. Contrarily, by altering their performance and behavior in real-time based on indoor-outdoor conditions, employing materials, components, and systems, adaptive façades can improve building energy efficiency and economics (Romano, Aelenei, Aeleini, & Mazzucchelli, 2018).

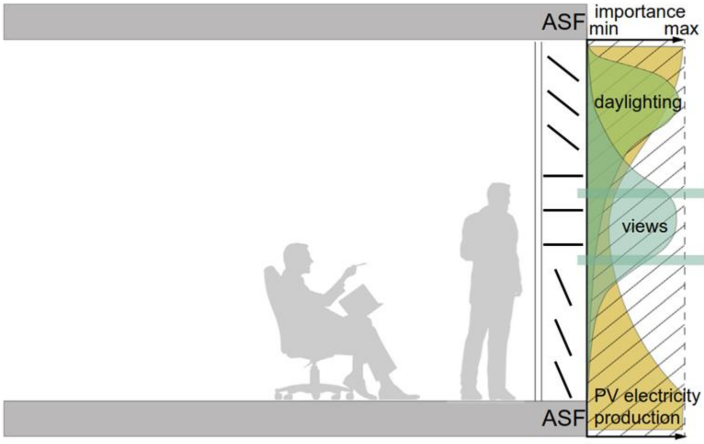


Figure 2-3: Between the inner and exterior environments, the facade mediates and serves several purposes.

Source: Modified from Jakica and Zanelli (2014).

2.2 Chronology of the development of window glazing technologies

Windows are one of the most important elements of a building's thermal envelope since they offer aesthetics, let in light, help with sound control, and serve as a source of natural ventilation. The development of windows' design is a reflection of not only the development of architecture but also the development of framing materials and glass manufacture. The history of windows is entwined with the history of architecture (NBS, 2022).

Knowing that early windows were simply holes in the walls is interesting. The next step of development required covering them with cloth, wood, or paper so that they could be shut or opened using the appropriate shutters. Later, windows were made to transmit light while also protecting the occupants from adverse environmental circumstances. For this purpose, glass was employed. In Alexandria in the second century AD, glass was employed by the Romans as a window material. For this purpose, they employed windows made of cast glass, which had poor optical qualities (Leftheriotis & Yianoulis, 2012).

Window glass was fashioned from big disks of crown glass until the seventeenth century. Larger glass sheets were created by blowing cylinders that were later flattened and cut into panes. The cylinder method predominated in the early nineteenth century while making window glass. Glass panes could only be cut to a maximum width of 2.0–2.5 m and a maximum diameter of 250–350 mm, resulting in windows with rectangular panels that were separated by transoms. English engineer Henry Bessemer was the first to patent automated glass manufacture in 1848. His method formed the ribbon between rollers to make a continuous ribbon of flat glass. The necessity to polish the glass's surfaces made this a costly operation. It would significantly reduce expenses if the glass could be mounted on a completely smooth body. There have been attempts to make flat glass over molten tin baths, particularly in the United States. H. Hill and H. Hitchcock received patents in 1902 and 1905, respectively, however, this method was not practical. Before the invention of float glass, thicker sheets of plate glass were produced by pouring a lot of glass onto an iron surface and then polishing both sides of the product, an expensive operation (Kondrashov, Fainberg, & VS, 2000).

In-line grinders and polishers were used to process a continuous ribbon of plate glass starting in the early 1920s, which decreased glass losses and expenses. The first successful commercial application for producing a continuous ribbon of glass using a molten tin bath, over which the molten glass flows freely under the effect of gravity, was developed between 1953 and 1957 by Sir Alastair Pilkington and Kenneth Bickerstaff of the UK's Pilkington Brothers. After Pilkington made its new technology known in January 1959, high-quality glass production quickly increased.

In 1960, Pilkington realized its first sizable profit from the sale of float glass. A float glass production line was put into operation in 1969 as a result of the Soviet Union's invention of a two-stage molding process (USSR Inventor's Certificate nos. 230393 and 556593, US Patent no. 4081260). PPG Industries (the US) received a patent for the method of creating float glass in 1974 (US patent no. 3843346) (Leftheriotis & Yianoulis, 2012).

Currently, the float method is the norm for making glass: Float glass makes up more than 90% of all flat glass made globally. As of 2009, four companies—Asahi Glass, NSG/Pilkington, Saint-Gobain, and Guardian Industries—controlled the majority of the global float glass market, excluding China and Russia (Wikipedia, n.d.). Modern windows were made possible by the development of the industrial glassmaking process, the application of low-E coatings to transparent surfaces, and the deposition of suitable thin films. Low-e coatings are spectrally selective thin films that improve the functionality of plain glass by enabling it to perform two functions as a part of fenestration systems at once: suppressing radiative heat losses and daylighting of buildings.

Low-e coatings for fenestration, automotive, and architectural applications are now routinely produced thanks to recent developments in the glazing industry (particularly in the field of metal-based coatings). These coatings are used as transparent conductors (TCs) in many devices, including light-emitting diodes, displays, dye-sensitized and organic solar cells, smart switchable windows, and gas sensors. They also have electronic conductivity. Due to the wide range of applications for these films, they are at the cutting edge of high technology (Leftheriotis & Yianoulis, 2012).

The first electrochromic materials, which change visible and near-infrared light with an applied voltage, were demonstrated in the 1950s and 1960s. This method has been evaluated in many ways during the intervening years. In window application designs, five thin film layers are frequently employed, either on a single glass substrate or sandwiched between two glass substrates (Sbar, Podbelski, Yang, & Pease, 2012).

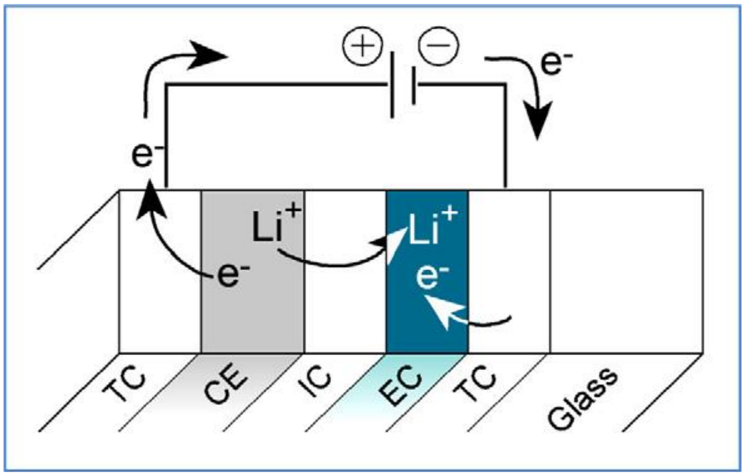


Figure 2-4: SAGE electrochromic thin film stack on glass. TC stands for a transparent conductor, CE for counter electrode, IC for ion conductor, and EC for electrochromic layer.
Source: (Sbar, Podbelski, Yang, & Pease, 2012)

2.3 Future adaptive façade technologies

To address concerns about well-being and overheating of ineffective and high-performing structures, adaptive facade solutions are becoming more and more common. On the other hand, conventional literature review studies might not necessarily offer significant perspectives on the development of adaptive façade technology (Attia, Lioure, & Declaude, 2020).

2.3.1 Classification of promising technologies

By 2050, the experts identified four key families of adaptive facade technologies that show promise for significant market penetration. The expert's understanding of each technology's maturity level, market presence, and market penetration (volume of sales) served as the basis for the classification (Attia, Lioure, & Declaude, 2020).

2.3.1.1.1 Dynamic shading facades

• Often coupled to a Venetian blind built into the glass are shutters, roller blinds, Venetian blinds, and CCF naturally operated, which are four adaptive façade technologies that fall under the category of dynamic shading and are made up of moveable pieces.

• Both motorized and human activation of these movable components are options.

- Sunlight is blocked by all of these technologies. Through participation in thermal insulation, summer comfort, or energy-saving cooling, they seek to regulate the amount of daylight.

2.3.1.1.2 Chromogenic facades

- Chromogenic facades include three chemically based techniques: electrochromic glazing, liquid crystal glazing, and thermochromic glazing.

- Although they are immediately integrated into the glazing, these technologies are neither internal nor external to the building. Their physical characteristics can alter depending on the voltage and power level, altering the glazing's look and making it more or less transparent.

2.3.1.1.3 Solar active facades

- Building-integrated PV, double-skin facades, green roofs and facades, and phase change materials can all be found in solar active facades.

- The first three make use of exterior tools that are in direct sunlight.

- By blocking sunlight, green facades, double-skinned facades, and roofs also accomplish the objectives of controlling sunlight and enhancing summer and winter comfort.

2.3.1.1.4 Active ventilative facades

- Actively ventilated CCFs and automatic operable windows are two of the technologies used in AFVs.

- Ventilation is the cornerstone of these two techniques. While actively ventilated CCF aims to control the airflow inside the cavity, automatically operable windows aim to control the air entering the building.

Figure 2-5: Four families of future adaptive façade technologies can be identified. Source: (Attia, Lioure, & Declaude, 2020)

2.4 Indoor Comfort

Natural and environmental influences are generally present in our daily lives. Our surroundings are likewise continually changing, albeit slowly and through nonphysical means. These alterations justify the fact that our comfort assessments are constantly regulated. As a result, buildings must be able to adapt and vary their configuration in reaction to changes in the surrounding environment and, changes in their users' abilities (Mourtzouchou, 2018). When a person feels content with his or her well-being and the surroundings, he or she is said to be in comfort. Comfort can be classified into distinct classes (Bluyssen, 2009), which is a useful method to explain it in this section. These are the categories:

- Thermal comfort
- Auditory comfort
- Visual Comfort
- Olfactory comfort
- Hygienic comfort

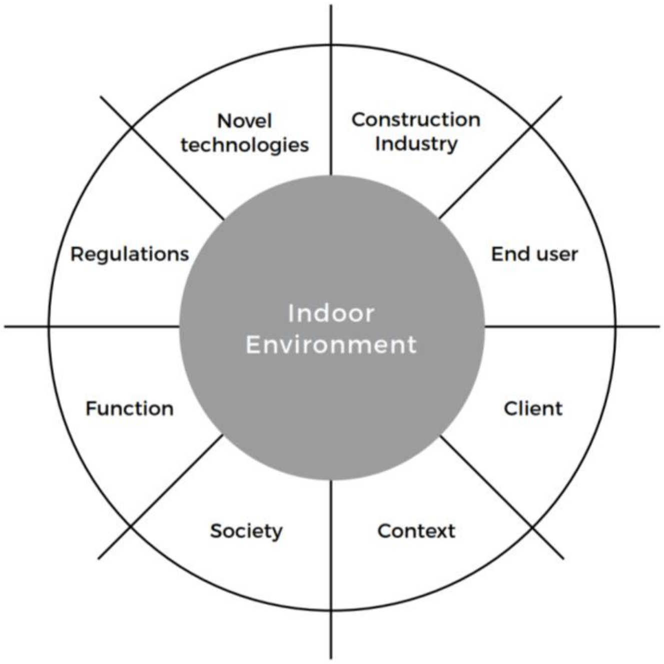


Figure 2-6: Drivers of indoor environmental aspects
Source: (Mourtzouchou, 2018)

2.4.1 Thermal Comfort

Different building facades equate to different levels of indoor comfort and strength. A brilliant facade design allows you to save money on power while increasing your internal comfort. As a result, passive building façade design is critical for reducing building power use (Pengfei, Chi, & Wang, 2021). Thermal comfort is influenced by both environmental and individual factors. Even though those components are unrelated, they all contribute to a worker's thermal comfort. Adaptive envelope structures can improve thermal comfort in real-time at the building scale because they can change their features, functions, and behavior in response to external environmental stimuli.

Environmental factors:

- Air temperature
- Radiant temperature
- Air velocity
- Sunlight
- Humidity

Personal factors:

- Clothing Insulation
- Metabolic heat

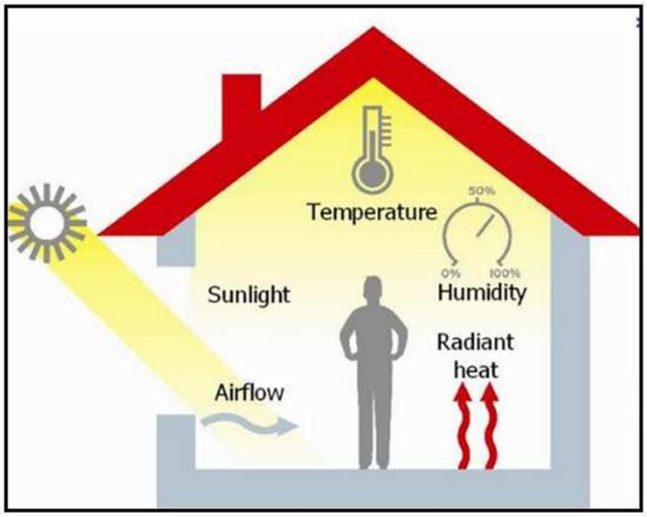


Figure 2-7: Factors affecting Human comfort
Source: Mamdooh Alwetaishi

2.4.2 Visual Comfort

When it comes to building design, daylighting has always been a priority. Artificial lighting gave independence from outside natural lighting, allowing for more arrangement flexibility. The quantity of light in a room, its coloration quality, the glare, and the view are all factors that influence visible comfort. The quality and quantity of light in buildings are seen as extremely important, as inadequate or poor lighting fixtures can cause individuals to become tense or even depressed (Mourtzouchou, 2018).

Visual comfort is determined by the following parameters (Bluyssen, 2009):

- Luminance and illuminance
- Reflectance(s)
- Color temperature and color index
- View and daylight
- Frequencies

2.5 Optical and Thermal Performance

The ventilation, daylighting, solar heat gain, and aesthetic functions of windows in buildings are crucial. In general, the three major variables that can be used to describe the thermal and optical properties of a window are the U-value, the Solar Heat Gain Coefficient (SHGC), and visible transmittance. The three well-known heat transmission modes of conduction, convection, and radiation dictate the evaluation of the aforementioned characteristics (Santana, Jarimi, Carrasco, & Riffat, 2019).

2.5.1 U-value

A window's U-value, also known as the total heat transfer coefficient or total thermal transmittance, is used to determine how effective it is as an insulator. The U-value is calculated using the air-to-air heat transfer measured in W/m2K from or into the building through the window components (i.e., glazing, frame, the gap between glass panes (if any), and spacers).

2.5.2 G-value

The SHGC often referred to as the G-value, is a measurement of how much solar transmittance—or energy—is absorbed by window materials before being radiated back into space as a result of solar radiation. To reduce the demand for heating loads in the winter, this factor is used to evaluate the solar shading capabilities of these transparent components to the shortwave radiation. Readings of the SHGC typically range from 0.2 to 0.7.

2.5.3 Visible Transmittance

This optical property includes the portion of the visible light spectrum that passes through a particular glazing material. For clear glazing and highly reflective coated glazing, it typically ranges between 90% and 10%. The type of glazing, the number of panes, and the presence of coatings that can alter transparency all have an impact on this factor. More daylight enters space as a result of high visual transmittance, which also frequently reduces the need for electric lighting and heating. A low-E coating and tinted films can further reduce the visual transmittance of double-glazed windows, which typically have a transmittance of 78%.

2.6 Commercially Available Glazings

2.6.1 Single Glazed units

2.6.1.1 Clear Single Glazing

A single piece of clear, uncoated glass makes up the most basic sort of window. The maximum apparent transmittance is provided, however, it has significant heat losses. Glazing of this type also suffers from mist condensation and inadequate sound insulation. These days, the usage of such glazing is restricted to inexpensive fixes or window retrofits in old buildings without thick enough frames to support double glazing (Adhikari & Bhattarai, 2014).

2.6.1.2 Tinted Single Glazing

Regular float glass with colorants is tinted glass. An essential component of architecture for the outer appearance of facades is colored glass. Due to its high extinction coefficient, low transmittance, and strong absorptance, tinted glass is often referred to as "absorptive." The inadequate optical transmittance reduces the amount of daylight that remains inside. Therefore, its main function in windows is to lessen glare and excessive sunlight transmission. Because the reduction in light transmission is achieved through absorption, such glazing exhibits high SHGCs. The absorbed radiant energy is initially transformed into heat inside the glass, raising the glass' temperature. The majority of it is then discharged once more. Tinted glazing allows for a greater drop in visual transmittance (Tvis) than SHGC due to reemission. In reality, transmittance in the visible and SHGC must simultaneously increase (winter, cold climates) or decrease (summer, hot climates) by a comparable proportion. Thus, single-tinted glazings fall far short of ideal performance. To solve this problem, other, better solutions have been developed, such as spectrally selective coatings with a light blue/green tint that have better visual performance and reduced SHGC (Leftheriotis & Yianoulis, 2012).

2.6.1.3 Reflective Single Glazing

To significantly reduce solar gains, glass can have a reflective coating put to it to improve its surface reflectivity. The reflective coating often consists of tiny layers of metal oxide or metallic materials and is available in a variety of metallic hues, including bronze, silver, and gold. The thickness, reflectivity, and placement of the coating inside the glazing system all affect the SHGC.

Some reflective coatings, such as those made of noble metals, must be protected by sealing in the cavities, but others are robust and can be added to exposed surfaces. Reflective glass' visual transmittance decreases faster than its SHGC, much like tinted glass does. Reflective glass is often favored by architects because of its glare control and attractive exterior appearance. The sun mirror effect, which could disrupt surrounding structures and traffic lanes, restricts the utilization. The residents of well-lit rooms may also worry about losing their nighttime visual solitude and outdoor views (Adhikari & Bhattarai, 2014).

2.6.1.4 Low Emittance Single Glazing

Float glass can have Low-E coatings put to it to either achieve solar control or thermal insulation. The position of the coating affects the efficiency of single Low-E coated glazing (indoors or outdoors). To reduce long-wave radiative heat losses to the environment, the coating should be installed indoors. In that situation, heat from indoor sources is reflected in the space. For instance, the heat would have been absorbed by the glass if the Low-E coating had been facing the exterior, raising its temperature and causing further convective heat losses. In current architecture throughout the world, Low-E coated glass is very common, usually in conjunction with double glazing (Leftheriotis & Yianoulis, 2012).

2.6.2 Multiple Glazed Windows

Multiple panes with air-sealed spaces may be used to improve the glazing's thermal insulation qualities without significantly lowering transmittance and heat uptake. Multiple glazing (double, triple, and quadruple) construction poses new challenges to the designers since the cavity must be airtight and moisture-proof, which calls for the creation of appropriate sealants (referred to as "spacers"). Additionally, the spacers must be strong enough to withstand the heat stress and differential expansion caused by the two (or more) glass sheets. To reduce both the heat transfer through the air gap and peripheral heat losses, such as conduction through spacers, to reduce heat losses through multilayer glazing, they must also be thermally insulating. If they are not, edge losses could outweigh the additional insulation that double glazing provides (Adhikari & Bhattarai, 2014).

2.6.2.1 Double Glazing

A similar single-pane window has a U-value that is 49% higher than double glazing with two clear panes. The reduction in SHGC of 12 percent required to improve the window's thermal performance is more than reasonable. When more solar gain reduction is sought, tinted and reflective glass can offer a reduction in the g-value of between 30 and 60%. Similar to single glazing, the U-value of double-glazed windows with reflective or tinted glass is not greatly changed. On the other hand, Low-E coatings significantly improve thermal insulation by reducing the U-value of clear double glazing by a factor of two. Depending on the type of Low-E coating used, specific qualities can be attained, each of which is ideal for a certain climatic type and use (for example, solar control with suppressed solar gains or thermal insulation with strong solar gains). The general properties of the window are little affected by where the Low-E coating is located on the window assembly (Leftheriotis & Yianoulis, 2012).

2.6.2.2 Triple and quadruple glazing provide the highest level of thermal insulation

The U-values of double glazing is not low enough in heating-dominated areas with exceptionally low temperatures to guarantee acceptable thermal losses of buildings. Triple and quadruple glazing is employed in these settings, with U-values as low as $0.6Wm^{-2}$ K^{-1}. The cost will be a decrease in solar gains and an increase in window size, weight, and price. Kr or Xe are employed as the filler gases in high-tech triple and quadruple glazing to narrow the overall width of the window. These gases make it possible to place glass panes closer together (Adhikari & Bhattarai, 2014).

2.7 Electrochromic glazing

Electrochromic glass (also known as smart glass or dynamic glass) is a tintable glass that can be electronically tinted and is commonly used in windows, skylights, facades, and curtain walls. Because it increases occupant comfort, maximizes access to sunshine and outdoor views, lowers energy costs, and provides architects with more creative freedom, electrochromic glass is popular (Sage Glass, 2018).

Switchable EC technology has been on the market since early 2006. The inner surface of the outer glass should receive the electrochromic coating since it is very absorbent, as a low-E coating shields the occupants from inward longwave radiative heat flux. The oxidation state of tungsten oxide changes as the voltage in an EC coating is changed. As a result, the glazing's optical qualities can be controlled (Kheybari, Steiner, Liu, & Sabine, 2021).

There are a variety of products available with varied tinting levels, ranging from clear (maximum transmissivity, also known as bleached) to colored (lowest transmissivity). These transmittance states are distinct, and the tinting level switches with the control signal. The EC systems are more efficient for controlling since they have a wider range of transmissivity and multiple stable intermediate states. Automated EC glazing permits visible light to enter space while obstructing solar radiation when overheating protection is required. EC glazing can reduce the need for heating and cooling while also protecting consumers from glare (Kheybari, Steiner, Liu, & Sabine, 2021).

2.7.1 Electrochromic Devices: The Mechanism of Coloration and Operation

The five layers of a typical EC device are made up of;

- a transparent electrical conductive film (TC), typically TFO (SnO2:F) or ITO (In2O3:Sn), placed on the glass;
- EC film, typically WO_3;
- a solid, liquid, or gel electrolyte (EL) that conducts ions;
- a layer of IS; and
- another translucent conductive film (TC).

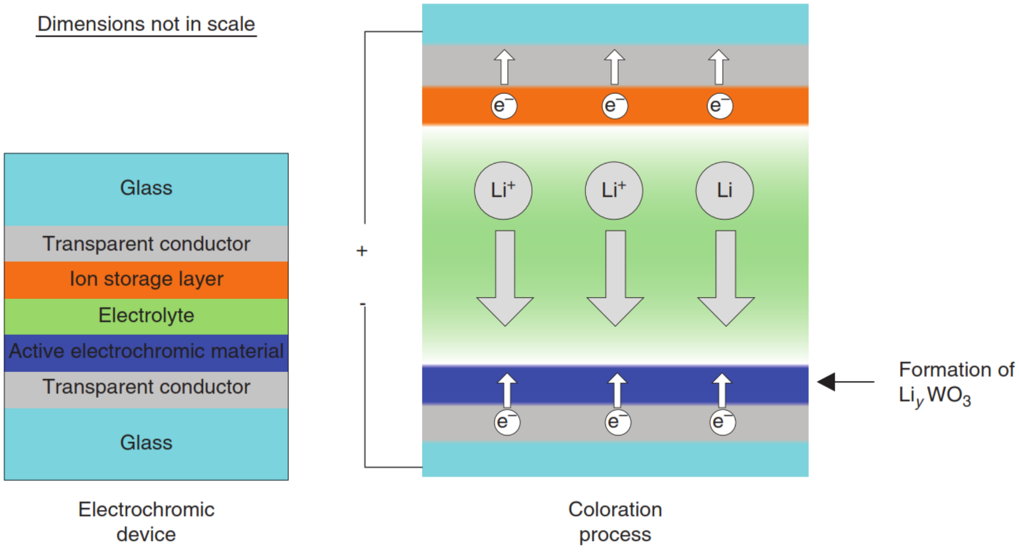


Figure 2-8: Structure and operation of a typical electrochromic device.
Source: : *(Leftheriotis & Yianoulis, 2012)*

As a result, the five-layer structure is composed of glass, TC, EC, EL, IS, and TC. Such an EC cell works by forcing the Li+ ions (or protons, depending on the type of electrolyte) from the electrolyte into the active EC layer using a voltage provided across the two electrodes. Additionally, for charge equilibration, electrons are introduced into the layer from the external circuit, changing its electrical density and coloring the substance. The material gets bleached as a result of the voltage polarity being reversed, which causes ions and electrons to flow oppositely from how they did previously. This phenomenon is best understood as a redox reaction, and the equation that applies in the instance of Li-ion intercalation into tungsten oxide (WO3) is as follows: (Leftheriotis & Yianoulis, 2012)

$$x\mathrm{Li}^{+} + xe^{-} + \mathrm{WO}_3 \leftrightarrow \mathrm{Li}_x\mathrm{WO}_3$$

In response to a low voltage signal, electrochromic windows (ECW) control the transmission of visible light and switch between tinted and transparent/semi-transparent states. Compared to other chromogenic devices, ECW creates a comfortable interior atmosphere and uses less energy since it controls transmitted light when the control voltage is not present while modulating reflected light when it is. Some benefits of electrochromic technologies include the ones listed below: Only when changing modes does electricity need to be used (Shchegolkov, et al., 2021);

- Only when changing modes does electrical energy need to be used;
- low activation voltage (between 1 and 5 V);
- a range of "Smart Window" tints, including blue, grey, and brown;
- Electrochromic devices have a transparency level of between 10 and 25 percent when colored and between 50 and 70% when bleached.

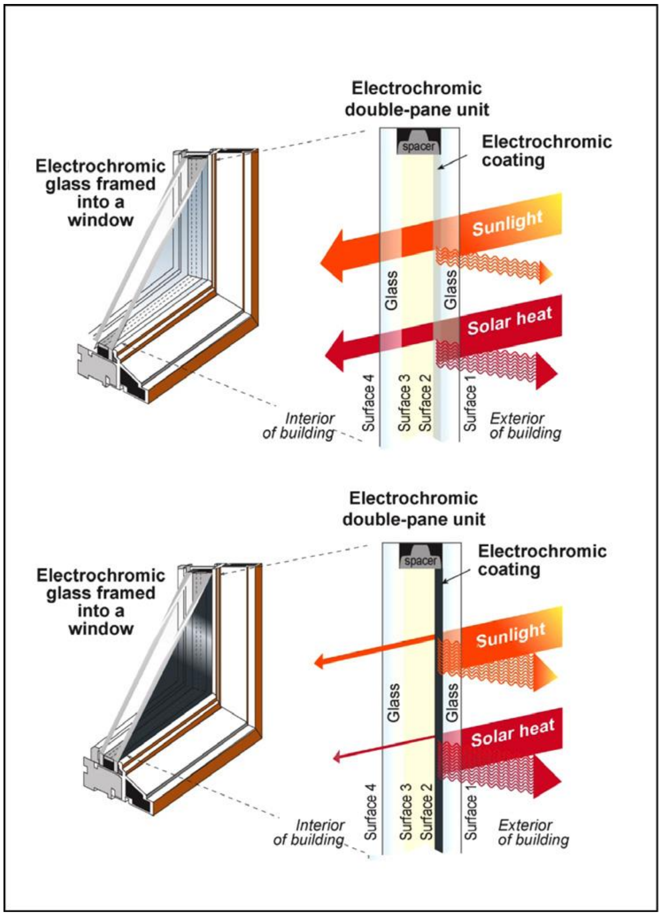
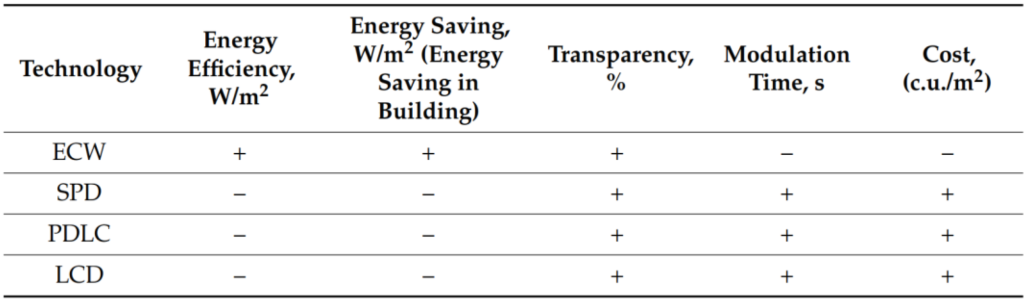


Figure 2-9: EC technology in clear and tinted states.
Source: (Sbar, Podbelski, Yang, & Pease, 2012)

The primary benefits and drawbacks of chromogenic materials used in "Smart Windows" are displayed in Table 1.

Table 1: Comparison of “Smart Window” technologies.

Source: (Shchegolkov, et al., 2021)



Technology	Energy Efficiency, W/m^2	Energy Saving, W/m^2 (Energy Saving in Building)	Transparency, %	Modulation Time, s	Cost, (c.u./m^2)
ECW	+	+	+	–	–
SPD	–	–	+	+	+
PDLC	–	–	+	+	+
LCD	–	–	+	+	+

2.7.2 Electrochromic devices

Electrochromic materials are property-changing smart materials that can change their color autonomously and reversibly in response to an external electrical stimulation through oxidation or reduction reactions. The glazing built of these chromogenic materials can change their optical properties of transparency and solar radiation absorption to suit users' needs by concurrently reducing Visible Light and NIR transmission through the window (Casini, 2017).

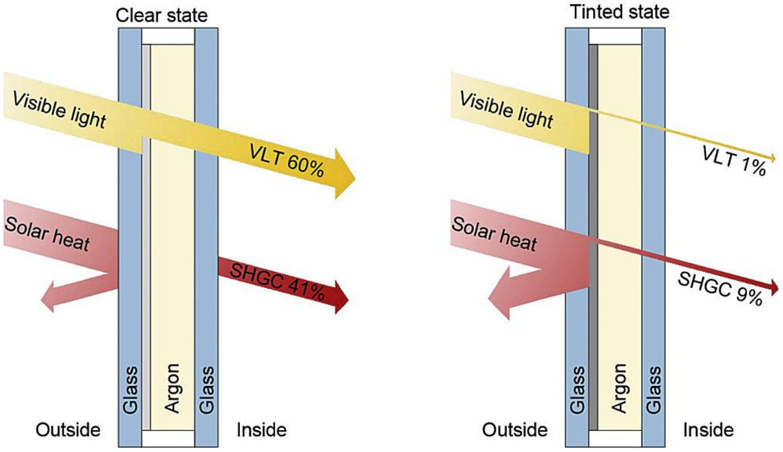


Figure 2-10: Electrochromic glazing control states.
Source: (Casini, 2017).

The market offers a wide range of glass pane sizes and shapes with independent modulation of up to three control zones on a single glass pane (Sageglass Lightzone). They may be controlled by smartphones and tablets over WiFi and are simpler to install, especially when replacing old windows. By using solar battery systems attached to the window edge (Sageglass Unplugged), they can be self-powered without the need for power wires. Electrochromic glazing on the market is frequently blue because WO3 is frequently used as an electrochromic material with modulation of transparency from clear (device off) to dark (device on) in intermediate control states (usually four). With light transmission levels (VLT) ranging from 69% to%, a typical solar heat gain coefficient (SHGC) varies from 0.49 in a transparent condition to 0.09 in a fully tinted state (Casini, 2017).

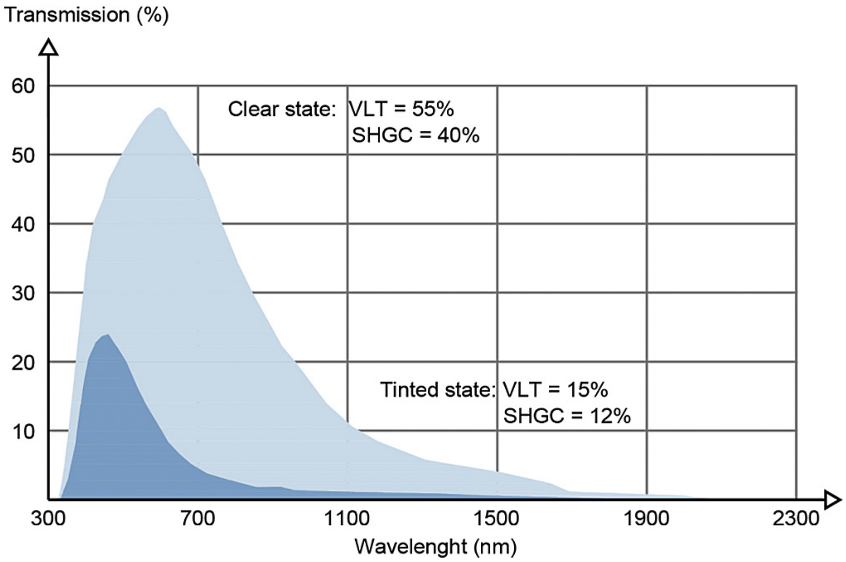


Figure 2-11: Electrochromic glass's spectral transmission in different tint states (EControlGlas).
Source: (Casini, 2017).

Because of the bistable configuration property of electrochromic materials moving between the various control states uses very little electricity (2.5 Wp/m^2), and maintaining a desired colored state requires even less (less than 0.4 W/m^2). The rate of color change is relatively modest; a 10 x 30 cm glass changes color in around 5 minutes, while a 1.2 x 0.8 m glass panel darkens and bleaches in about 12 and 8 minutes, respectively. Transition times differ depending on panel size and the speed of the bleaching cycle (which is usually faster), and they grow longer as the temperature of the glass decreases. However, it makes it challenging for EC glazing to handle abrupt variations in luminance, like clouds obscuring and illuminating the sun for a split second at a time. To achieve perfect comfort in these circumstances, physical shades with a rapid response time may also be required. Users can adjust to changes in daylighting gradually thanks to the modest switching speed, which is not a drawback. (Casini, 2017).

2.7.3 Smart glass benefits and features

To provide sun control and shield passengers from heat and glare, SageGlass has completed numerous installations in each of these locations. The electrochromic glass keeps windows and doors open to the outside, which has been linked to better learning and patient rehabilitation, greater emotional wellness, increased productivity, and fewer staff absences. There are many different ways to control electrochromic glass. The improved patented algorithms of SageGlass let users modify automated control settings to control light, glare, energy use, and color rendering. The controls can also be connected to a building automation system that already exists. SageGlass may be manually overridden via a wall panel for users who want more control, allowing them to change the hue of the glass. The SageGlass smartphone app also allows users to adjust the tint level (Sage Glass, 2018).

SageGlass also assists building owners in achieving their environmental goals by conserving energy. By maximizing solar energy and decreasing heat and glare, SageGlass enables building owners to save money throughout the building by reducing overall energy demands by an average of 20% and peak energy demand by up to 26%. Building owners and occupants gain, but architects are also given the flexibility to design without the usage of blinds and other shading devices that clog the face of the building (Sage Glass, 2018).

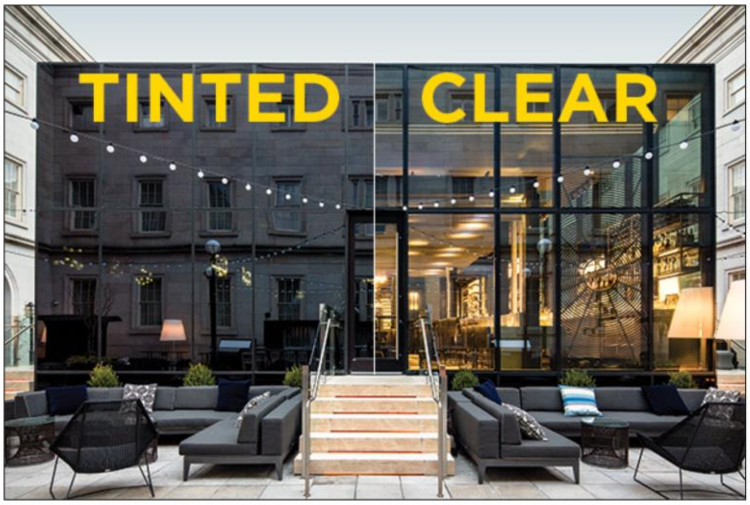


Figure 2-12: Application of sage glass in Dirty Habit restaurant- Washington DC
Source: (Sage Glass, 2018)

2.8 Daylighting

Daylight is dynamic, site-specific, and orientation-specific. Variability, psychology, vision, and vitality are all advantages of daylight. Natural light also has drawbacks, such as unpredictability, glare, and overheating. Physical elements play a role in some of these situations involving natural light. Temporal and seasonal fluctuations, as well as sunshine, color, temperature, and lux distribution, are all physical elements. The design of the building's exterior is influenced by both physical and occupant-related elements influenced by light (Luijten, 2021). The occupant's indoor environment could benefit from human and physical elements, and the building's energy performance could improve. The most important physical requirement for office-related activity is the presence of enough, ambient light in the area (Raymond,1997). The facility must provide the occupants with an attractive workspace where they can do their tasks. Visual comfort is influenced by the amount of daylight available, the direction the light is coming from, the contrast of the environment, and the reflectiveness of surfaces (Luijten, 2021).

The entire amount of visible radiation coming from the sun and the sky is what is known as daylight (Mardaljevic, 2013). Daylight is the term used to describe the natural light that an architectural space's occupants experience. Since we're discussing natural light, the entire experience varies according to the position of the sun throughout the day, the state of the sky and the cloud cover, as well as seasonal changes that have an impact on day and night in terms of their natural qualities. However, the illumination of a building is influenced by the man-made structure and its direction, as well as the adjacent buildings, the size of its apertures, and the optical qualities (reflective and transmissive) of the materials employed in the construction (Mardaljevic, 2013).

2.8.1 Daylight Terminologies

The following daylighting terminology theories are drawn from the paper (Aloupi, 2016).

Daylight | Part of global solar radiation capable of causing a visual sensation. (IEC, 1987) (ILV 845-09-84)

Daylight factor or daylight coefficient (D) | ratio of the light received from an unobstructed hemisphere of this sky on a horizontal plane to the light received directly and indirectly from a sky with an assumed or known illuminance distribution at a given location on a given plane (IEC,

1987) (ILV 845-09-97). The daylight factor, or capacity to admit natural light, can be thought of as a building's ability to do so.

Daylight zone | the size of this is specified as follows:

Depth = height of the lintel above the door - the height of reference plan * 2.5

Width = 1/4 * depth

Illuminance (E) | the amount of light incident per unit area, or the luminous flux density at a given point on a surface (Pritchard, D.C., 1995) Expressed in lux = lm/m2

Light | The range of electromagnetic solar radiation that can be perceived by the human eye.

Luminance (L) | The brightness of the light being reflected and emitted or transmitted from a surface per unit area in a given direction. Expressed in cd/m. (Lechner, 1991). L = ρ x E, where ρ = reflectance and E = Illuminance (Helms, R. N., & Belcher, M. C., 1991).

The luminance ratio | Is the ratio between the luminances of two surfaces (Michel, L., 1995). Typically, a maximum ratio of 40 to 1 should not be obtained (Helms, R. N., & Belcher, M. C., 1991).

Luminous flux (Φ) | the light that a source emits or that a surface receives. The amount is calculated from radiant flux (power in watts) by comparing the radiation to the "normal" eye's relative luminous efficiency [lumen] (Pritchard, 1995)

Lux (lx) | One lumen per square meter is the SI unit for brightness, 1lx = 1lm/m. (Pritchard, D.C., 1995)

Solar radiation | The sun's direct radiation in addition to the diffuse, indirect radiation that is reflected off of the surrounding environment and the sky [kWh/m2] (Herzog et all, 2004).

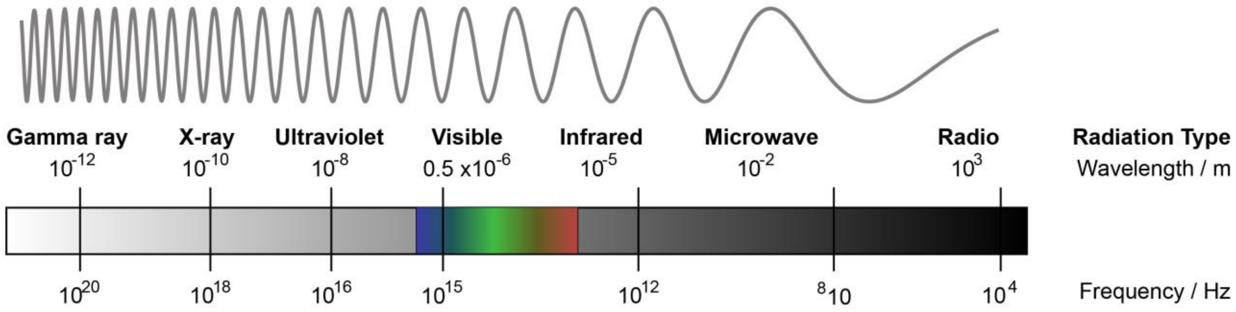


Figure 2-13: Spectrum Properties
Source: (Stavrou, 2016)

2.8.2 Visual Adaptation

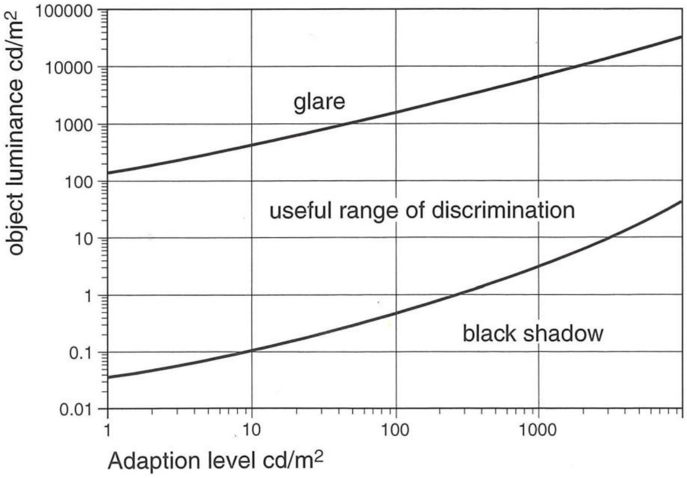


Figure 2-14: Luminance values thresholds.
Source: (Baker, N. V., & Steemers, K., 2002).

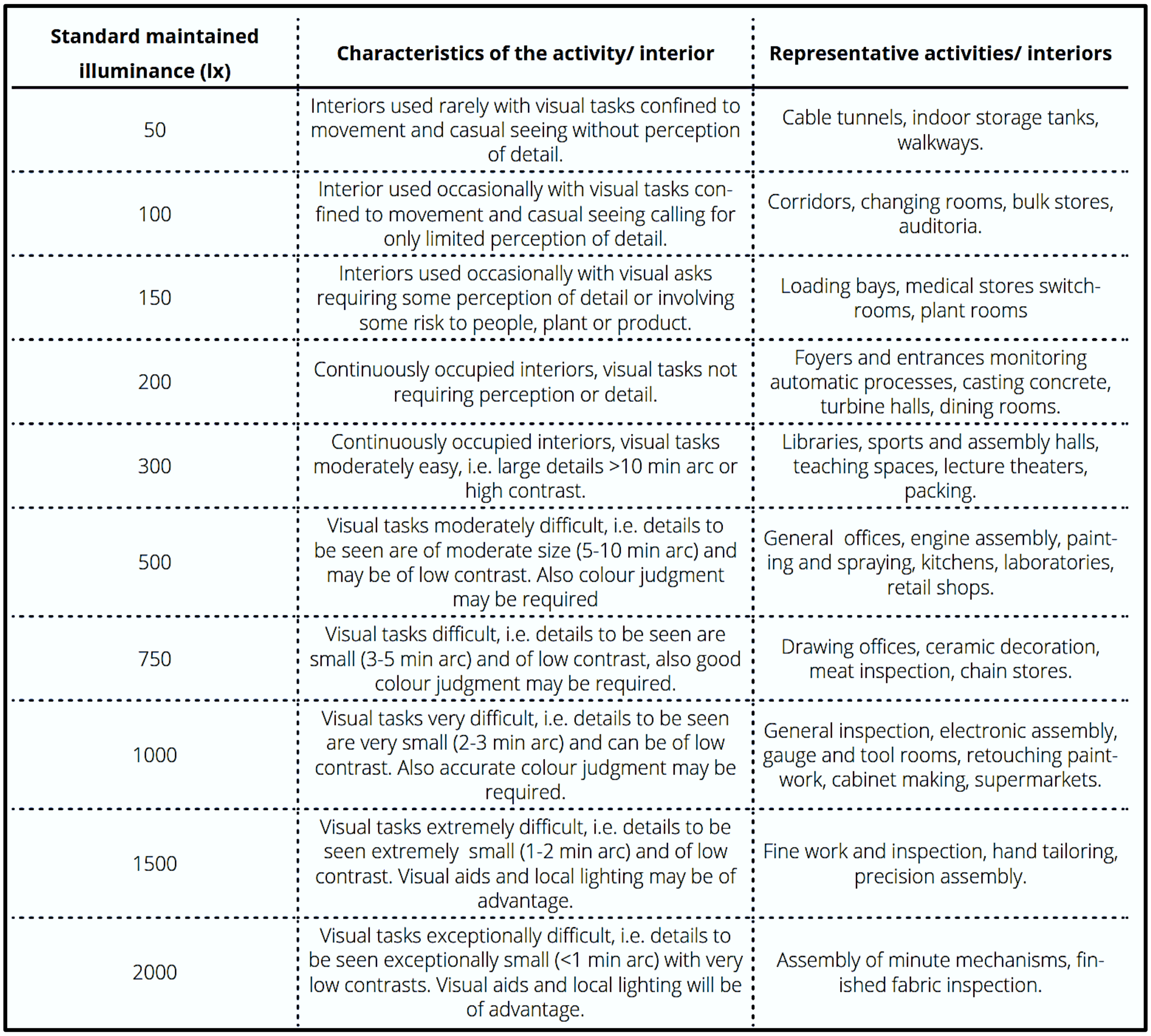
The eye always reacts to lighting conditions and adapts to them to perform better. The first mechanism reacting is the pupil's diameter which is adapted by the iris to control the amount of light entering the eye. Secondly, the retina ganglion cells adapt their response levels to the average illumination of the retina. The last one is the primary adaptation mechanism, and it establishes two thresholds: an upper limit for brightness values at which glare feeling will occur, and a lower border for the lowest luminance values at which it is possible to see a sight.

2.9 Visual Comfort

Visual comfort is defined as a state in which the occupant feels comfortable and has no desire to modify the illumination. In addition, the visual perception of the occupants should be optimal. According to this definition, visual comfort is subjective and is influenced by one's personality, culture, and customs in their bioregion (Guzowski, M., 2000). The physiology of the human eye, and more precisely the physical characteristics describing the amount of light and its dispersion in space, are said to have an impact on visual comfort (Carlucci et al., 2015).

As a result, objective lighting values can be used to assess visual comfort. When a person can distinguish the foreground from the background and all of the items in the space, he has sufficient vision. The illuminance level, which has certain needs, as shown in Table 1, fluctuating depending on the use of the space and the actions taking place in it, is the most important factor impacting his visual perception (Aloupi, 2016).

Table 2: Lighting specifications (BS EN 12464-1:2002) Illumination of workplaces- Part 1: Indoor workplaces, Light and Lighting



Standard maintained illuminance (lx)	Characteristics of the activity/ interior	Representative activities/ interiors
50	Interiors used rarely with visual tasks confined to movement and casual seeing without perception of detail.	Cable tunnels, indoor storage tanks, walkways.
100	Interior used occasionally with visual tasks confined to movement and casual seeing calling for only limited perception of detail.	Corridors, changing rooms, bulk stores, auditoria.
150	Interiors used occasionally with visual asks requiring some perception of detail or involving some risk to people, plant or product.	Loading bays, medical stores switch-rooms, plant rooms
200	Continuously occupied interiors, visual tasks not requiring perception or detail.	Foyers and entrances monitoring automatic processes, casting concrete, turbine halls, dining rooms.
300	Continuously occupied interiors, visual tasks moderately easy, i.e. large details >10 min arc or high contrast.	Libraries, sports and assembly halls, teaching spaces, lecture theaters, packing.
500	Visual tasks moderately difficult, i.e. details to be seen are of moderate size (5-10 min arc) and may be of low contrast. Also colour judgment may be required	General offices, engine assembly, painting and spraying, kitchens, laboratories, retail shops.
750	Visual tasks difficult, i.e. details to be seen are small (3-5 min arc) and of low contrast, also good colour judgment may be required.	Drawing offices, ceramic decoration, meat inspection, chain stores.
1000	Visual tasks very difficult, i.e. details to be seen are very small (2-3 min arc) and can be of low contrast. Also accurate colour judgment may be required.	General inspection, electronic assembly, gauge and tool rooms, retouching paintwork, cabinet making, supermarkets.
1500	Visual tasks extremely difficult, i.e. details to be seen extremely small (1-2 min arc) and of low contrast. Visual aids and local lighting may be of advantage.	Fine work and inspection, hand tailoring, precision assembly.
2000	Visual tasks exceptionally difficult, i.e. details to be seen exceptionally small (<1 min arc) with very low contrasts. Visual aids and local lighting will be of advantage.	Assembly of minute mechanisms, finished fabric inspection.

2.9.1 Daylight in office buildings

Offices are places where people must concentrate and be productive. As a result, a nice and relaxing environment is essential. Many factors influence a person's experience in a room, one of which is lighting. When it comes to indoor lighting control, two essential challenges are visual comfort and human acceptance of highly luminous indoor environments. Daylight is extremely helpful to the human body and mind, and most individuals prefer natural light over artificial light. As a result, the goal of lighting management in office buildings is to obtain adequate lighting, primarily from daylight, but also control it in a way that the user is content. The key aspects characterizing the lighting experience are glare, window luminances, and luminance ratios (Aloupi, 2016).

In terms of the modern office building structure, many of them have a fully glazed envelope or enormous glazed portions that cover the whole façade area. As a result, incident solar light has a significant impact on the visual comfort of indoor spaces.

As previously stated (Table 1), 300-500 lux are sufficient to give acceptable illuminance to a workspace, with 500 lux being required under more stringent norms such as the NS-EN 12464-1, 2011. Glare and the dispersion of incoming light, on the other hand, are equally essential elements in determining the users' visual comfort.

Now, focusing on the luminance ratio, which assesses light dispersion, most standards require a number more than 0.8 to claim uniformity and pleasant lighting conditions. This value, however, pertains to artificial light. When it comes to natural light, people show tolerance by tolerating lower values, which means larger variations, with a maximum of 0.1 or even 0.3 depending on the visual field (Aloupi, 2016).

Reihart CF. et al. created the "daylight autonomy" (Cm) index in 2006, which measures the percentage of time when the work plane's minimum illuminance needs are met. To put it another way, it's the duration of time that particular light levels may be achieved only by the usage of daylight. The illuminance needs to influence this index, which produces results that are comparable to the occupancy schedule (Aloupi, 2016).

The "useful daylight index" is another metric that measures how long it takes to achieve the desired illuminance levels (UDI). The time when the daylight level is neither too low nor too high, that is, when it is between the two extremes of 300 and 2000 lux, as defined by the UDI. Then, to determine daylight autonomy, the useable daylight index and the sun patch index are added. (Aloupi, 2016).

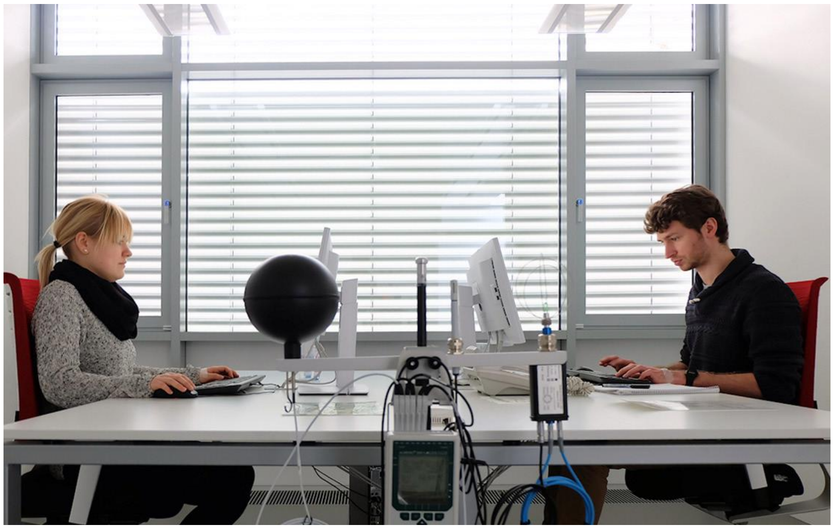


Figure 2-15: Indoor view of an office room with automatic solar shading devices and sensors.
Source: (Aloupi, 2016)

In addition, an index regarding glare was introduced. The term "Sun patch index on work plane" (SP) refers to the type of glare that results from a big source of light, such as windows, and is based on the presence of a solar illuminance beam and its reflection. With this index, you can also enjoy the glare you encounter when gazing out the window and at the outside scene. The ratio of the working area's surface where the amount of illumination is greater than 8000 lux is known as SP. The shading device can be described as being more efficient the lower this value is (David et al., 2011).

A solar illuminance beam is present in the working area and is reflected by a major source of daylight, such as windows, to form the "Sun patch index on the work plane" (SP), a glare index. With this index, you can evaluate the glare you get when gazing out the window and the view outside. SP is the ratio of the working area's surface to the illuminance level over 8000 lux. The lower this number is, the more efficient the shading device is (David et al., 2011).

2.10 Glare

"Glare is a vision condition in which an inadequate distribution or range of brightness, or high contrasts, produces discomfort or a reduction in a vision of objects or details" (LG7 CIBSE/SLL, 2005). We typically refer to glare difficulties when talking about visual comfort issues because both direct and indirect glare can hamper vision."Direct glare is generated by a bright light source in the field of view that causes annoyance, discomfort, or a reduction in visual performance." When it causes physical discomfort, it's termed discomfort glare, and when it decreases visual performance and visibility, it's called disability glare." (Meek et al, 2014). Indirect glare, which can be bothersome, is produced when glossy surfaces reflect excessively intense light sources. It is easily avoidable by employing rougher materials or diffuser lights (Stavrou, 2016).

2.10.1 Glare parameters and prediction

The physical elements that affect how uncomfortable you feel are widely known. The luminance of the glare source that is directed at the spectator is the most crucial element. The primary elements of existing complex glare formulas include the luminance of the glare source, the background luminance, the magnitude of the glare, and the position of the source concerning the viewing direction (Ganslandt, 1992).

2.10.1.1 Illuminance

The density of light flux is measured by illuminance. The Erco manual of lighting design states that "Illuminance can be inferred from the luminous intensity of the light source." Illuminance "declines with the square of the distance from the light source," according to the inverse square law (Ganslandt, 1992).

2.10.1.2 Luminance

Illuminance describes the amount of light flux falling on a particular surface, whereas luminance describes the brightness of an illuminated or luminous surface. The relationship between a surface's projected area (m2) and luminous intensity (cd) is known as the "luminance definition." Ganslandt, 1992.

2.10.1.3 Daylight Glare Index

In 1972, Hopkinson developed the Daylight Glare Index (DGI) (Hopkinson, 1972). Big glare sources, like a window view of the sky, were initially taken into account by the DGI. The results of the user polling and testing were made public. Direct sunlight and reflections are frequently overlooked, although they can be taken into account.

$$DGI = 10\log_{10} 0.48 \sum_{i=1}^{n} \frac{L_s^{1.6} \cdot \Omega_s^{0.8}}{L_b + 0.07\, \omega_s^{0.5} L_s}$$

L_s: Luminance of source [cd/m^2]

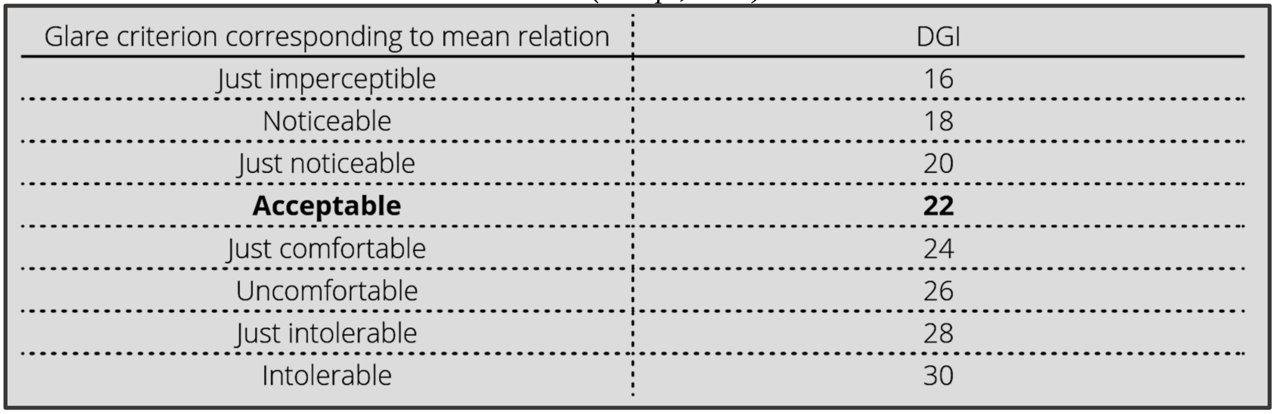
ω_s: Solid angle of source [sr]

L_b: Background luminance [cd/m^2]

Ωs: [ω_s/P] Solid angle subtended of the source

Table 3: Daylight glare index.

Source: (Aloupi, 2016)



Glare criterion corresponding to mean relation	DGI
Just imperceptible	16
Noticeable	18
Just noticeable	20
Acceptable	**22**
Just comfortable	24
Uncomfortable	26
Just intolerable	28
Intolerable	30

However, unlike artificial light, the association between glare from windows and expected glare is not as high.

2.10.1.4 Daylight Glare Probability

The Daylight glare probability, developed by Jan Wienold and Jens Christoffersen, is a new approach to daylighting (DGP). The "percentage of people distressed" is used in this index. Based on human reactions to illumination in an indoor area, as a result of impairment and glare discomfort. The final DGP equation was defined as follows, taking into consideration the vertical illuminance at the position of the individual's eye:

$$DGP = c_1 \cdot E_v + c_2 \cdot \log(1+\sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{L_v^{a_1} \cdot P_i^2}) + c_3$$

Ev: vertical Eye illuminance [lux]

ω_s: Solid angle of source [sr]

L_s: Luminance of source [cd/m^2]

P: Position index [-]

$c_1 = 5.87\ 10^{-5}$

$c_2 = 9.18\ 10^{-2}$

$c_3 = 0.16$

$a_1 = 1.87$

The light source's luminance is represented in the equation by Ls, its vertical illuminance by Ev, its solid angle by is, and its location index by Pi (Wienold, 2006). By employing the daylight coeffect method to determine the vertical eye illuminance, Wienold developed a more straightforward technique (Wienold, 2006).

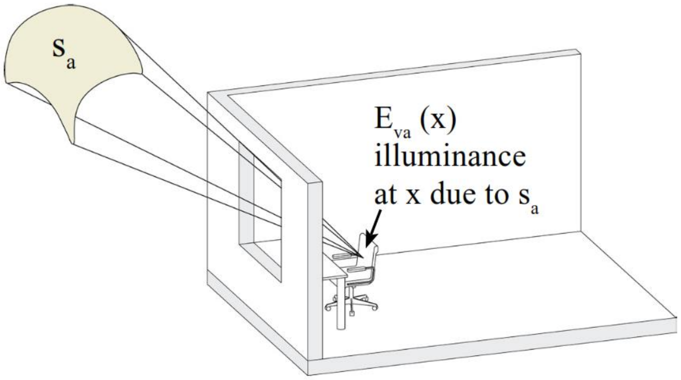
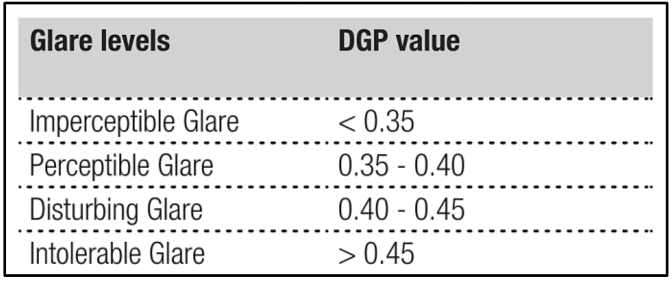


Figure 2-16: Illustration expressing the simplified DGP method
Source: (Wienold, 2006)

Table 4: DGP levels

Source: (Stavrou, 2016)



Glare levels	DGP value
Imperceptible Glare	< 0.35
Perceptible Glare	0.35 - 0.40
Disturbing Glare	0.40 - 0.45
Intolerable Glare	> 0.45

Daylight Autonomy (DA) Analysis: Daylit Area (DA-500lux[50%]) should be >50% of the space.

Continuous Daylight Autonomy (cDA) Analysis: the percentage of sensors with a DA_MAX > 5% should be >50%.

Useful Daylight Illuminance (UDI): For active occupant behavior, the proportion of the space with a UDI100-2000lux more than 50% should be >60%.

Daylight Glare Probability (DGP): <0.35

2.11 Simulation Tools

In architecture, complex/dynamic systems and technologies are becoming more popular, yet effective analysis and simulation of opposing dynamic systems inside a building model have yet to be achieved. The majority of simulation and analysis concepts revolve around a predetermined process: model one instance of a building (without changing parameters) and assess it in a separate application. In addition to increasing the accuracy of testing the effects of numerous dynamic systems, using a parametric base for analysis/simulation plugins would also serve as a platform for testing systems' compensatory or introduced factors (bio-responsiveness, enviro-responsiveness, manipulability, system responsiveness).

2.11.1 Energy Plus

Engineers, architects, and academics simulate the energy and water use of entire buildings using the application EnergyPlus. By simulating a building's performance with EnergyPlus, construction experts can improve the building design to use less energy and water. In addition to imitating lighting, ventilation, heating, and cooling, EnergyPlus simulates the use of water. Time steps of under an hour, modular systems and plants combined with heat balance-based zone simulation, multizone air flow, thermal comfort, water utilization, natural ventilation, and solar systems are just a few of the cutting-edge modeling elements that EnergyPlus offers (Rogler, 2014).

2.11.1 Open Studio

Using EnergyPlus for entire building energy modeling and Radiance for sophisticated daylight analysis, OpenStudio is a cross-platform suite of software applications.

2.11.2 Grasshopper plugins

Ladybug

Engineers and architects can use Ladybug, an open-source environmental plugin for Grasshopper3D, to generate environmentally responsible architecture designs. Ladybug integrates typical EnergyPlus Weather files (.epw) into Grasshopper and provides a variety of 3D interactive visualizations to assist with decision-making throughout the early stages of design.

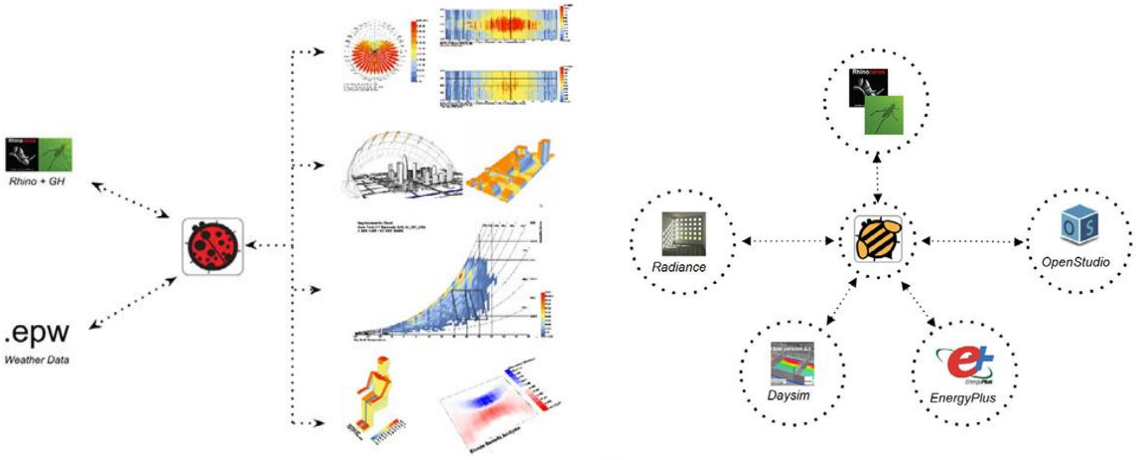


Figure 2-17: Working mechanisms of Rhino & Grasshopper plugins
Source: (Rogler, 2014)

Honeybee

To simulate building energy and daylighting, Honeybee connects Grasshopper3D to EnergyPlus, Radiance, Daysim, and OpenStudio. Many of these simulation tools' functionalities will be available parametrically thanks to the Honeybee project.

2.12 Existing policies regarding energy efficiency in Nepal

Nearly 25% of Nepal's population still lacks access to modern energy sources, there is a significant gap between energy demand and supply, the supply is vulnerable, and the country's foreign exchange reserves are declining as a result of its dependency on energy imports. (Government of Nepal, 2018).

Since 1985, Nepal has conducted energy efficiency research and analyses, with activities such as energy audits, energy efficiency-related training, and increased public awareness occurring between 1999 and 2005 AD. The Nepal Electricity Authority launched measures such as demand-side management of electricity, efficiency audits, load profiling studies, and the replacement of traditional lights with energy-efficient bulbs from 2009 to 2011 (Government of Nepal, 2018).

There is currently a lack of knowledge and public understanding regarding the benefits of energy efficiency in guaranteeing Nepal's supply of sustainable, adequate, and reliable electricity. Energy efficiency as a secondary source of energy, as well as the elimination of potential barriers to its promotion, has yet to be established in regulatory, legal, and institutional frameworks. Neither energy efficiency nor the wider energy system has been fully integrated.

Energy efficiency could not be recognized as a crucial element of the entire energy system due to a lack of understanding, not only among regular users but also among policymakers and at the implementation level. Energy efficiency has been neglected in Nepal due to a lack of an institutional framework with the necessary tools, accountability, and clear jurisdiction to address the problem. Nepal has encountered several difficulties in implementing and institutionalizing energy efficiency initiatives.

The component "Policy" seeks to improve the political environment through the implementation of energy efficiency and conservation measures. The Alternative Energy Promotion Centre is the first government agency in Nepal devoted to energy efficiency (AEPC). Communication between national organizations and parties engaged in energy efficiency in Nepal is made easier by the AEPC. The Nepalese government is creating an energy efficiency and conservation bill as well as a National Energy Efficiency Action Plan as the next stage in institutionalizing energy efficiency in the country (NEEAP) (NEEP, n.d.).

Since 2010, Nepal's energy efficiency has been encouraged by the Nepal Energy Efficiency Program (NEEP). The Ministry of Energy, Water Resources and Irrigation (MoEWRI) of the Government of Nepal is executing NEEP on behalf of the German Federal Ministry for Economic Cooperation and Development with technical support from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (BMZ). The program promotes the development and use of energy efficiency services for both the public and private sectors, as well as the development and use of improved biomass-based cooking stoves for rural families. It also gives direct assistance to the government on policy and institutional frameworks for promoting energy efficiency in the country. It also helps strengthen the Nepal Electricity Authority's (NEA) capacity to manage power supply and demand, as well as the establishment of market development elements for energy efficiency services and products and the start of the process of integrating energy efficiency into university education and vocational training (Awale, 2021).

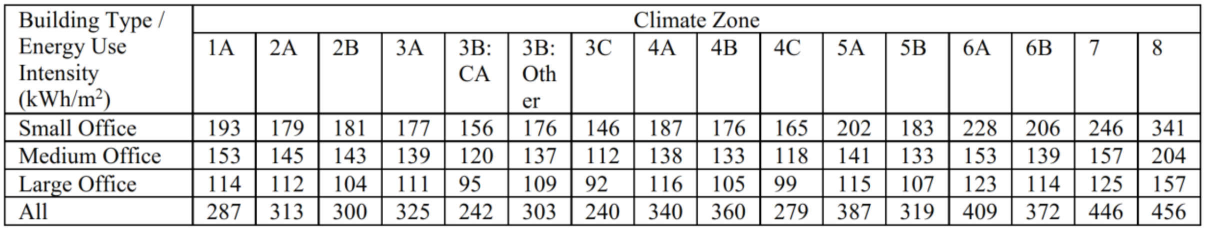
2.13 International Policies

2.13.1 Performance Goals of Energy

The effectiveness of shading and glazing solutions could be assessed and calculated using a variety of performance goals. The ASHRAE handbook and DOE-2 Daylighting were used to determine the solar heat gain and hourly interior illumination. To assess the potential advancements of novel shading methods, benchmarking was crucial. Many standards should be utilized as baselines or calculating standards when multiple factors need to be taken into account. There were data from the National Renewable Energy Laboratory (NREL) Evaluation (Table 5) that assessed data from ASHRAE 90.1 and 189.1 about the energy use of various building types from various climate zones. Additionally, data on commercial buildings in various U.S. areas were gathered by the Commercial Buildings Energy Consumption Survey (CBECS) (Table 6). California's 3B climate zone EUI objective for ASHRAE 90.1 was 95 kWh/m2, while the hot and dry climate zone EUI value for CBECS was 185 kWh/m2 (Lu, 2022).

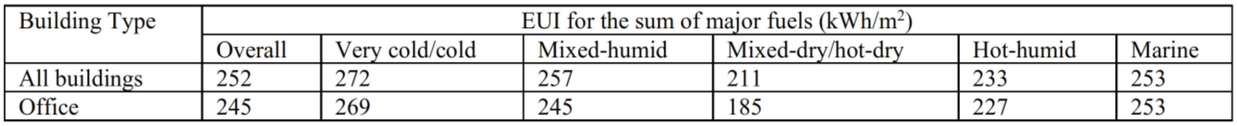
To complete the Architecture 2030 Challenge, a second stage was to use the EUI data as baselines to determine whether the test circumstances might assist the buildings in achieving a EUI that was 80% lower than the baseline value. The Architecture 2030 Challenge was completed by buildings that were either newly constructed or rebuilt with energy use that was 70% lower than the regional average for the same building type. 2020 had an 80% reduction target, while 2025 saw a 90% reduction target (Architecture 2030). The benchmark EUI for commercial buildings was provided by ASHRAE 90.1, the benchmark EUI for high-performance green buildings by 189.1, and the baseline EUI by CBECS. As a result, the experiment's baseline EUI of 185 kWh/m2 was used, while the value after an 80% reduction was 37 kWh/m2. If the test conditions had a EUI of less than 37 kWh/m2, the Architecture 2030 Challenge would be achieved (Lu, 2022).

Table 5: NREL Evaluation of ASHRAE 90.1-2007 (Long 2010)



Building Type / Energy Use Intensity (kWh/m^2)	Climate Zone															
	1A	2A	2B	3A	3B: CA	3B: Other	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Small Office	193	179	181	177	156	176	146	187	176	165	202	183	228	206	246	341
Medium Office	153	145	143	139	120	137	112	138	133	118	141	133	153	139	157	204
Large Office	114	112	104	111	95	109	92	116	105	99	115	107	123	114	125	157
All	287	313	300	325	242	303	240	340	360	279	387	319	409	372	446	456

Table 6: Commercial Buildings Energy Consumption Survey (CBECS 2012)



Building Type	EUI for the sum of major fuels (kWh/m^2)					
	Overall	Very cold/cold	Mixed-humid	Mixed-dry/hot-dry	Hot-humid	Marine
All buildings	252	272	257	211	233	253
Office	245	269	245	185	227	253

2.14 Research Findings on the study done on Electrochromic windows

Various research on this topic has been undertaken all around the world, with some of the following methodological techniques leading to key conclusions in Table 7.

Table 7: Methodological review of research findings on the study of EC windows

Research Topics	**Methodology**	**Key Findings**
1) (Sbar, Podbelski, Yang, & Pease, 2012) Electrochromic dynamic windows for office buildings	1. A commercial office building's EC windows' performance evaluation 2. Analysis of energy variables 3. EC glass control strategies 4. Energy modeling protocol	1. When dynamic glazings are a part of the building envelope, the peak load is dramatically lowered for integrated building control systems. 2. When used in new building and remodeling projects, EC glass can cut peak load carbon emissions by up to 35% and 50%, respectively.
2) (Loddo & Luddoni, 2016) Smart facades; Declination with Electrochromic Glass	1. Testing of full-scale models: size (4x4x2.70 m) done in three steps	1. The best performance in connection to the envelope materials, particularly the façade configuration, may be seen in the utilization of electrochromic technology.
3) (Kheybari, Steiner, Liu, & Sabine, 2021) Controlling Switchable Electrochromic Glazing for Energy Savings, Visual Comfort and Thermal Comfort: A Model Predictive Control	1. Simulation methods 2. The Operation and Control Strategies	1. For a temperate climate (Mannheim, Germany), according to the findings, an MPC for EC glazing can reduce energy use by up to 14%, 37%, 37%, and 34%, respectively, depending on which direction it faces to the base-case.
(Isaia, Fiorentini, Serra, & Capozzoli, 2021) Enhancing energy efficiency and comfort in buildings through model predictive control for dynamic façades with electrochromic glazing	1. Case Studies 2. Control formulation 3. Control oriented model 4. Cost functions 5. Constraints 6. Implementation	1. The suggested hybrid model predictive control technique beat two baseline rule-based controllers, lowering energy use, peak power, and the proportion of uncomfortable hours by as much as 82%, 71%, and 51%, respectively, according to the results.

3 Chapter 3: Research Methodology

3.1 Conceptual Framework

"The set of common views and agreements shared by scientists about how problems should be understood and treated" is what a research paradigm is. Kuhn is a scientist who is well-known (1962). In positivism, the researcher's role is confined to data gathering and objective interpretation, and it is founded on complete understanding, experimentation, and observation. The post-positivist paradigm originated from the positivist paradigm and is concerned with reality's subjectivity, moving away from the logical positivists' objective attitude (Ryan, 2008).

The fundamental purpose of this research is to determine how energy-efficient adaptable facade systems may be. As a result, the research concentrates on the facts that surround it. Building energy efficiency is a reality with numerous realities as well as a single objective reality. The evaluation technique involves a methodical approach to investigation that replaces the logical request's traditional three-stage thinking handling. Characterizing the including entirety (the framework) of which the wonder or issue may be a part, analyzing the including whole's behavior or properties, and depicting the wonders or problem's behavior or properties in terms of its parts or capacities within the enveloping entirety are all part of systems analysis.

The investigation of energy behavior takes on the same importance as the investigation of a single objective fact. As a result, science is moving away from positivism and toward post-positivism. A pragmatic model is formed by the combination of positivism and post-positivism, and this research for energy efficiency evaluation will employ a pragmatic approach. According to Creswell (2003), the pragmatic paradigm comprises merging data gathering techniques and data analysis procedures during the study phase. By adopting the adaptive facade system, we are employing a quantitative technique to quantify thermal comfort in this study.

To grasp energy actions from an ontological perspective, we need a systematic description that can't be estimated using qualitative data. As a result, a quantitative, calculable procedure should be employed. The ontological claim of the study is that the traditional facade system is less effective than the most recent adaptable façade system. Building professionals are unaware of the amount of productivity that can be gained via the use of various adaptive façade systems.

Energy assessment must be quantified to reflect adaptive façade systems, according to the study's epistemological viewpoint. The study of singular dependent realities such as the operating temperature, ground temperature, daily solar radiation, indoor design temperature, and other factors that affect system efficiency, as well as the analysis of the energy consumption pattern of heating/cooling loads by implementing the adaptive system, can provide such knowledge/information.

3.2 Methodology

This study takes a simulation-based approach, in which we try to create simulative models that alter the events under consideration to see how the consequences change as the conditions change. Another important strategy for this study is a simulation, which involves a model processing an approximation of the real world in various forms of computer software.

3.2.1 Methods

3.2.1.1 Literature review

The fundamentals of energy efficiency offer an overview of the state of the art, enabling the discovery of pertinent ideas, approaches, and gaps. Different variables were considered for guideline development like building envelope, commercially available glazings, future adaptive façade technologies, daylighting, electrochromic glazing glare, etc.

3.2.1.2 Research Setting: The Kathmandu Metropolitan City

The Kathmandu Metropolitan City was chosen for the study because it is Nepal's most developed city, with more imaginative and forward-thinking building construction. Throughout recent years, the development of office buildings using curtain wall technology has exploded in the city. Climate data obtained from a primary source, namely the Department of Hydrology and Meteorology, is used in the study. Charts are used to evaluate air temperature, relative humidity, wind speed, and rainfall, among other things.

3.2.1.3 Field Study

To collect both primary data from field surveys and secondary data from market research, a field study was conducted. Market research was conducted on two glass products: SageGlass and AIS Glass (EC). AIS glasses, one of the most popular energy-efficient options for glasses, are available in Nepal. Three offices with different building sizes and types were the subjects of a field survey. At each of the three offices—Prabhu Bank, Kumari Bank Limited, and Kumari Capital—120 questionnaires were collected.

3.2.1.4 Base modeling

To conduct simulations, a medium-sized office structure will be used for case modeling. The case model will be used as the foundation for future optimizations in various contexts. The model will be given construction sets that are identical to the originals. Along with the base case, the previously selected typology of adaptive façade will be modeled as having both static and dynamic features.

3.2.1.5 Modeling and simulation

Various scenarios will be created to compare the adaptive system's energy efficiency to that of a traditional shading system. Rhino and Grasshopper will be used for the modeling and along with plugins like Ladybug, Honeybee, Radiance, etc. Open studio and Energy plus will produce the simulation findings.

3.2.1.6 Data analysis parameters

The literature evaluations show that adaptive facades not only reduce energy consumption but also improve visual comfort. Following the modeling of multiple scenarios, a comparison study will be done to evaluate the systems' energy consumption, thermal comfort, and visual comfort, producing definitive findings, conclusions, and recommendations. Three variables are investigated: (i) Energy use; ii) Daylighting; and iii) Glare

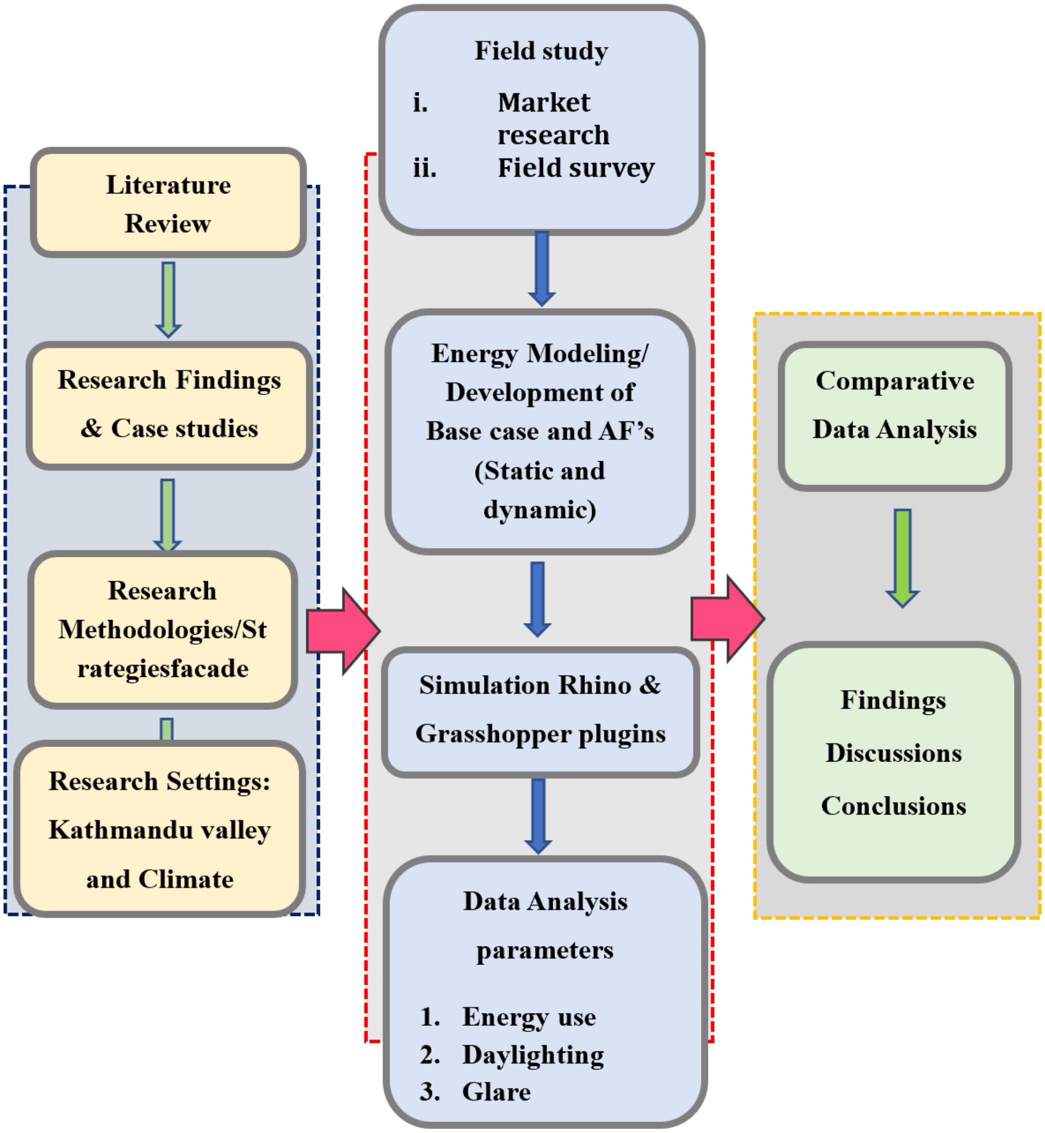


Figure 3-1: Flow chart of the methodology of the study

4 Chapter 4: Research Setting

4.1 Site context and background

The Kathmandu valley is situated in the temperate zone between 27°36' and 27°50’ north latitude and 85°7' to 85°37' longitude, at an altitude of roughly 1337 meters above sea level. Kathmandu Metropolitan City contains 254,292 dwellings and 975,453 residents as of the 2011 Census. The metropolitan region has an area of 50.67 square kilometers and a density of 19,250 inhabitants per square kilometer. The city is virtually in the center of Nepal's Kathmandu Valley, at a height of around 1,400 meters (4,600 feet). Kathmandu represents Nepal's warm temperate climate, which is primarily found in hilly regions, with neither a harsh winter nor oppressive tropical heat and rain. Kathmandu enjoys all four seasons: summer, autumn, winter, and spring (Wikipedia).

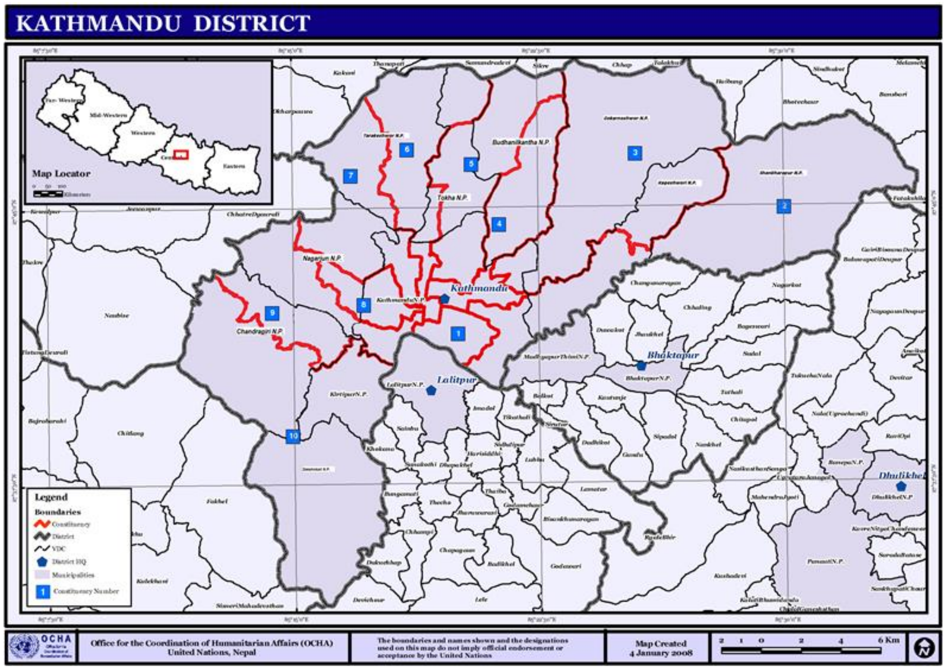


Figure 4-1: District Map of Kathmandu Metropolitan City.
Source: www.gov.np

4.2 Climatic Study of Kathmandu valley

The meteorological data for the Kathmandu valley from 2012 to 2021 A.D. was collected from The Department of Hydrology and Meteorology at Babarmahal, Kathmandu. Then, several key climate parameters in the Kathmandu valley using the collective data were examined. The following types of information were gathered and examined: temperature, relative humidity, rainfall, wind speed, etc.

4.2.1 Temperature data of the Kathmandu valley

From the year 2012-2021; the yearly average maximum temperature is found to be 26.04 °C in July whereas the average minimum temperature is found to be 13.74°C in January.

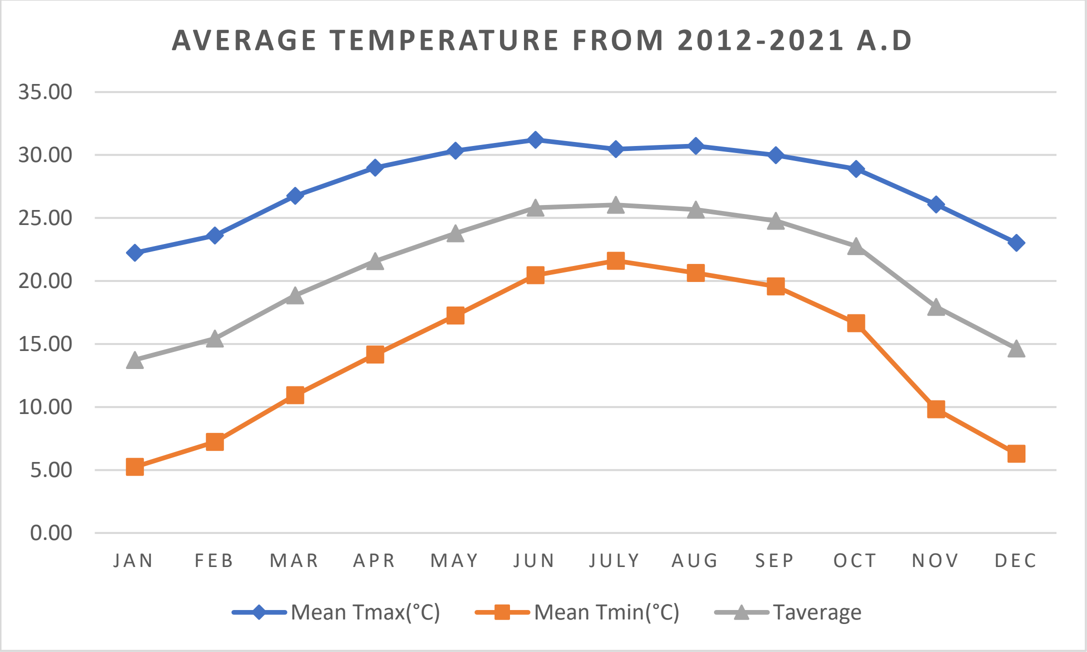


Chart 1: Yearly average maximum and minimum temperature data of the Kathmandu valley from 2012-2021

Source: Department of Hydrology and Meteorology, Kathmandu, Nepal

4.2.2 Solar radiation of Kathmandu valley

Since the solar radiation data could not be obtained from the Department of Hydrology and Meteorology, we obtained it from a secondary source which is mentioned below:

The maximum total solar radiation – is 777.27 W/m^2 (Poudyal, Bhattarai, Sapkota, & Kjeldstad, 2012)

Annual Global Solar radiation – 5.19 Kwh/m^2/day (Poudyal, Bhattarai, Sapkota, & Kjeldstad, 2012)

4.2.3 Relative humidity of Kathmandu valley

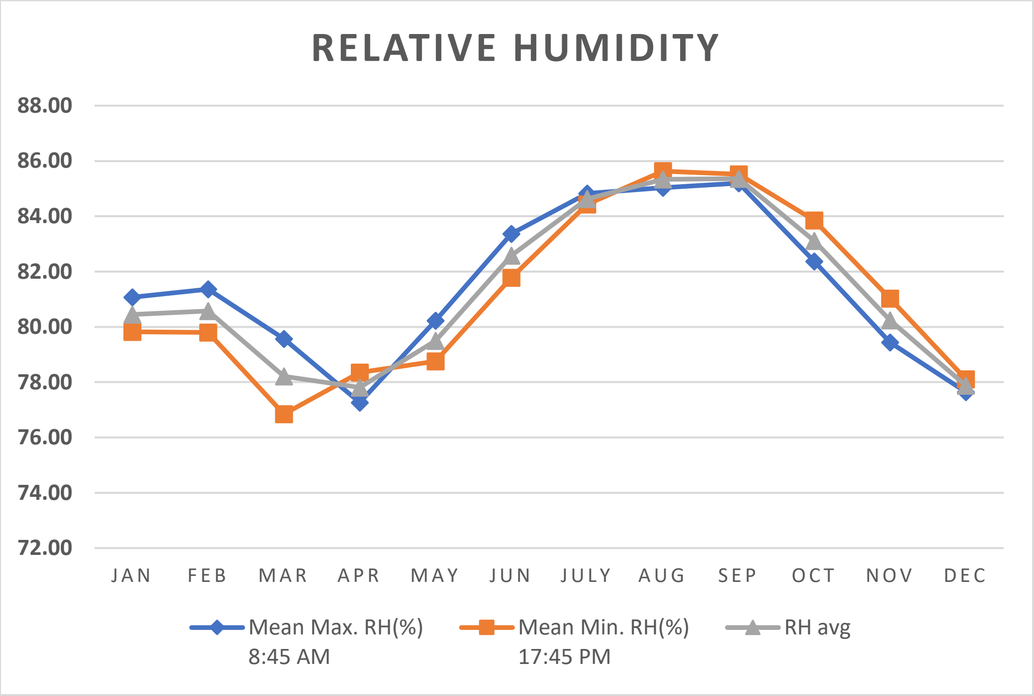


Chart 2: Average maximum and minimum relative humidity data of Kathmandu from 2012-2021

Source: Department of Hydrology and Meteorology, Kathmandu, Nepal

The chart above shows the maximum and minimum relative humidity data of Kathmandu from the year 2012-2021A.D.

Maximum relative humidity- 85.20 % in September.

Minimum relative humidity- 76.85 % in March.

4.2.4 Rainfall data of Kathmandu valley

In the chart below; the month of July has the highest amount of rainfall i.e., 402.27 mm whereas the minimum amount of rainfall is 6.65 mm in December.

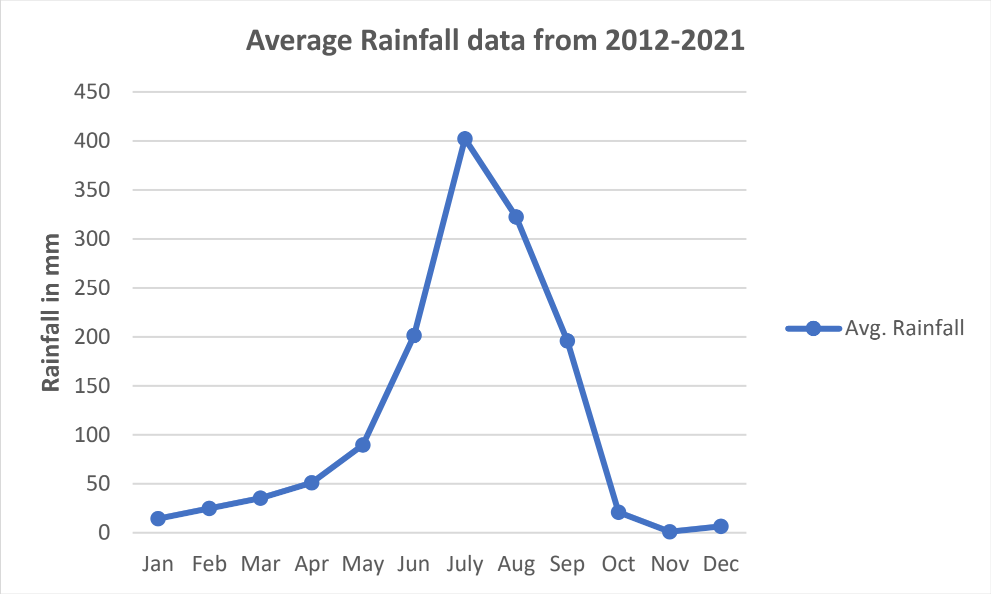
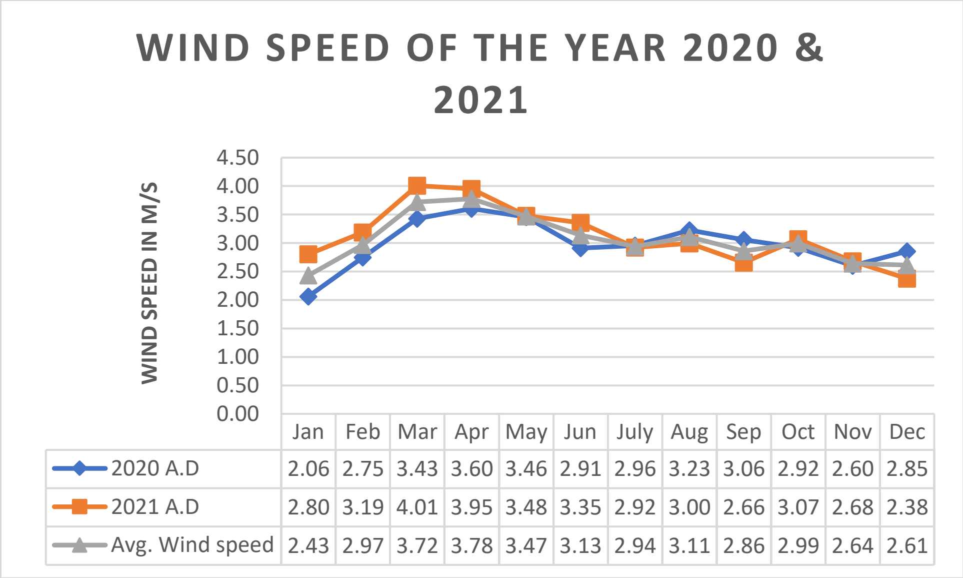


Chart 3: Average rainfall data of Kathmandu from 2012-2021A.D.
(Source: Department of Hydrology and Meteorology, Kathmandu, Nepal)

4.2.5 Wind velocity of Kathmandu valley

From the chart below, we know that the maximum average wind velocity is 3.78 m/s in April and the minimum wind velocity is 2.43 m/s in January.



	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
2020 A.D	2.06	2.75	3.43	3.60	3.46	2.91	2.96	3.23	3.06	2.92	2.60	2.85
2021 A.D	2.80	3.19	4.01	3.95	3.48	3.35	2.92	3.00	2.66	3.07	2.68	2.38
Avg. Wind speed	2.43	2.97	3.72	3.78	3.47	3.13	2.94	3.11	2.86	2.99	2.64	2.61

Chart 4: Wind speed data from the years 2020 & 2021 of Kathmandu valley
(Source: Department of Hydrology and Meteorology, Kathmandu, Nepal)

4.2.6 The Wind rose from Kathmandu valley

Ecotect Analysis 2011 was used to create the wind rose using the typical Kathmandu Valley epw file. The Kathmandu valley experiences most of its wind from the west, as can be seen from the wind rose. The southern and southwest sides also experience strong winds. The South-east side experiences the least wind.

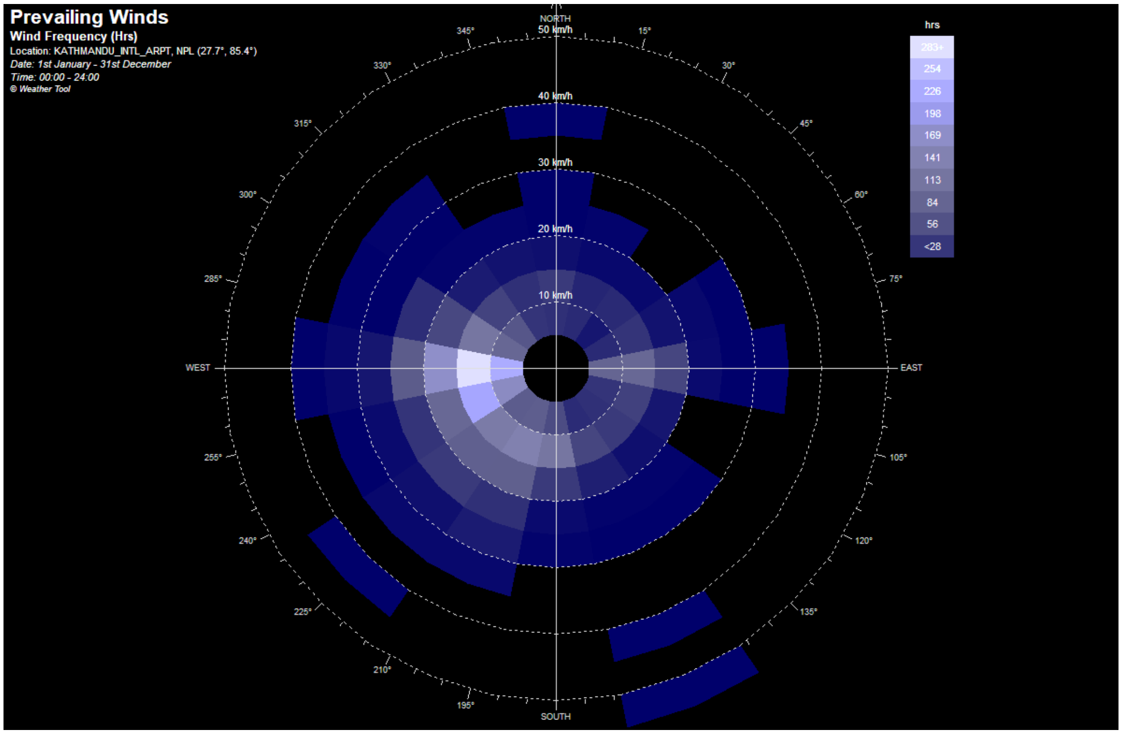


Chart 5: Wind rose of Kathmandu valley

Source: Ecotect Analysis 2011

4.3 Mahoney's table

To determine the suggestion for the design as shown in Appendix A, monthly mean maximum and minimum temperature data from the Department of Meteorology are compiled along with the associated afternoon (PM) and morning (AM) humidity.

4.3.1 The result from Mahoney’s table

After tabulating the data in Mahoney’s table, the following set of suggestions was found as shown in the given table below:

Table 8: Results from Mahoney's Table

1	**Layout**	Orientation north and south (long axis east-west)
2	**Spacing**	As above, but protection from hot and cold wind.
3	**Air movement**	Rooms single banked, permanent provision for air movement
4	**Openings**	Large openings, 40–80%
5	**Walls**	Light walls, short time-lag
6	**Roofs**	Light, well-insulated
7	**Outdoor sleeping**	Not required
8	**Rain protection**	Protection from heavy rain is necessary
9	**Size of opening**	Large openings, 40–80%
10	**Position of openings**	In the north and south walls at body height on the windward side
11	**Protection of openings**	Protection from rain Exclude direct sunlight
12	**Walls and floors**	Light, low thermal capacity
13	**External features**	Adequate rainwater drainage

5 Chapter 5: Field Study

With the current expanding trend of building high-rise structures in the valley, the requirement for suitable glazing for high-rise buildings in the Kathmandu Valley is becoming apparent. However, as more people become aware of the aesthetic, financial, and energy-saving benefits of these materials, the requirement for a variety of glazing solutions becomes increasingly obvious. Nowadays, most glazing is used with little or no knowledge of all the qualities that come with it, which could have very negative effects. They originate from glass manufacturers in India such as Pilkington Glass, Asahi India Glass Limited, and St. Gobain's Glass, among others. Understanding the underlying physics of glass is crucial since glass producers mark their goods with unique nomenclature. Taking into account our needs and the usual circumstances, the best decision should be made. Although there are many commercially available glazing, electrochromic glazing—the most recent significant advancement in energy-efficient window technology—has regrettably not yet been commercialized in Nepal.

Two methodologies were used for the field study: Market research was used to gather secondary data, and Field surveys were used to gather primary data.

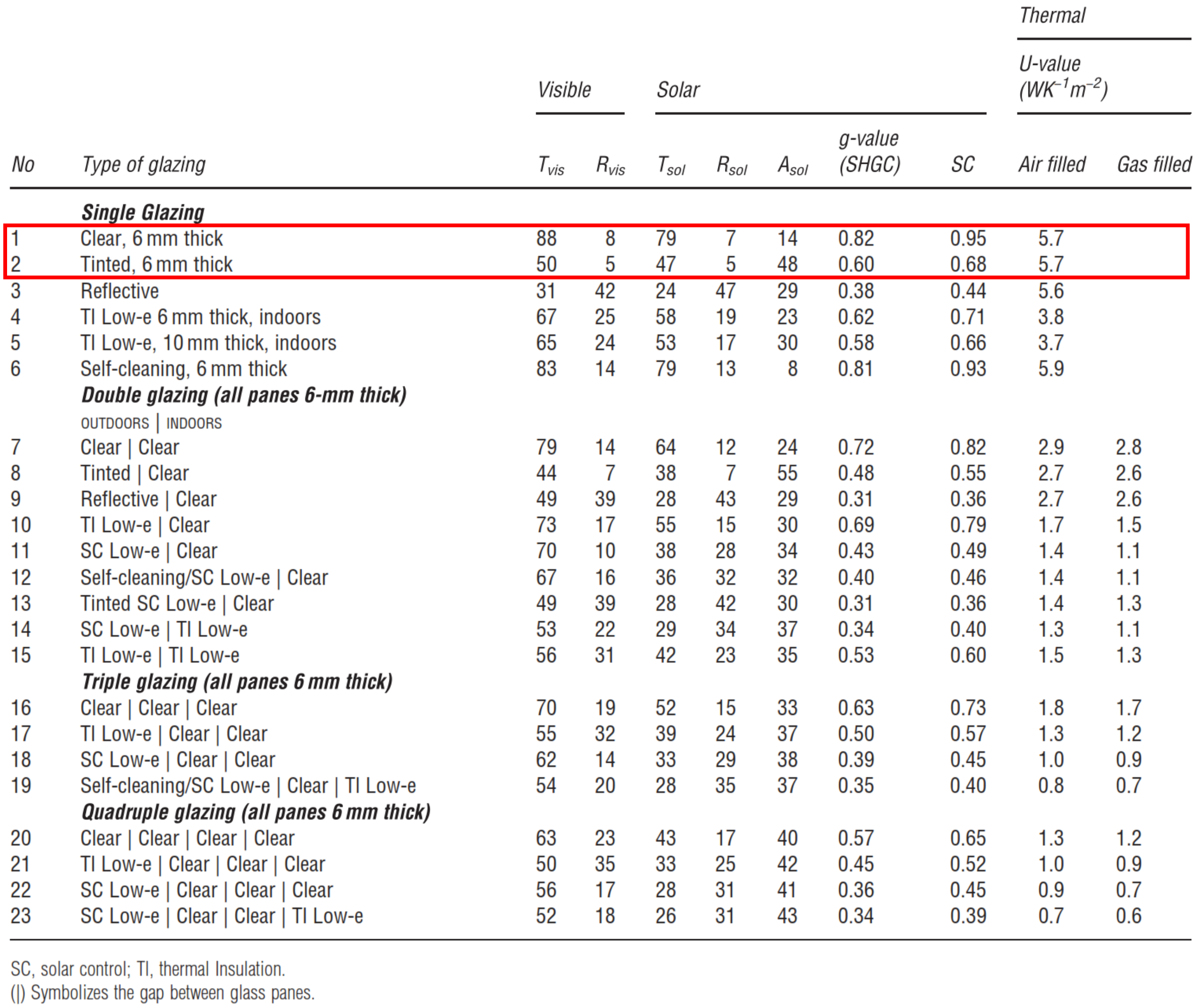
Table 9: Field study methodologies

Field study methodologies			
Market Research		**Field Surveys**	
AIS Glass	**Sage Glass**	**Questionnaire Survey**	**On-site measurements**
✓ **Performance Parameters**		✓ **General Information**	✓ **Standard Illuminance**
✓ **Environment Product Declaration**		✓ **Daylighting**	✓ **Temperature**
▪ **Life cycle assessment**		✓ **Thermal Comfort**	✓ **Humidity**
▪ **Environmental assessment**		✓ **Human Behaviours**	
▪ **Material & Cost**		✓ **Luminous Comfort**	

5.1 Market Research

To comprehend the market patterns of commercially available glazing for buildings, a thorough field investigation was conducted. Around the valley, clear and tinted shades of single-glazed units are still the most common type of glazing. However, smaller-scale multiple-glazed windows are also gradually making their way into Nepalese marketplaces. Architecturally, buildings in Nepal have not yet employed electrochromic glasses. However, offices have adopted switchable electrochromic glasses for privacy.

Table 10: Optical and thermal performance indicators for various types of coatings, as measured at the mid-pane (Leftheriotis & Yianoulis, 2012)



									Thermal	
		Visible		Solar					U-value ($WK^{-1}m^{-2}$)	
No	Type of glazing	T_{vis}	R_{vis}	T_{sol}	R_{sol}	A_{sol}	g-value (SHGC)	SC	Air filled	Gas filled
	Single Glazing									
1	Clear, 6 mm thick	88	8	79	7	14	0.82	0.95	5.7	
2	Tinted, 6 mm thick	50	5	47	5	48	0.60	0.68	5.7	
3	Reflective	31	42	24	47	29	0.38	0.44	5.6	
4	TI Low-e 6 mm thick, indoors	67	25	58	19	23	0.62	0.71	3.8	
5	TI Low-e, 10 mm thick, indoors	65	24	53	17	30	0.58	0.66	3.7	
6	Self-cleaning, 6 mm thick	83	14	79	13	8	0.81	0.93	5.9	
	Double glazing (all panes 6-mm thick)									
	OUTDOORS | INDOORS									
7	Clear | Clear	79	14	64	12	24	0.72	0.82	2.9	2.8
8	Tinted | Clear	44	7	38	7	55	0.48	0.55	2.7	2.6
9	Reflective | Clear	49	39	28	43	29	0.31	0.36	2.7	2.6
10	TI Low-e | Clear	73	17	55	15	30	0.69	0.79	1.7	1.5
11	SC Low-e | Clear	70	10	38	28	34	0.43	0.49	1.4	1.1
12	Self-cleaning/SC Low-e | Clear	67	16	36	32	32	0.40	0.46	1.4	1.1
13	Tinted SC Low-e | Clear	49	39	28	42	30	0.31	0.36	1.4	1.3
14	SC Low-e | TI Low-e	53	22	29	34	37	0.34	0.40	1.3	1.1
15	TI Low-e | TI Low-e	56	31	42	23	35	0.53	0.60	1.5	1.3
	Triple glazing (all panes 6 mm thick)									
16	Clear | Clear | Clear	70	19	52	15	33	0.63	0.73	1.8	1.7
17	TI Low-e | Clear | Clear	55	32	39	24	37	0.50	0.57	1.3	1.2
18	SC Low-e | Clear | Clear	62	14	33	29	38	0.39	0.45	1.0	0.9
19	Self-cleaning/SC Low-e | Clear | TI Low-e	54	20	28	35	37	0.35	0.40	0.8	0.7
	Quadruple glazing (all panes 6 mm thick)									
20	Clear | Clear | Clear | Clear	63	23	43	17	40	0.57	0.65	1.3	1.2
21	TI Low-e | Clear | Clear | Clear	50	35	33	25	42	0.45	0.52	1.0	0.9
22	SC Low-e | Clear | Clear | Clear	56	17	28	31	41	0.36	0.45	0.9	0.7
23	SC Low-e | Clear | Clear | TI Low-e	52	18	26	31	43	0.34	0.39	0.7	0.6

SC, solar control; TI, thermal Insulation.
(|) Symbolizes the gap between glass panes.

The aforementioned table lists optical and thermal performance metrics for a variety of commercially available coatings, ranging from single-glazed to quadruple-glazed units. It is safe to conclude that in the Nepalese market, tinted glasses are the most popular kind of glasses in building types, including commercial, office, institutional, etc., and are used extensively. Grey, blue, green, black, and bronze are just a few of the colors that tinted glasses can be found in. However, because of its high extinction coefficient, poor transmittance, and great absorptance, colored glass is sometimes referred to as being "absorptive." Thus, single-tinted glazings fall far short of ideal performance. To solve this problem, other, better approaches have been developed, such as spectrally selective coatings with a light blue/green tint that have better visual performance and lower SHGC.

As a result, this study examines performance measures for all potential glazing options that are applied in Nepali offices. Additionally, we will conduct a thorough analysis of the energy-efficient glazing solutions offered by AIS Glass and the electrochromic glasses offered by Sage Glass.

5.1.1 AIS Glass

Asahi India Glass Limited (AIS), which offers a wide variety of glasses ranging from typical clear float glasses to high-performance glazing that has been imported in Nepal to date, was discovered through several interviews and preliminary field surveys of the availability of glasses for buildings in Nepal. The top integrated glass solutions provider in India and a market leader in both the automotive and architectural glass sectors is Asahi India Glass Ltd. (AIS).

5.1.1.1 Performance parameters

In addition to Clear & Tinted, Heat Reflective, Frosted, and Back-painted High-Performance glass, Processed glass, and Mirrors, AIS is a firm with ISO 9001 and ISO 14001 certifications. AIS continues to innovate and broaden its line of all-inclusive glass solutions. All of these items are meant to alter how we think about and utilize glass. (AIS, 2020). Some of the selective performance parameters of ranges of glasses are shown in the table below: Clear Float Glass has clarity of vision but has high visible transmittance of light whereas tinted glasses can block solar the sun’s heat but has high absorption.

AIS- Clear and Tinted Glass – Performance Parameters (2-12mm)

Table 11: AIS- Clear and Tinted Glass – Performance Parameters (2-12mm)

Source: (AIS Glass, 2022)

Glass Details		**Light Factors**			**Energy Factors**		
Product Name	Shade	Transmission	Reflection				
			External	Internal	SF	SC	U-value
		%	%	%	%		W/m^{2}K
AIS Clear Float glass (6mm)	Clear	86.6	7.7	-	81	0.93	5.68
AIS Clear Float glass (12 mm)	Clear	81.6	7.3	-	72.5	0.83	5.49
AIS Clear Tinted glass (6 mm)	Dark Grey	14.2	4.4	-	48.3	0.56	5.68
AIS Clear Tinted glass (5 mm)	Green	72.9	5.5	-	59.4	0.68	5.71
AIS Clear Tinted glass (6 mm)	Dark Blue	48.4	5.3	-	60	0.69	5.68

AIS Ecosense – Performance Parameters

The high-performance, energy-saving AIS Ecosense family of products provides the perfect blend of thermal comfort and visual comfort, daylight and energy savings, technology, and eco-sensitivity. AIS Ecosense product line includes the following items: Enhance, Exceed, Essence, Edge, and Excel (AIS, 2020).

Table 12: AIS Ecosense Enhance – Performance Parameters (Solar Control glass- 6mm)

Source: (AIS Glass, 2022)

Glass Details		**Light Factors**			**Energy Factors**		
Product Name	Shade	Transmission	Reflection				
			External	Internal	SF	SC	U-value
		%	%	%	%		W/m^{2}K
Spring	Clear	65	21	24	69	0.79	5.7
Solaris	Clear	8	44	36	14	0.16	3.6
Oasis	Blue	30	17	26	41	0.47	4.8
Oceanic Blue Plus	Blue	22	20	29	33	0.38	5.0
Meadow Green	Green	56	14	21	48	0.56	5.7

Citrus Green	Green	18	25	21	31	0.36	4.9
6 mm (Solar Control Glass) - 12 mm (Air Gap) - 6 mm (Clear Glass)							
Spring	Clear	59	24	26	60	0.70	2.8
Solaris	Clear	7	43	33	9	0.10	1.9
Oasis	Blue	27	17	29	31	0.36	2.5
Meadow	Green	49	17	25	39	0.44	2.8
Citrus	Green	16	25	24	21	0.24	2.6
Gold	Gold	44	27	29	48	0.56	2.8

AIS Ecosense Exceed– Performance Parameters

Table 13: AIS Ecosense Exceed– Performance Parameters

Source: (AIS Glass, 2022)

Glass Details		Light Factors			Energy Factors		
Product Name	Shade	Transmission	Reflection				
			External	Internal	SF	SC	U-value
		%	%	%	%		W/m^{2}K
6 mm Solar Control Low-E Glass – 12 mm Air Gap – 6 mm Clear Glass							
Clear Lite Plus	Clear	54	15	11	38	0.44	1.7
Clear Brook Plus	Clear	33	39	21	22	0.25	1.6
Tropic Blue	Blue	44	16	16	34	0.39	1.8
Blue Berry	Blue	29	21	20	26	0.30	1.7
Green Lite Plus Green	Green	47	14	11	29	0.33	1.7
Green Platina	Green	24	28	17	18	0.21	1.6
Aurelia Gold	Gold	30	41	46	24	0.28	1.6

AIS Ecosense Excel – Performance Parameters

Table 14: AIS Ecosense Excel – Performance Parameters

Source: (AIS Glass, 2022)

Glass Details		Light Factors			Energy Factors		
Product Name	Shade	Transmission	Reflection				
			External	Internal	SF	SC	U-value
		%	%	%	%		W/m^{2}K
6 mm Double Low-E Glass – 12 mm Air Gap – 6 mm Clear Glass							
Clear Sparkle	Clear	46	19	17	25	0.29	1.6
Green Sparkle	Green	41	17	18	22	0.25	1.6

AIS Ecosense Edge – Performance Parameters

Table 15: AIS Ecosense Edge – Performance Parameters

Source: (AIS Glass, 2022)

Glass Details		Light Factors			Energy Factors		
Product Name	Shade	Transmission	Reflection				
			External	Internal	SF	SC	U-value
		%	%	%	%		W/m^{2}K
AIS Ecosense Edge / Edge Plus – 6 mm (Solar Control & Thermal Insulation Glass)							
Natura	Clear	28	27	10	30	0.35	3.7
Chroma	Green	23	21	10	26	0.30	3.7
Natura Plus	Clear	45	20	6	42	0.48	4.6
Chroma Plus	Green	38	19	6	31	0.36	4.6
Natura Advantage	Clear	34	23	8	34	0.39	4.0
Chroma Advantage	Green	28	17	9	29	0.33	3.6
AIS Ecosense Edge / Edge Plus – 6 mm (Solar Control & Thermal Insulation Glass) – 12 mm (Air Gap) – 6 mm (Clear Glass)							
Natura	Clear	25	28	16	24	0.28	2.0
Chroma	Green	20	21	16	19	0.22	2.0
Natura Plus	Clear	40	22	12	33	0.38	2.4
Chroma Plus	Green	35	12	12	23	0.26	2.4
Natura Advantage	Clear	30	24	14	25	0.29	1.9
Chroma Advantage	Green	25	18	16	21	0.24	2.0

AIS Ecosense Essence – Performance Parameters

Table 16: AIS Ecosense Essence – Performance Parameters

Source: (AIS Glass, 2022)

Glass Details		Light Factors			Energy Factors		
Product Name	Shade	Transmission	Reflection				
			External	Internal	SF	SC	U-value
		%	%	%	%		W/m^{2}K
6 mm Low-E Glass – 12 mm Air Gap – 6 mm Clear Glass							
Clear Essence Plus	Clear	71	10	12	53	0.61	1.8
Green Essence Plus	Green	59	9	11	37	0.43	1.8

5.1.1.2 Environmental Product Declaration (EPD)

This statement aims to outline the impacts of 1 m2 of Processed Glass - Insulated Glass Unit (IGU) produced by Asahi India Glass Ltd. that can be measured and independently validated (AIS). India is included in the geographic scope of this EPD. According to PCR 2012:01 Construction Products and Construction Services, the LCA was completed to create an Environmental Product Declaration (EPD) (EN 15804) (EPD, 2019).

5.1.1.2.1 Life Cycle Assessment (LCA)

System Boundaries

The LCA model of processed glass illustrates a cradle-to-gate system where raw materials are extracted at the beginning and flat glass is treated at the finish (A1 to A3). The system boundary taken into consideration for the LCA of float glass is described in the table below. The environmental effects of all the remaining phases of the average float glass life cycle are not evaluated (MNA). (EPD, 2019)

What is not part of the system boundary is:

- the upkeep of the production facility's equipment
- Equipment upkeep and operation
- Human work
- the distribution of the product
- its use and disposal

Table 17: System boundary description (MNA = Module Not Assessed, X = Included in LCA)

Source: (EPD, 2019)

Product Stage			Installation Stage		Use stage							End-of-Life Stage				Benefits beyond system boundary
Supply of raw materials	Transportation	Manufacturing	Transport to a building site	Installation into building	Use / application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction / demolition	Transport to EoL	Waste processing for reuse, recovery, or recycling	Disposal	Reuse, recovery, or recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA	MNA

Table 18: The study includes specifics regarding the system boundary

Source: (EPD, 2019)

Life Cycle stages	Life Cycle sub-stages	Definitions	Module
Materials	Manufacture of primary raw materials	Manufacture of raw materials including silica, soda ash, lime, dolomite, etc. by extraction and production.)	A1
Upstream Transport	Transport by Road, Rail, and Ocean	Transport of the raw materials	A2
Manufacturing	Production of processed glass involves combining raw ingredients, getting rid of waste, coating, and processing.	Production of float glass, processing of such glass, and disposal of waste	A3

LCA Results of IGU (Glazed) Glass

The environmental effects of a 1 m2 soft-coated glazed glass product with a 6mm thickness are shown in the tables below.

Table 19: LCIA for a soft-coated, glazed glass that is 1 m2 and 6 mm thick.

Source: (EPD, 2019)

Parameter	Unit	Module A1-A3
Global warming potential (GWP)	kg CO_2-eq	52.7
Depletion potential of the stratospheric ozone layer (ODP)	kg CFC 11-eq	7.97E-10
Acidification potential of land and water (AP)	kg SO_2-eq	0.463
Eutrophication potential (EP)	kg PO_4^{3-}-eq	0.029
Formation potential of tropospheric ozone photochemical oxidants (POCP)	kg ethene-eq	0.022
Abiotic depletion potential for non-fossil resources (ADP elements)	kg Sb-eq	4.0E-04
Abiotic depletion potential for fossil resources (ADP fossil fuels)	MJ	603.6

Table 20: For 1 m2 of a 6mm-thick soft-coated glazed glass, use of natural resources study was performed.

Source: (EPD, 2019)

Parameter	Unit	Module A1-A3
Renewable primary energy as an energy carrier	MJ	64.8
Renewable primary energy resources as material utilization	MJ	0
Total use of renewable primary energy resources	MJ	64.8
Non-renewable primary energy as an energy carrier	MJ	621.7
Non-renewable primary energy as material utilization	MJ	0
Total use of non-renewable primary energy resources	MJ	621.7
Use of secondary material	kg	6.30
Use of renewable secondary fuels	MJ	0
Use of non-renewable secondary fuels	MJ	0
Use of net fresh water	m^3	0.055

Table 21: One square meter of soft-coated, 6-mm thick glass falls under the waste category.
Source: (EPD, 2019)

Parameter	Unit	Module A1-A3
Non-hazardous waste	kg	0.57
Hazardous waste	kg	8.32E-07
Radioactive waste	kg	0.004

5.1.2 Sage Glass Electrochromic Glass

SageGlass products offer unhindered outside vistas and improved occupant comfort by dynamically adjusting tints in reaction to the sun. Without the use of conventional solutions like blinds, shades, or low-E glass, the items offer outstanding control over sunlight, glare, and energy consumption. Their creation, which pioneered electrochromic technology, is changing what glass can accomplish in the built environment. Due to its contribution to the development of electrochromic technology, SageGlass is a crucial subject for this inquiry. (SageGlass, 2022).

5.1.2.1 Performance parameters

Saint- Gobain's SageGlass dynamic glass, which comes in a range of tinted or coated substrates (Clear, Blue, Grey, and Green), can be used to match the building's exterior design. The tables below contain performance information for a few SageGlass products filled with argon:

Clear- SageGlass

4mm clear w/SR2.0, 0.89mm SentryGlas, 2.2mm SageGlass, 12mm air space w/90% Argon fill, 6mm clear

Table 22: SageGlass Clear-Performance parameters
Source: (SageGlass, 2022)

Tint level	Inner Lite	%Tvis	%Rf Ext.	%Rb Int.	%Tsol	SHGC	U-factor (Btu/hr. ft^2. ˚F)
Clear State	6mm Clear	60	16	14	33	0.41	0.28
Intermediate state 1	6mm Clear	18	10	9	7	0.15	0.28
Intermediate state 2	6mm Clear	6	10	9	2	0.10	0.28
Fully Tinted	6mm Clear	1	11	9	0.4	0.09	0.28

SageGlass Blue (6mm blue, 0.89mm SentryGlas, 2.2mm SageGlass, 10mm air space w/90% Argon fill, 6mm clear)

Table 23: SageGlass Blue - Performance parameters

Source: (SageGlass, 2022)

Level of tint	Inner Lite	%Tvis	%Rf Ext.	%Rb Int.	%Tsol	SHGC	U-factor (Btu/hr. ft^2. ˚F)
Clear State	6mm Clear	40	7	10	21	0.30	0.29
Intermediate state 1	6mm Clear	19	5	9	8	0.17	0.29
Intermediate state 2	6mm Clear	7	5	9	3	0.13	0.29
Fully Tinted	6mm Clear	< 1	5	9	0.3	0.10	0.29

SageGlass Gray (6mm gray, 0.89mm SentryGlas, 2.2mm SageGlass, 10mm air space w/90% Argon fill, 6mm clear

Table 24: SageGlass Gray - Performance parameters

Source: (SageGlass, 2022)

Level of tint	Inner Lite	%Tvis	%Rf Ext.	%Rb Int.	%Tsol	SHGC	U-factor (Btu/hr. ft^2. ˚F)
Clear State	6mm Clear	45	7	11	23	0.33	0.29
Intermediate state 1	6mm Clear	19	5	9	8	0.20	0.29
Intermediate state 2	6mm Clear	6	5	9	3	0.12	0.29
Fully Tinted	6mm Clear	< 1	5	9	0.2	0.10	0.29

SageGlass Green (6mm green, 0.89mm SentryGlas, 2.2mm SageGlass, 10mm air space w/90% Argon fill, 6mm clear)

Table 25: SageGlass Green - Performance parameters

Source: (SageGlass, 2022)

Level of tint	Inner Lite	%Tvis	%Rf Ext.	%Rb Int.	%Tsol	SHGC	U-factor (Btu/hr. ft^2. ˚F)
Clear State	6mm Clear	49	8	11	18	0.27	0.29
Intermediate state 1	6mm Clear	21	5	9	7	0.17	0.29
Intermediate state 2	6mm Clear	7	5	9	3	0.12	0.29
Fully Tinted	6mm Clear	< 1	5	9	0.3	0.10	0.29

5.1.2.2 Environmental Product Declaration (EPD)

The environmental product declaration (EPD) of SageGlass Electrochromic glass was created following ISO 14025. Life Cycle Assessment (LCA) is used by EPD to give data on a variety of environmental effects of the product SageGlass Electrochromic glass throughout their life cycles.

According to customer requirements, a variety of product variants for SageGlass electrochromic insulating glass are available. Figure 5-1 displays an example of an IG arrangement (Environmental Product Declaration, 2016). Each configuration consists of:

i. a float glass light that is 2.2 mm thick and onto which the EC coating stack is coated (referred to as the base lite),
ii. a second float glass lite, or "support lite," to which the 2.2 mm lite is bonded; the thickness of which varies depending on the application,
iii. the thickness and kind of the third float glass lite, which is the inboard lite of the insulating glass unit, depending on the application.
iv. related insulating glass components, including wiring, sealants, desiccant, sealants, and laminating interlayer materials.

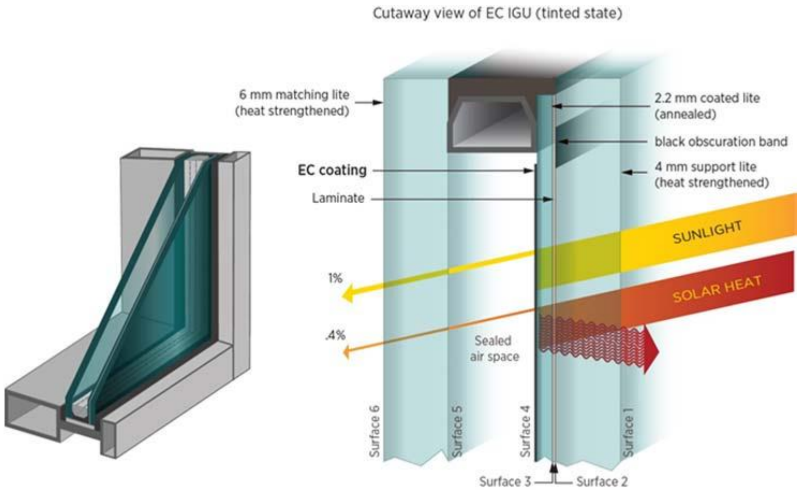


Figure 5-1: A SageGlass electrochromic insulating glass unit's schematic
Source: (Environmental Product Declaration, 2016)

5.1.2.2.1 Life Cycle Assessment (LCA)

System Boundaries

Life cycle stages from "cradle to gate" are included in the life cycle analysis done for this EPD of SageGlass Electrochromic glass. The supply, production, and transportation of raw materials; the production of electrochromic glass in Faribault, Minnesota; and packaging are all included within the system boundary.

Table 26: System Boundary

Source: (Environmental Product Declaration, 2016)

The System Boundary's description (MND = Module not declared; x indicates Included in LCA)																
Product Stage			Construction Process Stage		Use Stage							End of Life Stage				Benefits and Loads Outside of the System
Raw Material Supply	Transport	Manufacturing	Transport from gate to the site	Assembly/ Install	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction	Transport	Waste Processing	Disposal	Reuse, Recovery, Recycling Potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND

LCA Results and Interpretation

The tables and figures below display the environmental effect potentials for the system border modules A1–A3, raw material supply, transportation, and manufacturing, as specified for Europe and the Rest of the World. Throughout its life cycle, from raw materials to manufacturing, 1 square meter of SageGlass electrochromic glass had the following embodied environmental impacts, which are represented on the display. The weighted average configuration (2.2 mm standard component + 11.7 mm weighted average secondary component), the two most common configurations, and the standard components are all represented (Environmental Product Declaration, 2016)

(i) 2.2 mm standard component plus 4 mm of support lite and 6 mm of the cover lite secondary component

(ii) Utilizing the scaling factor calculation described above, the following dimensions were determined: 2.2mm standard component + 6mm support lite, 3mm/1.5mm PVB/3mm cover lite secondary component.

CML 4.1 Impact Assessment for 1 square meter of electrochromic glass, for system boundary, per EN 15804:2012 + A1:2013modules A1-A3 (raw material supply, transport, and manufacture)						
Parameter	**Parameter**	**Unit**	**Standard Components**	**w/ Weighted Average Secondary Component (11.7mm nominal thickness)**	**w/4mm Support Lite & 6mm Cover Lite Secondary Component (9.6mm nominal thickness)**	**w/ 6mm Support Lite 3mm/1.5mm PVB/3mm Cover Lite Secondary Component (11.9mm nominal thickness)**
GWP	Global warming potential	kg CO2 eq	1.86E+03	1.94E+03	1.93E+03	1.94E+03
ODP	Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	4.50E-05	5.18E-05	5.06E-05	5.19E-05
AP Air	Acidification potentials for air emissions	kg SO2 eq	1.63E+01	1.70E+01	1.69E+01	1.70E+01
EP	Eutrophication potentials	kg (PO4)3 eq	9.17E-01	9.99E-01	9.84E-01	1.00E+00
POCP	Formation potential of tropospheric ozone	Kg ethene eq	7.68E-01	7.93E-01	7.88E-01	7.93E-01
ADP Elements	Abiotic depletion potential for non-fossil resources	kg Sb eq	4.90E-03	5.23E-03	5.17E-03	5.23E-03
ADP Fossil Fuels	Abiotic depletion potential for fossil resources	MJ	2.68E+04	2.77E+04	2.75E+04	2.77E+04

Table 27: CML 4.1 Impact Assessment – Environmental Impact Potentials

Source: (Environmental Product Declaration, 2016)

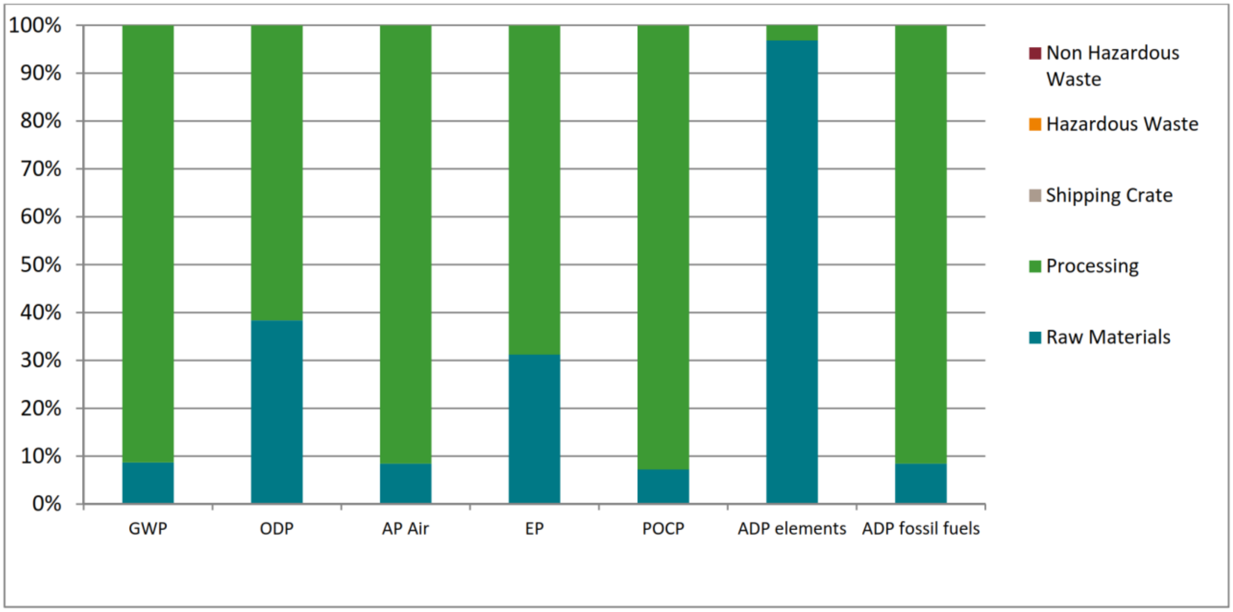


Chart 6: Environmental Impact Potentials in CML 4.1 Impact Assessment (Standard Components)

Source: (Environmental Product Declaration, 2016)

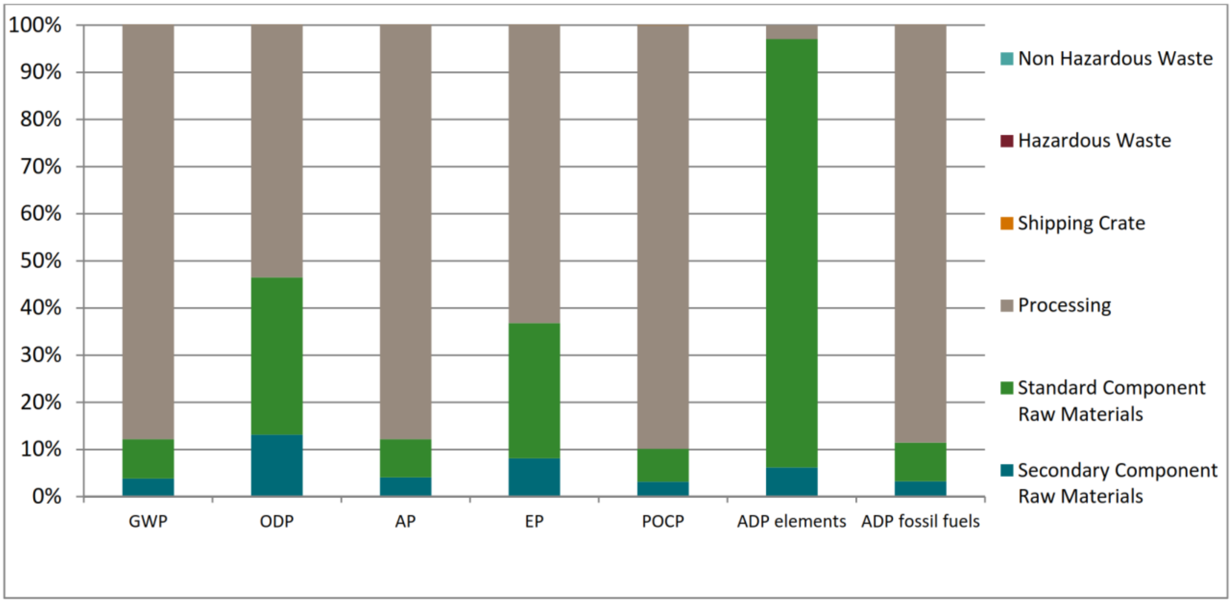


Chart 7: Impact Evaluation - Potential Environmental Impacts (Standard Components + Weighted Average Secondary Component) (CML 4.1)

Source: (Environmental Product Declaration, 2016)

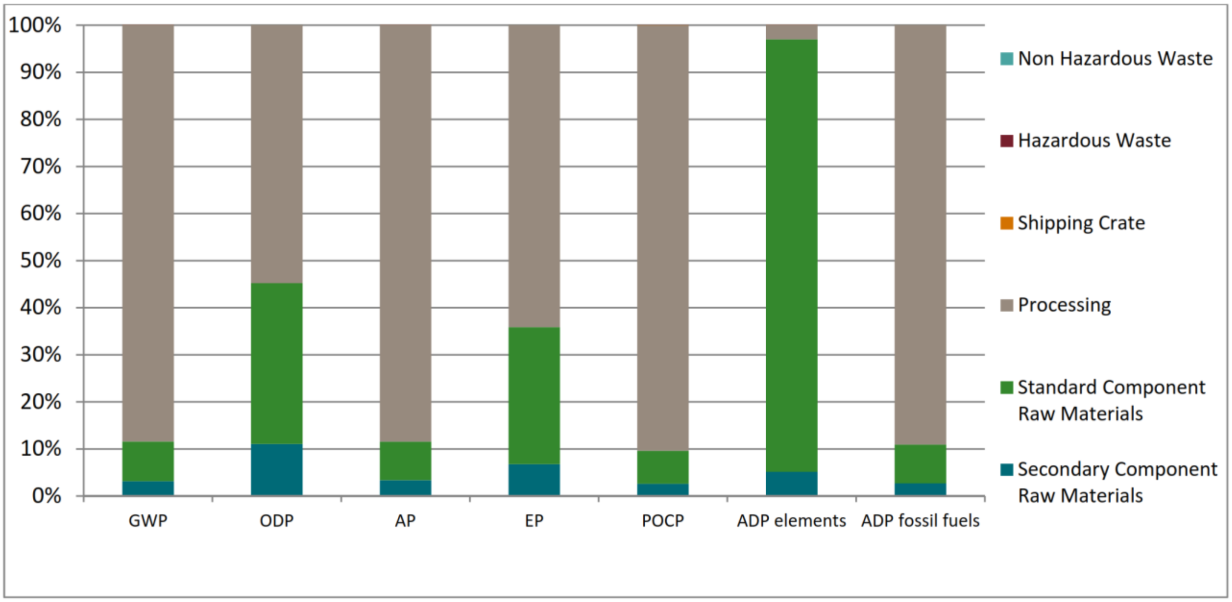


Chart 8: Environmental Impact Potentials (Standard Components + Weighted Average Secondary Component) Impact Assessment (CML 4.1)

Source: (Environmental Product Declaration, 2016)

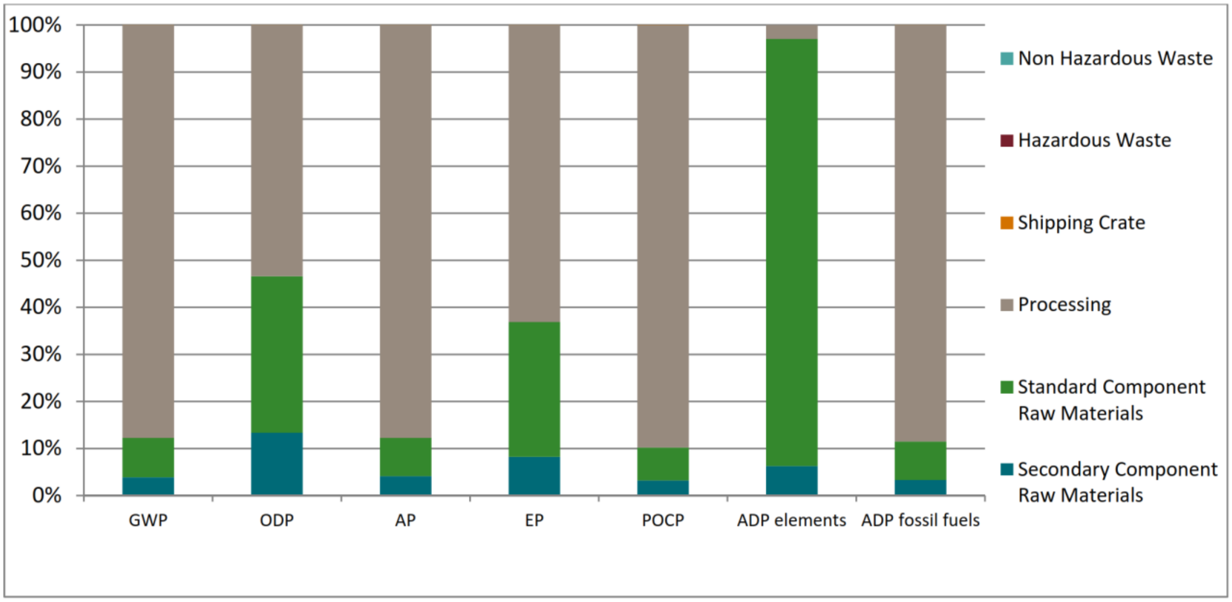


Chart 9: Environmental Impact Potentials (Standard Components + 6mm Support Lite, 3mm/1.5mm PVB, and 3mm Cover Lite) Impact Assessment (CML 4.1)

Source: (Environmental Product Declaration, 2016)

5.2 Field surveys

Three offices were chosen for the field surveys based on a variety of factors, including their built-up area, glazing options, and ownership/tenants. On-site measurements and a questionnaire survey were used to collect the primary data. All of the structures are offices with banking facilities.

Figure 5-2: Site locations of three office sites

Table 28: Building features of the surveyed buildings

Features	**Prabhu Bank Limited**	**Kumari Bank Limited**	**Kumari Capital**
Location	Babarmahal, Kathmandu	Bhatbhateni, Kathmandu	Naag Pokhari, Kathmandu
Size	Large Corporate Office	Mixed-use Medium office	Mixed-use Small office
Site orientation	Long axis East-West	Long axis East-West	N-S; E-W
Façade Orientation	East	East	South
Floor	8 floors	4 floors	4 floors
Office Floors	All 8 floors	(2nd & 3rd floors)	Ground floor & 1st floor
Façade Envelope	6mm ACP cladding with 50mm air gap+9” brick wall	Curtain wall+9” brick wall	6mm ACP cladding with 50mm air gap+9” brick wall
Type of Glazing	Single-glazed (Tinted green)	Single-glazed (Clear)	Single-glazed (Tinted+Clear)
Shading	Interior Blinds	Interior Blinds	Interior Blinds
Roofing	CGI roofing	Concrete roofing	CGI roofing
Air Conditioned	Yes	Yes	Yes

5.2.1 On-site measurements

According to EN 12464, the minimum illuminance for walls is 50 lx and for ceilings, it is 30 lx. Light and lighting - Indoor workplaces - Workplace lighting. In the past, tasks were typically performed in light levels between 100 and 300 lux. Today, depending on the activities, the light level is more frequently in the 500 to 1000 lux range. The light level may even get up to 1500–2000 lux for precise and thorough work.


(a) (b)

(c)

Figure 5-3: (a) Prabhu Bank Limited (b) Kumari Bank Limited (c) Kumari Capital Limited

The standard illumination of the three offices was measured on-site for this investigation using a light meter (RT-912). Using a digital thermo-hygrometer, the temperature and humidity were also measured. The on-site measurements are tabulated below:

(a) (b)

Figure 5-4: (a) Light meter (RT-912) (b) Digital Thermo-hygrometer

Table 29: On-site measurements of standard illuminance, temperature & humidity of three offices

Features	**Prabhu Bank Limited**	**Kumari Bank Limited**	**Kumari Capital**
Location	Babarmahal, Kathmandu	Bhatbhateni, Kathmandu	Naag Pokhari, Kathmandu
Date of Measurement	29th June 2022	11th July 2022	11th July 2022
Time	12:45 to 1 pm	3 pm	4:15 pm
Sky Conditions	Partly Cloudy/Partly Sunny	Mostly Cloudy	Mostly Cloudy
Standard Illuminance	At the height of the work plane - (80-95 lux)	At the height of the work plane - (150-170 lux)	At the height of the work plane - (300-350) lux)
	Light source -(300-350 lux)	Light source - (500-600 lux)	Light source - (500-600 lux)
	Main façade east side Green tinted window-(890-900 lux)	-	-
Temperature	29.6 °C	27.5 °C	26.6 °C
Humidity	59%	65%	86%

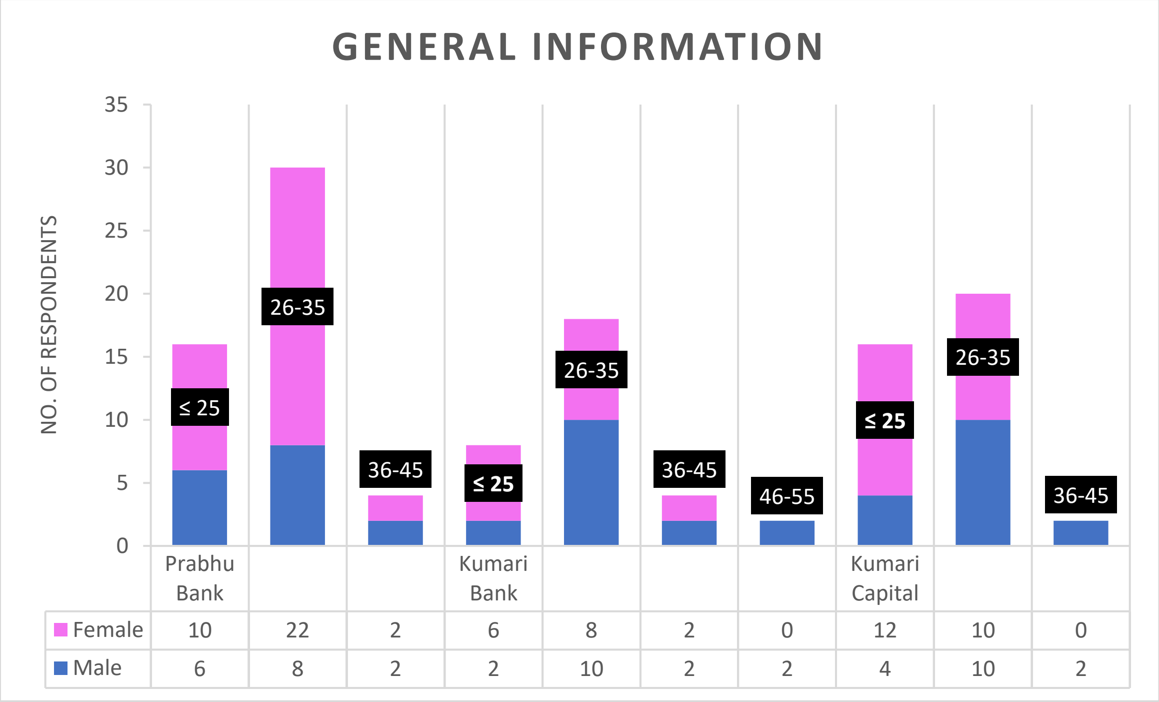
5.2.2 Questionnaire survey

The purpose of the questionnaire survey was to evaluate the thermal comfort and indoor daylighting of three office buildings. The number of questionnaires given was appropriate for the number of employees working in the three offices, and the data were manually gathered. On a single sheet of paper the size of an A4, the responders could check or pick the answers to the questions. 120 surveys were conducted throughout the three offices, with 50 surveys coming from

Prabhu Bank Limited, 32 from Kumari Bank Limited, and the remaining 38 from Kumari Capital Limited. The questionnaire format is provided in Annex C. There were five main sections to the questionnaire: (i) General Information, (ii) Daylighting in the office, (iii) Thermal Comfort, (iv) Human Behavior, and (v) Luminous Comfort. The questionnaire is attached in Appendix B.

5.2.2.1 General information

The general information portion includes the respondents' names, ages, and genders. In all three workplaces, women made up the majority of the respondents. The age range of 26 to 35 was determined to have the highest percentage of responders, followed by that 25 and under.



	Prabhu Bank			Kumari Bank				Kumari Capital		
🟪 Female	10	22	2	6	8	2	0	12	10	0
🟦 Male	6	8	2	2	10	2	2	4	10	2

Chart 10: Chart showing general information of the respondents from all three offices

5.2.2.2 Daylighting in office

It was found that Prabhu Bank had the greatest daylighting compared to the other two banks, while Kumari Bank had the least when it came to the topic of how many hours of enough daylight there were in a typical day. Prabhu Bank and Kumari Capital both enjoy three to five hours of good light each day.

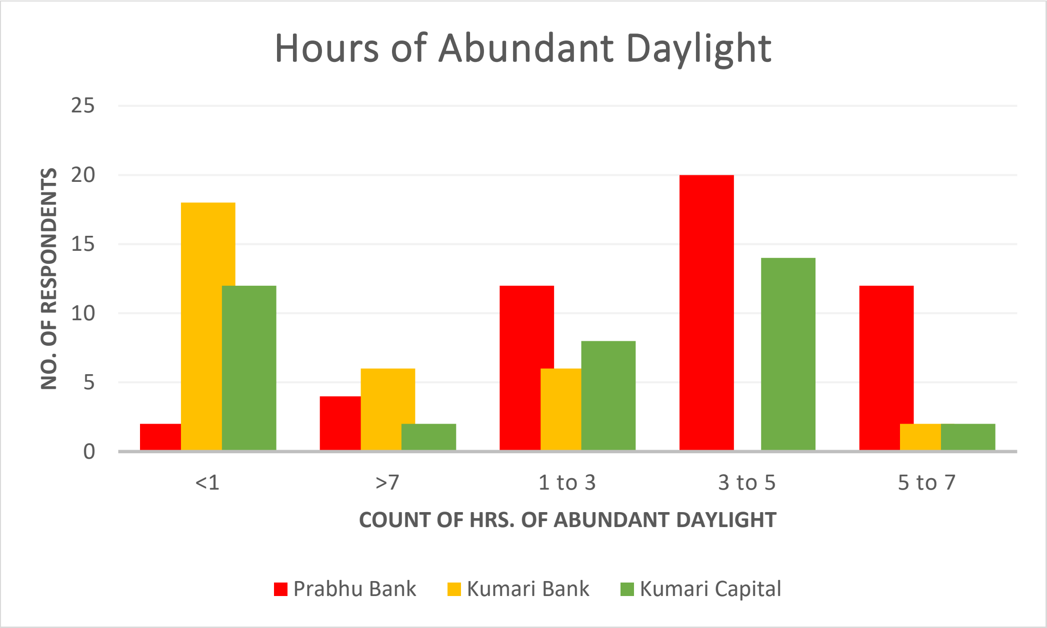


Chart 11: Chart showing hours of Abundant Daylight in three offices

The distribution of natural light and the total illumination impact of both types of lighting in the respondents' separate offices were both inquired about. Despite the unhindered daylighting, all three offices made heavy use of artificial lighting. Additionally, all three workplaces are banks, which demand greater illumination than other types of offices. Full-length glass partitions for the cabins and semi-height aluminum panels are two additional factors contributing to the uneven distribution of daylight.

In chart 12, it is seen that most of the respondents in Prabhu bank agree that there is even distribution of daylighting and both daylighting artificial lighting. In Kumari bank, there is disagreement on the even distribution of illumination in the workplace. However, in Kumari Capital, it is seen that there is even distribution of daylighting only.

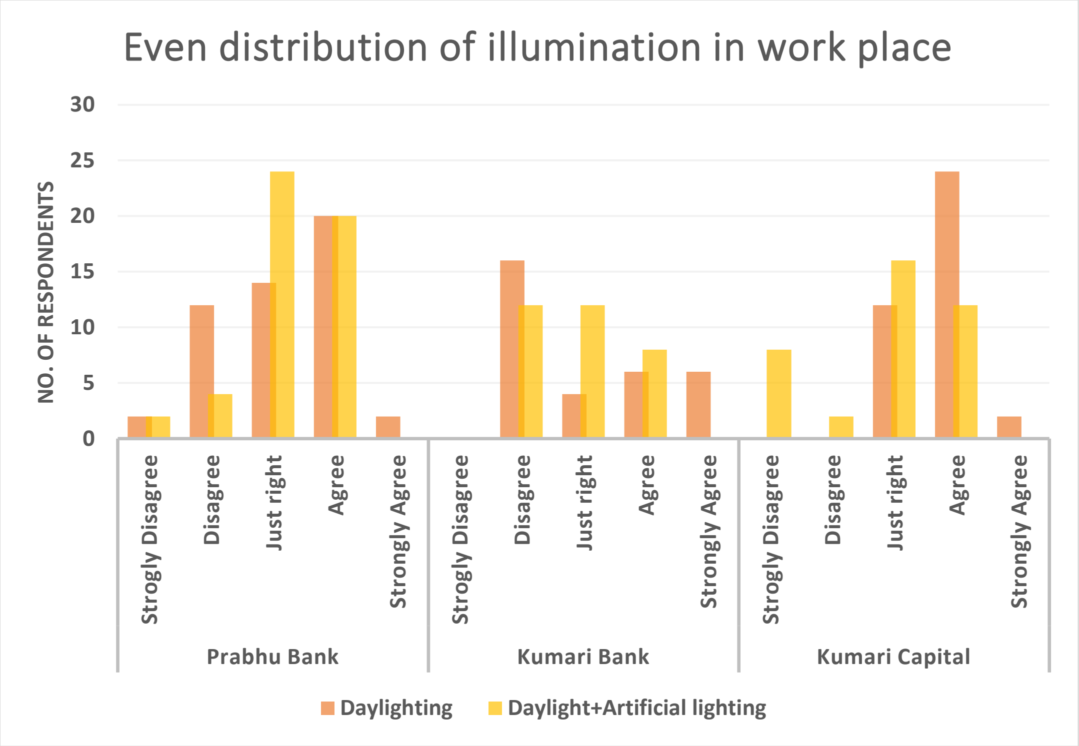


Chart 12: Chart showing even distribution of illumination in the workplace

According to chart 13, Prabhu Bank receives 3–4 hours of maximum sunlight per day in the summer, compared to the projected 2-3 hours. The highest sunlight in the case of Kumari Bank is less than an hour, but unexpectedly, the anticipated sunlight hours are evenly divided from 1 to 3 to 4 hours. While the projected sunlight hours in Kumari Capital are between 1-2 hours, the actual sunlight hours there are less than an hour.

Prabhu Bank receives a range of sunlight hours in the winter, with a maximum forecast of about 3–4 hours, as shown in chart 14. In the instance of Kumari Bank, the actual amount of sunlight is less than an hour and can even be as little as one or two hours, although more than four hours are predicted. The other half of the respondents advocated for a variety of sunlight hours, while the other half predicted that sunlight hours in Kumari Capital would be less than an hour. In Kumari Capital, more than four hours of sunlight is the maximum quantity anticipated.

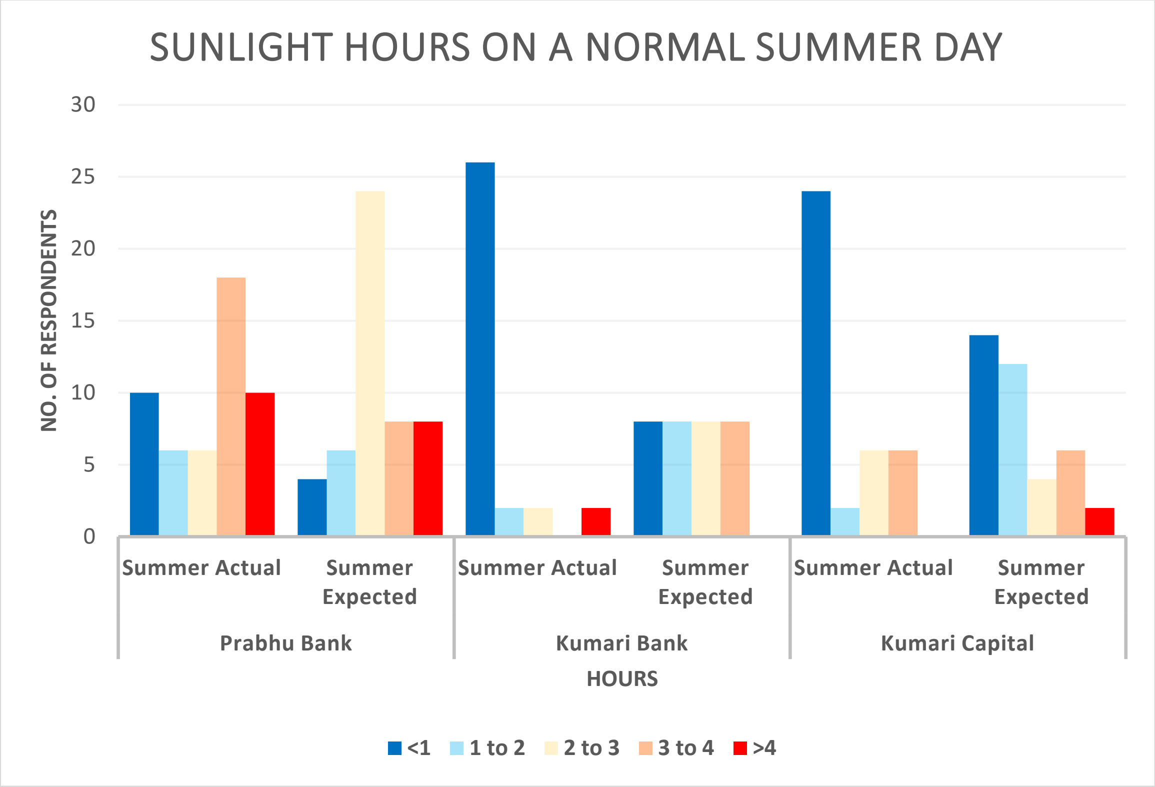


Chart 13: Chart showing sunlight hours on a normal summer day

In Prabhu Bank, the summertime actual sunlight hours are between 3 and 4 hours, compared to the 2 to 3 hours that are predicted. In Kumari Capital and Kumari Bank, the summertime actual sunlight hours are less than an hour and the anticipated sunlight hours are 1 to 2 hours.

On an average winter day in Prabhu Bank, there should be 3 to 4 hours of sunlight. As can be observed, in both Kumari Bank and Kumari Capital, the projected sunlight hours are larger than 4 hours whereas the actual sunlight hours in winter are less than an hour.

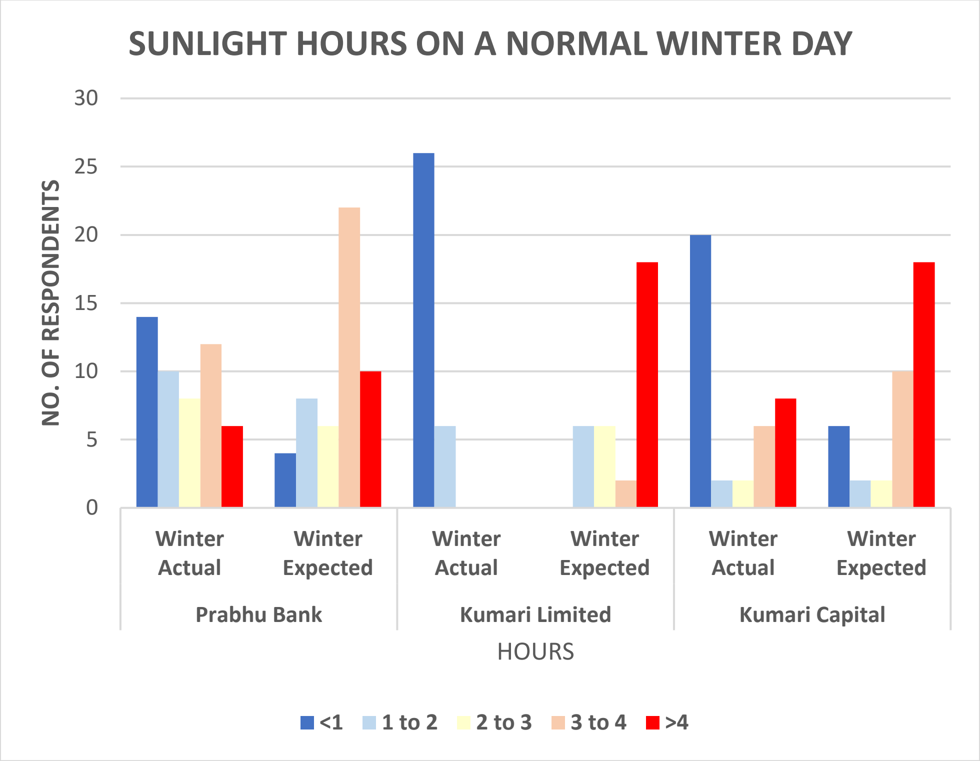


Chart 14: Chart showing sunlight hours on a normal winter day

All three banks' employees occasionally experience a glare sensation.

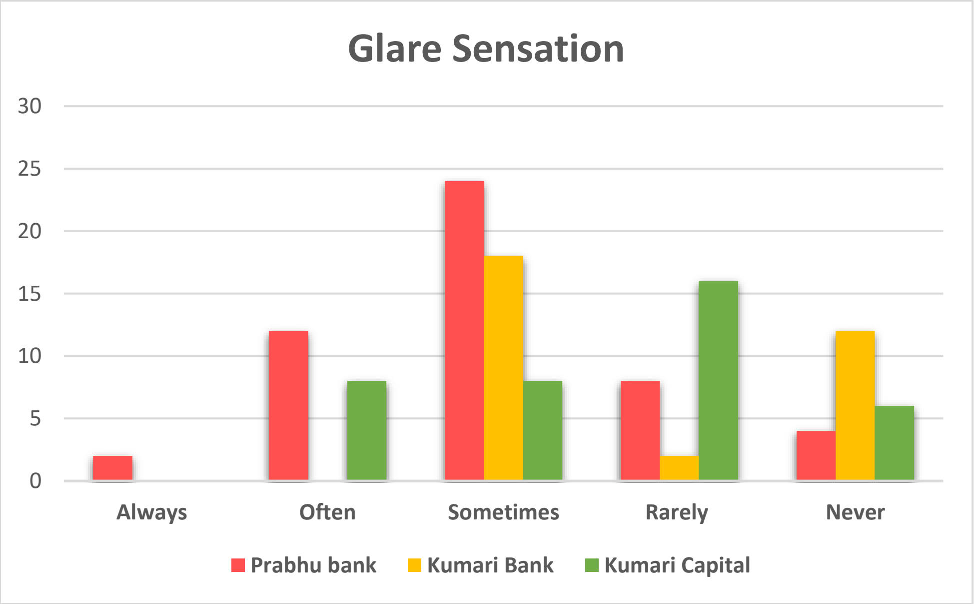


Chart 15: Chart showing Glare sensation felt by respondents in three offices

5.2.2.3 Thermal Comfort

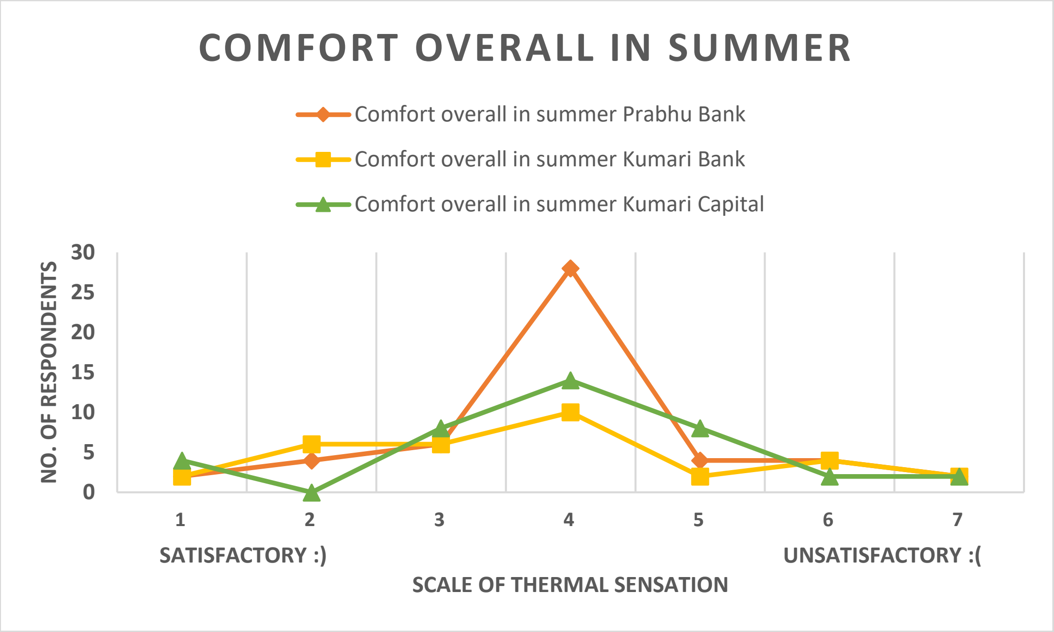


Chart 16: Chart showing the scale of comfort overall in Summer

The scale has a range of 1 to 7, with 1 being the most satisfactory and 7 being the least satisfactory result. Similarly, the scale has a range of 1 to 7, with 1 being the most comfortable and 7 being the most uncomfortable. The maximum temperature on a scale of one to four is four, and similarly, the temperature in summer is four on the same scale. The scale has a range of 1 to 7, with 1 being the most satisfactory and 7 being the least satisfactory result.

Wintertime thermal senescence varies, with a maximum scale between 3 and 5. Similar to summer, winter has a thermal sensation of 4 and 5, respectively.

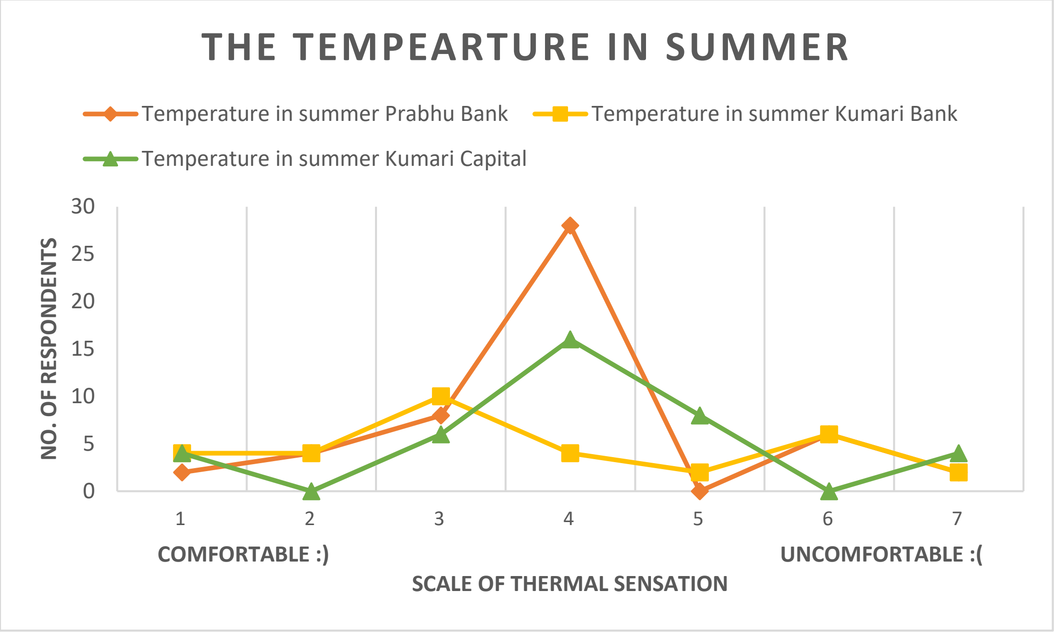


Chart 17: Chart showing the scale of temperature in summer

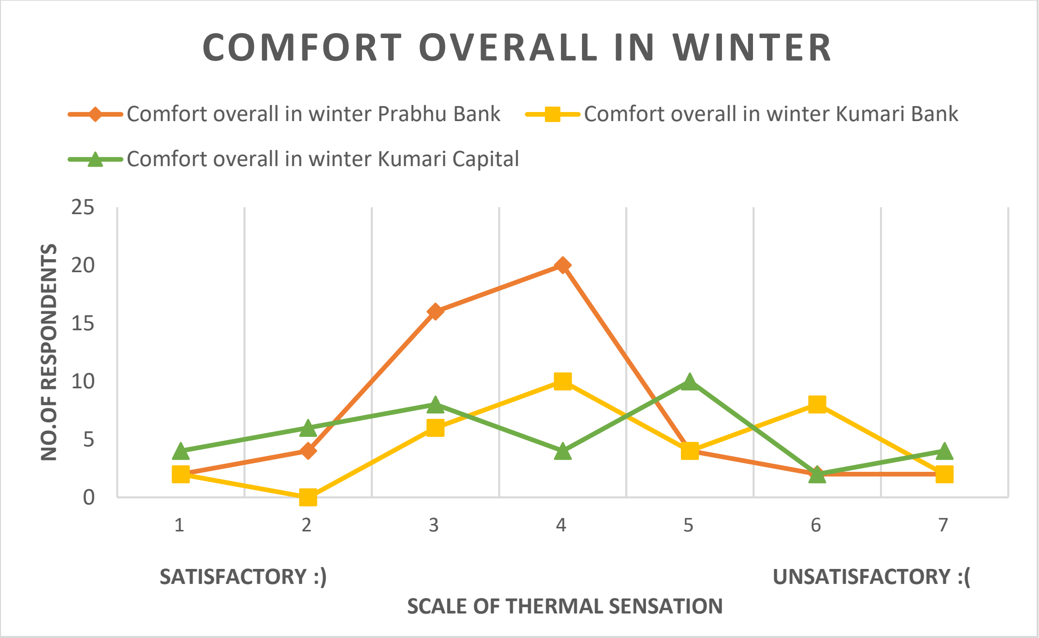


Chart 18: Chart showing the scale of comfort overall in winter

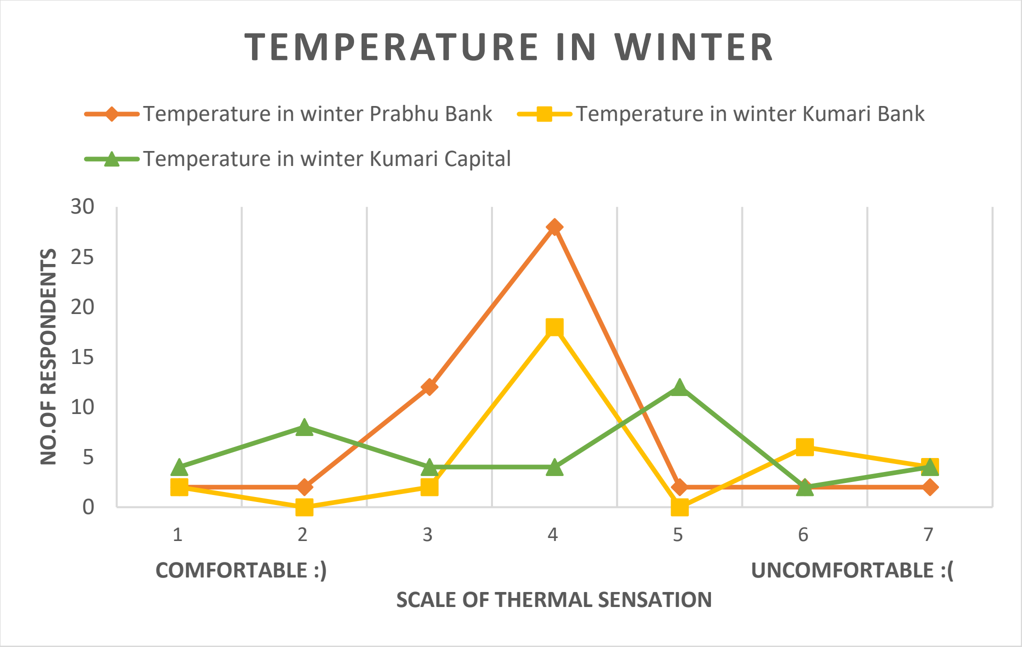


Chart 19: Chart showing the scale of temperature in winter

5.2.2.4 Human Behaviours

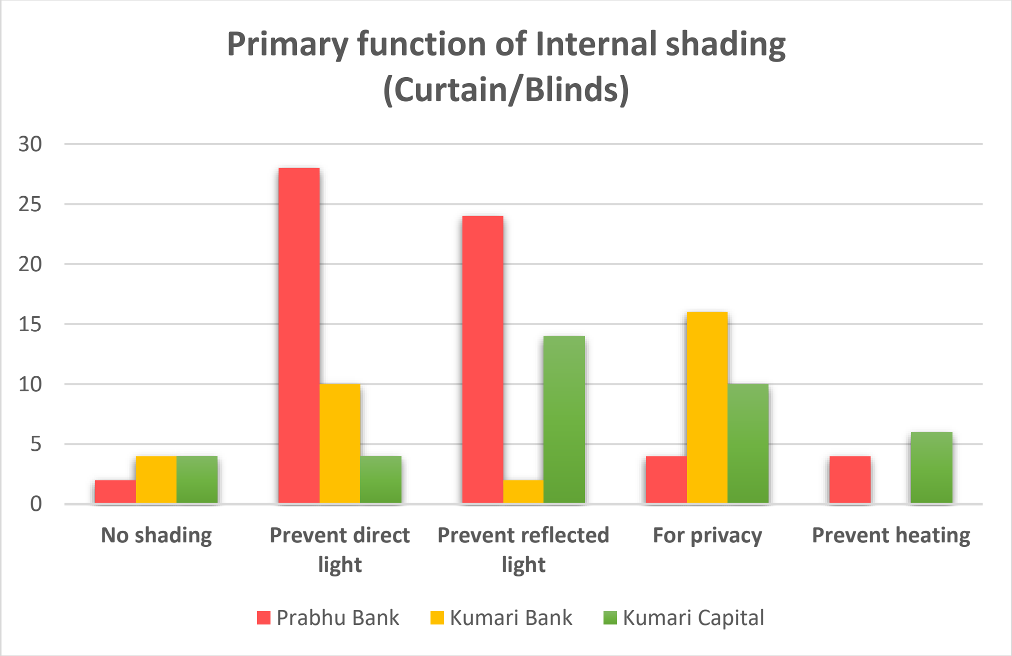


Chart 20: Chart showing the primary function of internal shading in three offices

As can be seen, internal shading (curtains and blinds) serves the dual purpose of reducing direct and reflected light. In the office, the internal shading frequently varies greatly and is drawn at a higher angle than half. All offices have a large amount of artificial lighting, ranging from 5 to 7 hours and sometimes even more.

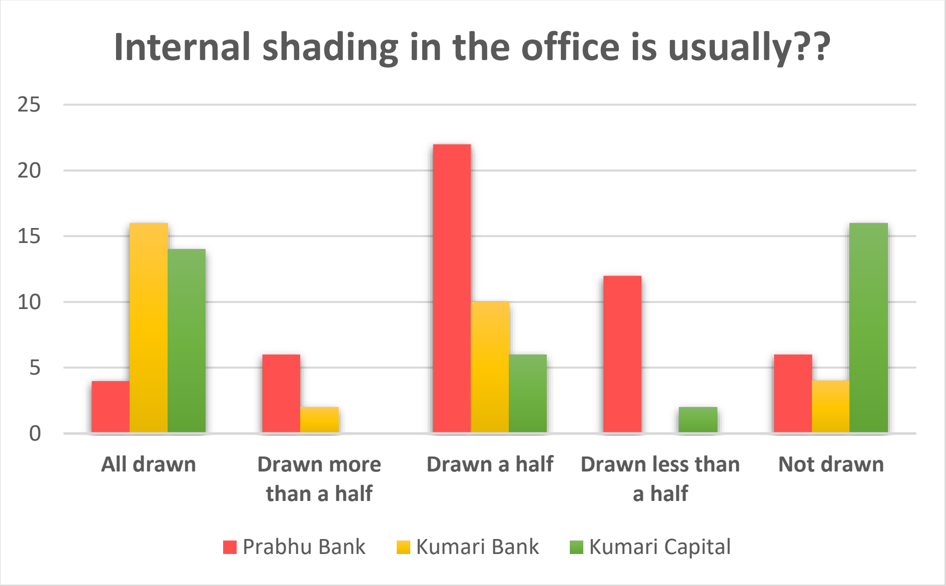


Chart 21: Chart showing the state of internal shading in three offices

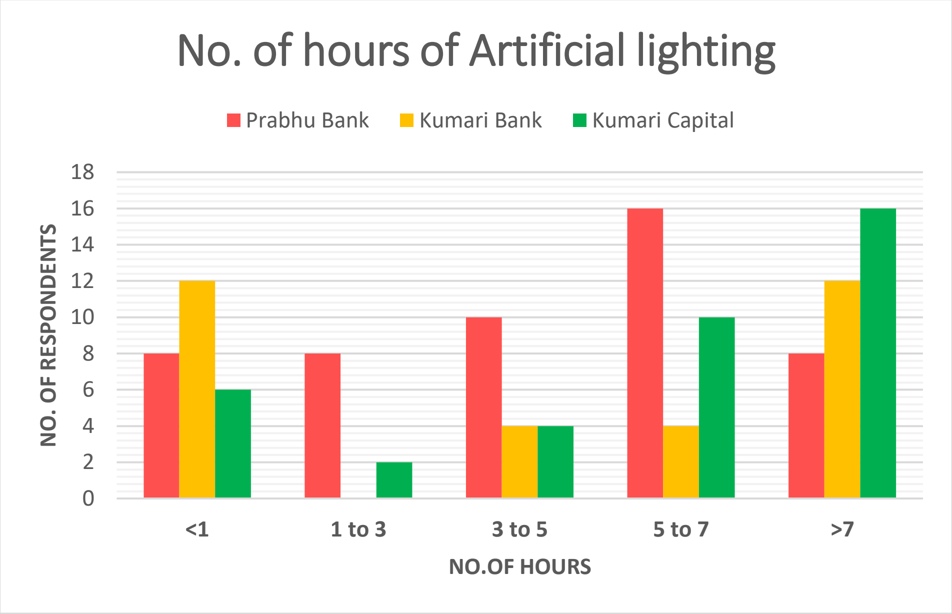


Chart 22: Chart showing the number of hours of artificial lighting in three offices

5.2.3 Luminous Comfort

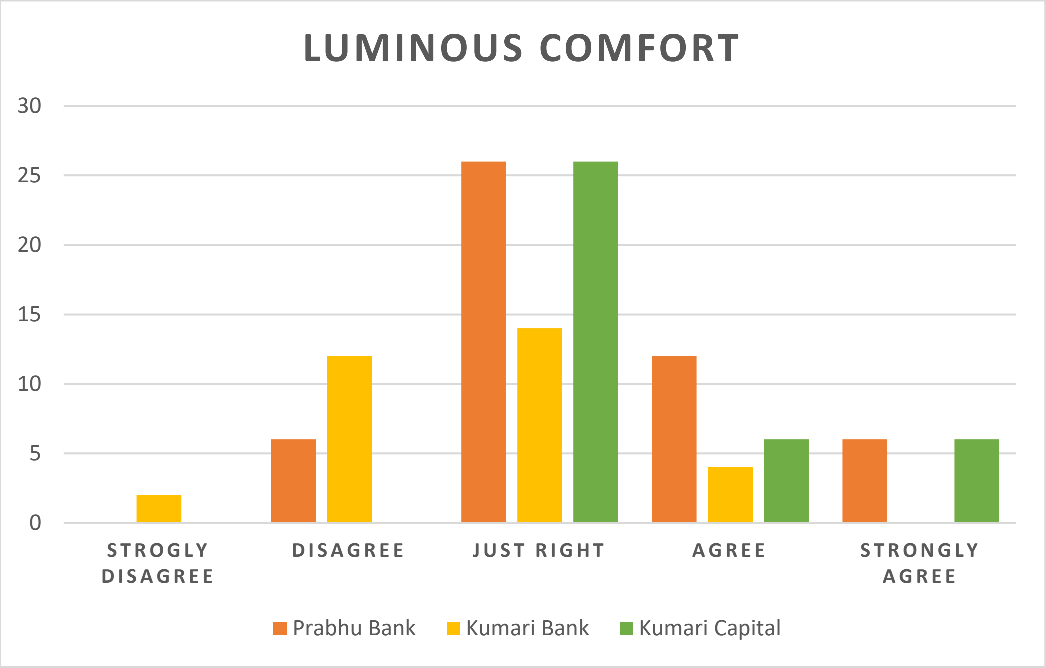


Chart 23: Chart showing the satisfaction of luminous comfort of three offices

All three offices' responders agree that the overall lighting impact is comfortable and bright.

5.2.4 Field Survey- Summary of Findings

- Single-glazed units in clear and tinted tints are still the most typical style of glazing in the valley.
- Wide-range of energy-efficient glasses are commercially available: Low-E, solar control glass, and thermally insulated glass having U-value up to 1.6 W/m2K.
- Electrochromic glasses have up to 4 tint shades and VLT is less than 1 in the darkest tint state.
- Both LCA of IGU glasses and EC glasses have low carbon emissions.
- Electrochromic glasses are very expensive and can cost up to $400-$800 per sq.m which is 4 times more expensive than normal single-glazed clear glass.
- The optimum standard illuminance in offices ranges from 100 to 300 lux but in Prabhu bank, it was found that the standard illuminance ranged from 80-90 lux which does not meet the required standard.
- Surveyed offices lack abundant hours of daylight. Maximum- (3-5) hrs.

- Expected sunlight hours in summer- (2-3) hrs.
- Expected sunlight hours in winter- (3-4) & >7 hrs.
- Glare sensation- Sometimes
- Comfort overall in summer- Scale of 4 (Range-1 to 7)
- Temperature overall in summer- Scale of 4 (Range-1 to 7)
- Comfort overall in winter- Scale of 4,5 (Range-1 to 7)
- Temperature overall in winter- Scale of 4,5(Range-1 to 7)
- The primary purpose of shading is to prevent reflected and direct light.
- All offices relied hugely on artificial lighting- (5-7) and >7 hrs.
- The staff of all three offices was okay with the luminous comfort despite the inadequate daylighting means that people were more accustomed to artificial lighting.

6 Building Energy Modeling

6.1 Preliminary Shoe-box Model

Following research into existing structures, several glazing systems were developed and simulated on computer programs. It was crucial to assess all the test conditions using a straightforward shoebox model with simple operations before conducting tests on a standard-sized model. EnergyPlus and Radiance were both legitimate simulation engines that supported Grasshopper's Ladybug Tools, as was previously mentioned. As a result, the Ladybug Tools were first evaluated with the shoebox model before being applied to the typical office building model. Since the Ladybug Tools could replicate the energy and thermal performance of the EC glazing and other glazing systems, they were used for this investigation.

6.1.1 Create a model of office space with a window

A little area from a floor of an office building was portrayed by the shoebox model. Four external walls with an opening were present. The most effective WWR for various climates, according to research on daylighting, was found to be between 30% and 45% (Sayadi, Hayati, & Salmanzadeh, 2021). Consequently, the model started with a WWR of 45%. The window was on the west façade, so it was easy to see how the light was changing as it passed through the window. The shoebox model measured 12 meters in length, 8 meters in width, and 3.15 meters in height. To control the dynamic glazing of electrochromic windows, a sensor was positioned on the window surface to detect solar irradiance.

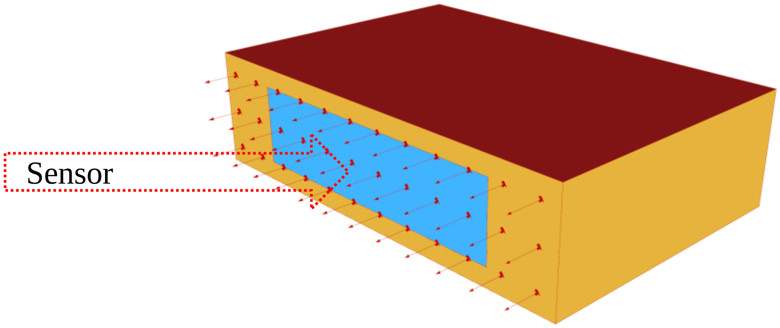


Figure 6-1: Shoe-box model

6.1.2 Simulate Visual, Energy, and Thermal Results

When the VLT of the glass changed, it was anticipated that the hourly illuminance and glare simulation results would alter. Results in daylight should differ noticeably between clear glass and tinted glass due to the VLT. The Ladybug Tools in Grasshopper were used to develop a formula with VLT values changing with the vertical solar irradiation on the window.

Table 30: Details about the shoe-box design

Shoe-Box model		
Dimension	12m*8m*3.15	
WWR	45%	
City	Kathmandu	
Climate	Temperate	
Controller	Solar irradiance on the window surface (sensor)	
EC Clear state	VLT	0.40
	U-value	1.64
	SHGC	0.30
	Setpoint	≥ 0 W/m^2
EC Intermediate State 1	VLT	0.10
	U-value	1.64
	SHGC	0.17
	Setpoint	≥ 10% of the highest solar irradiance of a year
EC Intermediate State 2	VLT	0.07
	U-value	1.64
	SHGC	0.13
	Setpoint	≥ 20% of the highest solar irradiance of a year
EC Fully Tinted	VLT	0.009
	U-value	1.64
	SHGC	0.10
	Setpoint	≥ 30% of the highest solar irradiance of a year

6.2 Scenarios of Simulations

It was crucial to think about what kinds of settings were included in this research because various glazing conditions were compared. It is important to examine and compare the effectiveness of both static and dynamic glazing systems. The underlying premise was that dynamic glazing produced the best overall performance in terms of energy, visual, and thermal comfort. The data for all eight test scenarios of simulation are included in the table.

Table 31: Scenarios for the simulations

Scenario # 1	**Scenario # 2**	**Scenario # 3**	**Scenario # 4**
Single pane - Clear	Single pane - Tinted	Single pane -Thermal insulation (TI) Low-e	Double pane – Clear | Clear
VLT- 0.88 U-value (W/m^2-K): 5.7 SHGC-0.82	VLT- 0.50 U-value (W/m^2-K): 5.7 SHGC-0.60	VLT- 0.67 U-value (W/m^2-K): 3.8 SHGC-0.62	VLT- 0.79 U-value (W/m^2-K): 2.9 SHGC-0.72
Scenario # 5	**Scenario # 6**	**Scenario # 7**	**Scenario # 8**
Double pane – Tinted | Clear	Double pane– Thermal insulation (TI) Low-E | Clear	Double pane – Solar control (SC) Low-E | Thermal insulation (TI) Low-E	Electrochromic (EC) glazing U-value: 1.64 W/m^2-K
VLT- 0.44 U-value (W/m^2-K): 2.7 SHGC-0.48	VLT- 0.73 U-value (W/m^2-K): 1.7 SHGC-0.69	VLT- 0.53 U-value (W/m^2-K)-1.3 SHGC-0.34	Clear State: VLT-0.40; U-value- 1.64; SHGC 0.30 Intermediate state 1: VLT- 0.10; U-value- 1.64; SHGC- 0.17 Intermediate state 2: VLT- 0.07; U-value- 1.64; SHGC- 0.13 Fully Tinted: VLT- 0.009; U-value- 1.64; SHGC- 0.10

6.3 Selecting performance parameters

The effectiveness of each test condition was assessed using a variety of performance indicators, including energy, visual, and thermal factors. A building may not perform as well in terms of other indoor environmental factors if it was just designed to use minimal energy. Reduced WWR, for instance, would result in less solar heat gain and less energy being required for cooling loads. Reduced WWR would decrease daylight, increasing the requirement for electrical illumination and thus raising energy consumption. As a result, the test conditions could only be deemed successful if all of the indicators showed satisfactory performance (Lu, 2022).

6.3.1 Visual Comfort

In terms of daylighting and glare, visual comfort was evaluated as the first performance category.

6.3.1.1 Daylighting

There were no available figures for dynamic glazing's annual sunlight exposure (ASE) or spatial daylight autonomy (sDA). The program found it challenging to handle the electrochromic windows' dynamic states and changes. Therefore, in this study, Useful Daylight Illuminance (UDI) and glare were utilized to evaluate how comfortable different visual environments were.

6.3.2 Glare

The primary parameter for assessing how well each test scenario performed about glare was Daylight Gare Probability (DGP). To illustrate the variations in sky luminance at various times during the day, the "Small Multiple" method was once more applied. The glare was evaluated more harshly in the test condition with the higher average DGP value.

6.3.3 Energy use

On the summer design day—the day with the largest cooling load the HVAC system uses—the peak cooling load was measured. The annual energy use of a structure, including its components for heating, cooling, artificial lighting, and interior equipment, was the focus of a different statistic called Energy Use Intensity (EUI).

6.3.3.1 Peak Cooling Loads

The capacity of various test circumstances to minimize energy during the hottest day of the year was assessed using the peak cooling demand, which was expressed in Watts (W). Due to the EC glazing's ability to block sunlight and reduce solar heat gain, the test conditions should be successful in lowering peak cooling loads. The test condition scoring the highest in cooling was the one with the lowest peak cooling loads.

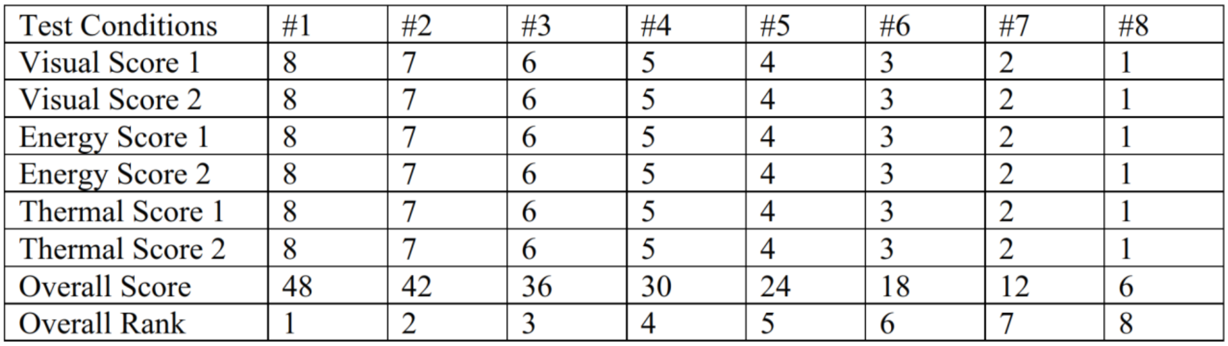
6.3.3.2 EUI

It is also possible to calculate EUI and compare it to benchmarking EUI when the annual loads are known. EUI is presented in kWh/m2. Due to the limitations of simulations, not every component of the EUI could be computed with complete accuracy. For instance, the impact of the glazing on equipment use and occupancy was not considered. The main factor was the annual energy consumption for lighting, heating, and cooling. For all test situations, the simulation program offers a constant level of interior lighting. Because natural light with an illuminance greater than 300 lux can offset the effects of artificial lighting, the daylight harvesting technique was adopted. As a result, the EUI value was decreased by multiplying the quantity of artificial lighting by the typical percentage of regions with illumination greater than 300 lux. Preventing yearly heating EUI from growing too much was just as important as keeping annual cooling EUI from declining, especially for regions where heating was more common since the end goal was to have lower overall energy usage. Ultimately, the efficient test circumstances ought to be able to establish equilibrium and preserve energy. The EUI score was higher when the EUI value was lower.

6.3.4 Performance evaluation method

The most efficient glazing system might be determined based on performance using the scores for, glare, peak cooling, and EUI. There may be variations in how much each category weighs. Energy use and visual comfort were all equally important in this study. One to eight points were assigned to each of the performance metrics speak cooling loads and EUI were included in the energy use, and both of them ranged in score from one to eight. The test condition with the highest individual performance was indicated by the rank of each performance indicator.

Table 32: The Overall Scoring and Ranking Sample (Lu, 2022)



Test Conditions	#1	#2	#3	#4	#5	#6	#7	#8
Visual Score 1	8	7	6	5	4	3	2	1
Visual Score 2	8	7	6	5	4	3	2	1
Energy Score 1	8	7	6	5	4	3	2	1
Energy Score 2	8	7	6	5	4	3	2	1
Thermal Score 1	8	7	6	5	4	3	2	1
Thermal Score 2	8	7	6	5	4	3	2	1
Overall Score	48	42	36	30	24	18	12	6
Overall Rank	1	2	3	4	5	6	7	8

6.4 Simulation results

6.5 Preliminary Shoe-box model

Eight test scenarios were simulated repeatedly. First, the initial test using the shoebox model has been carried out and the data was gathered. The experiment was then conducted using a model of an actual office building. The outcomes were different from those of the shoebox model. The latter, however, was more applicable to actual circumstances. The simulation findings for Useful Daylight Illuminance (UDI), Glare, Peak Cooling Loads, and Energy Use Intensity are presented in this chapter (EUI).

6.5.1 Visual Comfort

6.5.1.1 Daylighting

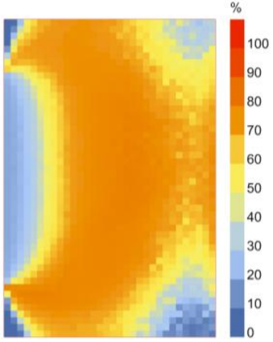
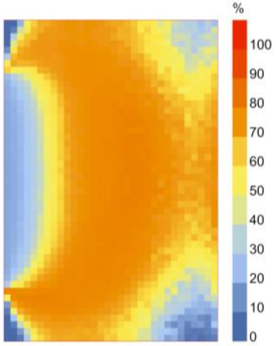
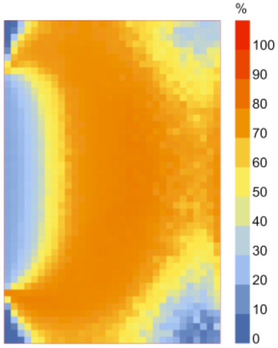
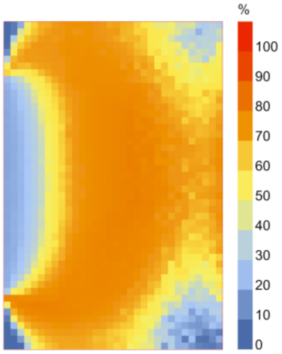
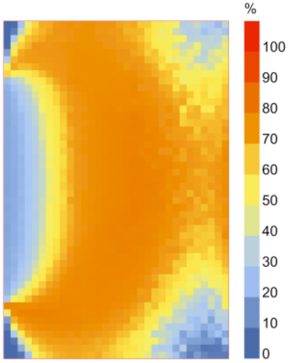
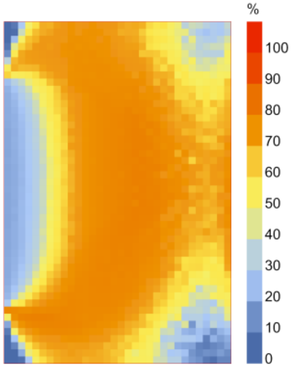
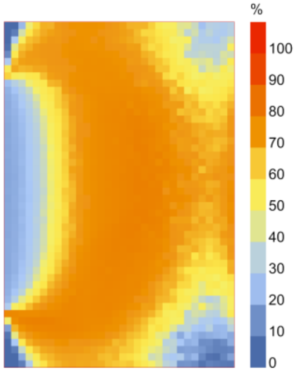
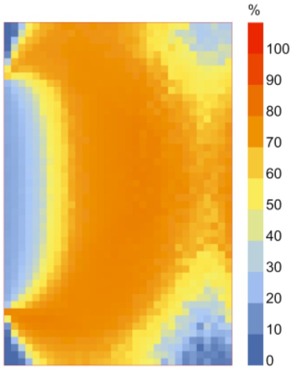
The UDI parameter, developed by (Nabil & Mardaljevic, 2005), takes into account the amounts of absolute daylight illumination based on hourly weather data throughout a complete year. UDI is calculated as a percentage of the time that the sensors' illuminances fall within a band of values that the users deem to be acceptable. A range of 300–3000 lx has been deemed appropriate in prior research studies (based on occupants' preferences and actions). Daylight illuminances of more than 3000 lx are likely to cause visual or thermal discomfort. Daylight illuminances lower than 300 lx are typically regarded as inadequate (Cannavale, Ayr, & Martellota, 2018). Various transmission systems have been proposed as control methods for electrochromic glazing. Tests were conducted on the first performance objective, daylight availability. According to the occupancy schedule of momentary illuminance graphs, annual daylight data on the working surface (1 meter above the floor) has been recorded. The solar irradiance on the window surface regulates EC glazing.

Table 33: Annual UDI distribution in all 8 scenarios

Evaluated Scenario	Low illuminance (<300 lux)	UDI (between 300lux and 3000 lux)	High illuminance (>3000 lux)
Scenario 1: Singe pane-Clear glass	33.75%	56.76%	9.47%
Scenario 2: Single pane-Tinted Glass	33.77%	56.75%	9.47%
Scenario 3: Single pane-Low-e Glass	33.69%	56.81%	9.49%
Scenario 4: Double pane-Clear | Clear	33.71%	56.81%	9.47%

Scenario 5: Double pane-Tinted | Clear	33.71%	56.81%	9.47%
Scenario 6: Double pane-TI Low-e | Clear	33.68%	56.84%	9.47%
Scenario 7: Double pane-SC Low-e | TI Low-e	33.74%	56.76%	9.48%
Scenario 8: EC glazing	43.17%	56.83%	0%

Table 34: Annual UDI of all 8 scenarios

Scenario 1: Singe pane-Clear glass	**Scenario 2: Single pane-Tinted Glass**	**Scenario 3: Single pane-Low-e Glass**	**Scenario 4: Double pane-Clear | Clear**
UDI: 56.76% UDI_low: 33.75% UDI_up: 9.47%  	UDI: 56.75% UDI_low: 33.77% UDI_up: 9.47%  	UDI: 56.81% UDI_low: 33.69% UDI_up: 9.49%  	UDI: 56.81% UDI_low: 33.71% UDI_up: 9.47% 
Scenario 5: Double pane-Tinted | Clear	**Scenario 6: Double pane-TI Low-e | Clear**	**Scenario 7: Double pane-SC Low-e | TI Low-e**	**Scenario 8: EC glazing**
UDI: 56.81% UDI_low: 33.71% UDI_up: 9.47%  	UDI: 56.84% UDI_low: 33.68% UDI_up: 9.47%  	UDI: 56.76% UDI_low: 33.74% UDI_up: 9.48%  	UDI: 56.83% UDI_low: 43.17% UDI_up: 0% 

Values given in Table 35 demonstrate the outcomes of simulating eight distinct daylighting penetration scenarios in the test room to offer a yearly assessment of the UDI level during office hours. What can be seen is that every year, during office hours, all the hypothesized techniques offer remarkably uniform values for daylight penetration. In particular, it is noted that, except for EC glazing, all eight cases had a proportion of hours when the illuminance value fell within the UDI range (between 300 lux and 3000 lux), which ranged from 57% for all eight cases. In each of the seven circumstances, the high UDI above 3000 lux was around 10%, and the low UDI below 300 lux was around 34%. The performance of the irradiance-based method for EC glazing indicated high percentages of dimly lit hours of 43.17%, and only one scenario with 0% high illuminance.

6.5.1.2 Glare

Indicators of visual comfort and building performance were significantly influenced by the glare. The luminance of the sky is depicted in the fisheye diagram facing the window. From 7 am to 6 pm on the day of the fall equinox, "Small Multiples" of sky brightness were graphed hourly. A candela per square meter (cd/m2) scale from 0 to 3000 was used. Additionally, a Daylight Glare Probability (DGP) was recorded for the simulation, indicating whether or not the glare was perceptible or tolerable. The performance of the eight test conditions was ranked using DGP, which served as the experiment's glare indicator.

6.5.1.2.1 Scenario #1: Single pane – Clear glass

The first scenario had the most severe glare impact because it just had one clear glass window. The shoebox model's window was on the west façade, thus the sky brightness was only low in the morning, higher in the midday, and then lower in the evening. Between 9 am and 6 pm, the sky's brightness increased and DGP peaked. There was imperceptible glare from 7 to 8 in the morning. The glare grew intolerable from 9 am to 6 pm for the remainder of the day. It was clear from the simulation findings that unique glazing solutions were required to lessen glare and enhance visual comfort.

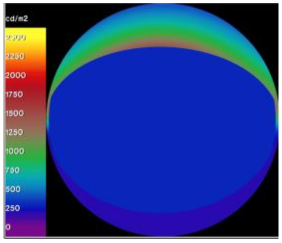
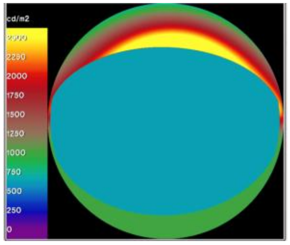
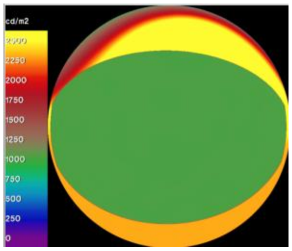
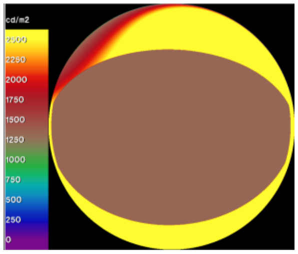
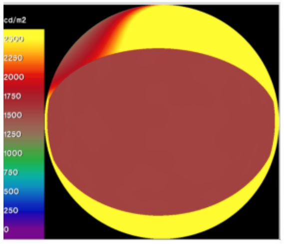
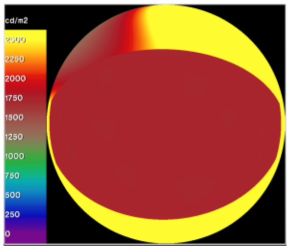
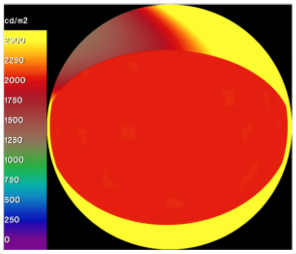
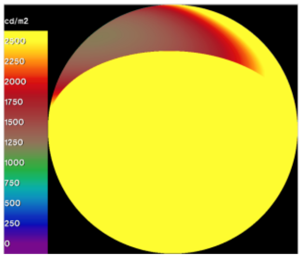
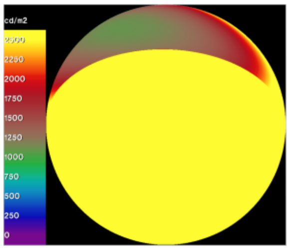
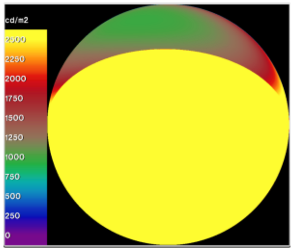
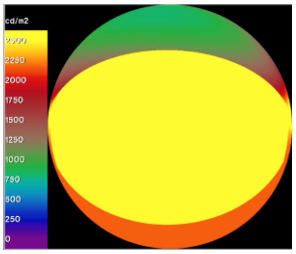
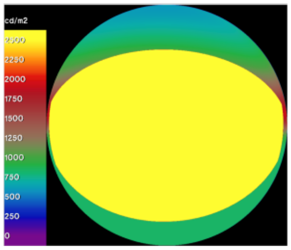
DGP: 0.228 Imperceptible Glare  	DGP: 0.322 Imperceptible Glare  	DGP: 0.477 Intolerable Glare  	DGP: 1 Intolerable Glare 
7 am	8 am	9 am	10 am
DGP: 1 Intolerable Glare  	DGP: 1 Intolerable Glare  	DGP: 0.651 Intolerable Glare  	DGP: 1 Intolerable Glare 
11 am	12 pm	1 pm	2 pm
DGP: 1 Intolerable Glare  	DGP: 1 Intolerable Glare  	DGP: 1 Intolerable Glare  	DGP: 1 Intolerable Glare 
3 pm	4 pm	5 pm	6 pm

Figure 6-2: Sky Luminance and DGP of Scenario # 1

6.5.1.2.2 Scenario #2: Single pane – Tinted glass

The tinted single glass in the second scenario had a VLT and SHGC of 0.50 and 0.60, respectively. The sky became more bright between 7 and 8 in the morning, DGP peaked, and the glare became intolerable immediately away. From nine to ten in the morning there was a disturbing glare. Between 11 am and noon, the glare became perceptible. From 12 p.m. until 6 p.m., the glare was imperceptible. The simulation results showed that scenario #2 caused less glare annoyance than clear glass.

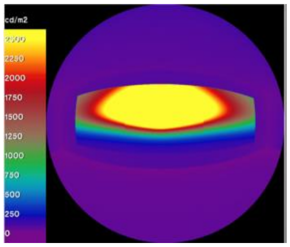
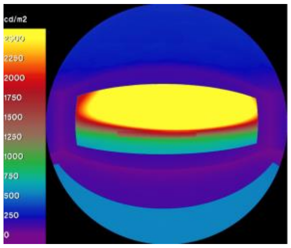
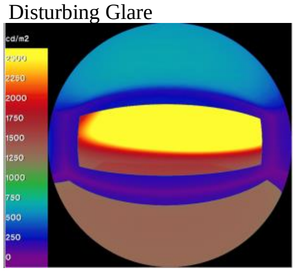
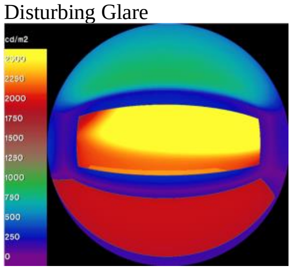
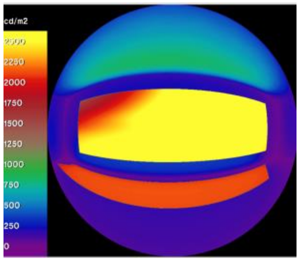
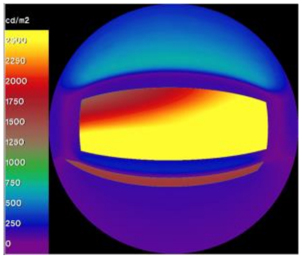
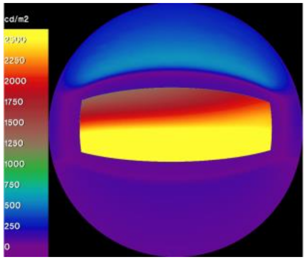
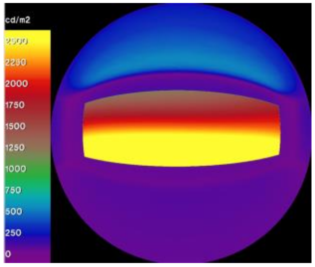
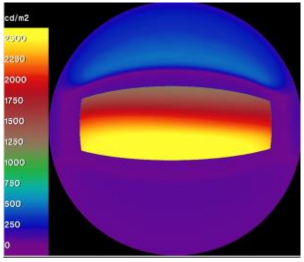
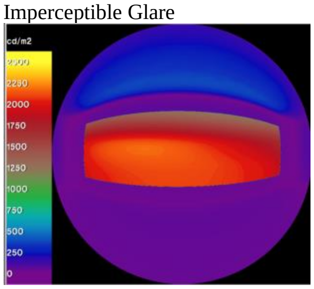
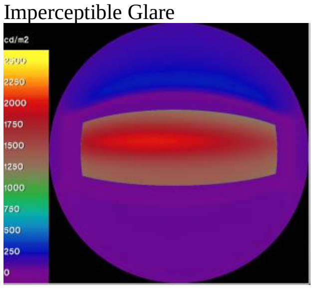
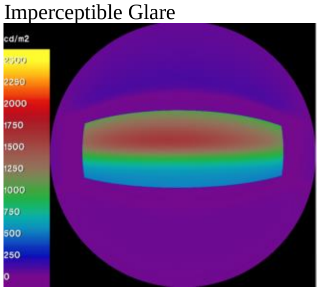
DGP: 1 Intolerable Glare 	DGP: 1 Intolerable Glare 	DGP: 0.444 Disturbing Glare 	DGP: 0.449 Disturbing Glare 
7 am	8 am	9 am	10 am
DGP: 0.397 Perceptible Glare 	DGP: 0.354 Perceptible Glare 	DGP: 0.336 Imperceptible Glare 	DGP: 0.3277 Imperceptible Glare 
11 am	12 pm	1 pm	2 pm
DGP: 0.317 Imperceptible Glare 	DGP: 0.297 Imperceptible Glare 	DGP: 0.244 Imperceptible Glare 	DGP: 0.211 Imperceptible Glare 
3 pm	4 pm	5 pm	6 pm

Figure 6-3: Sky Luminance and DGP of Scenario # 2

6.5.1.3 Scenario #3: Thermal Insulation (TI) Low-e glass

In the third scenario, the thermally insulated (TI) single Low-e glass had a VLT and SHGC of 0.67 and 0.62, respectively. From seven in the morning until eight in the evening, the glare was barely noticeable. Surprisingly, the glare was as intolerable from nine in the morning until six in the evening.

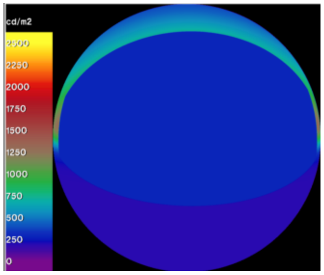
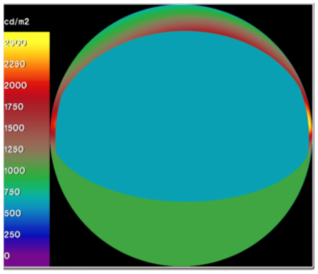
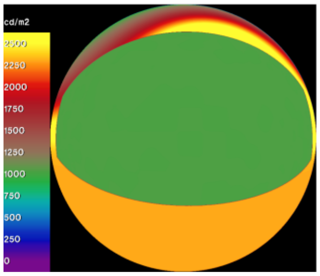
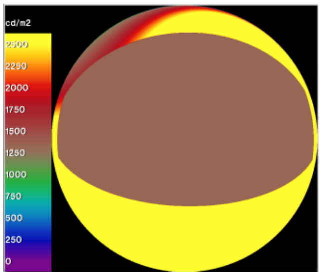
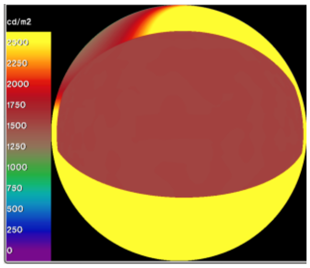
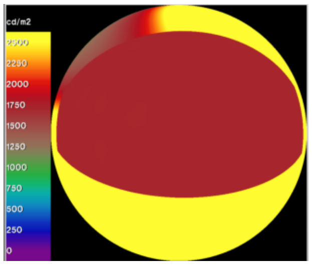
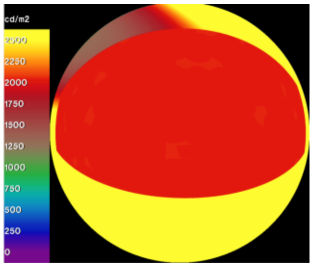
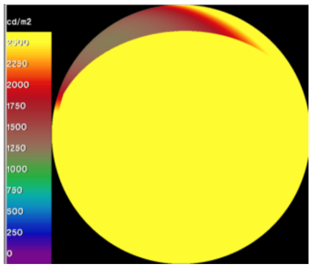
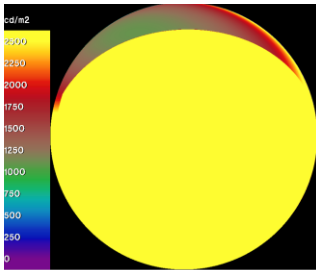
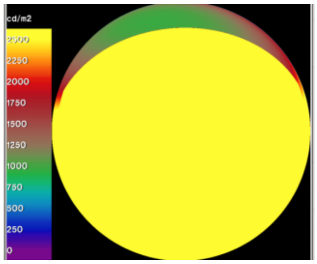
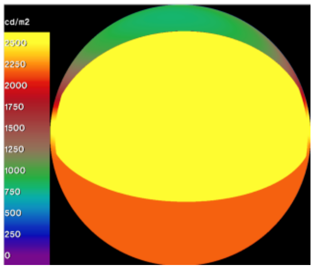
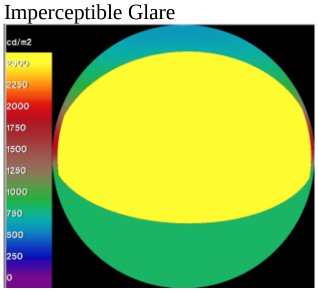
DGP: 0.213 Imperceptible Glare 	DGP: 0.303 Imperceptible Glare 	DGP: 0.452 Intolerable Glare 	DGP: 0.564 Intolerable Glare 
7 am	8 am	9 am	10 am
DGP:1 Intolerable Glare 	DGP: 1 Intolerable Glare 	DGP: 0.722 Intolerable Glare 	DGP: 1 Intolerable Glare 
11 am	12 pm	1 pm	2 pm
DGP: 1 Intolerable Glare 	DGP: 1 Intolerable Glare 	DGP: 1 Intolerable Glare 	DGP: 0.211 Imperceptible Glare 
3 pm	4 pm	5 pm	6 pm

Figure 6-4: Sky Luminance and DGP of Scenario # 3

6.5.1.4 Scenario #4: Double pane: Clear | Clear glass

In the fourth scenario, the double pane of two clear glasses with a 10 mm air cavity had a VLT and SHGC of 0.79 and 0.72, respectively with a U value of 2.9 W/m^2-K. From seven to eight in the morning there was intolerable glare. From 9 to 10 am it decreased to disturbing and further decreased to perceptible glare at 11 am. From noon to 6 pm there was imperceptible glare.

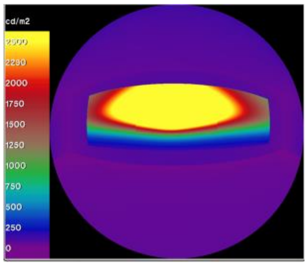
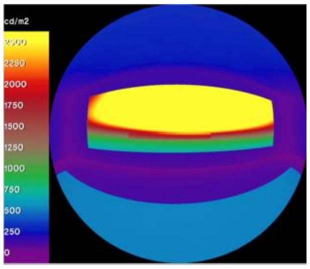
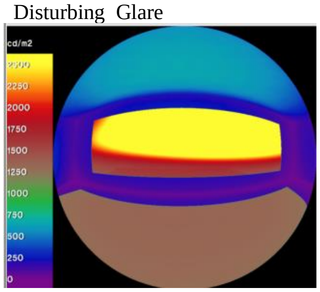
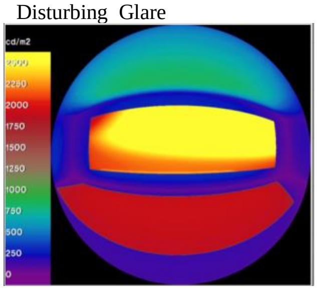
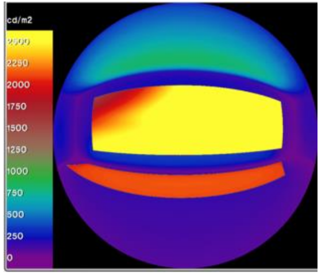
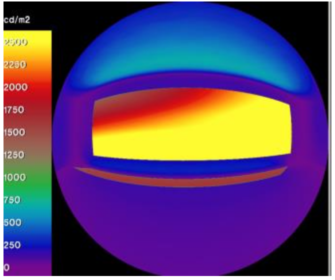
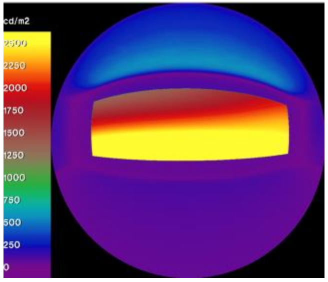
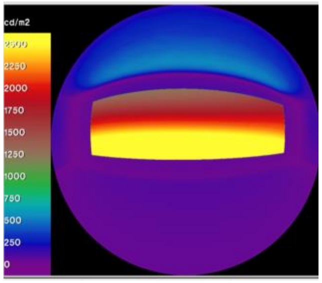
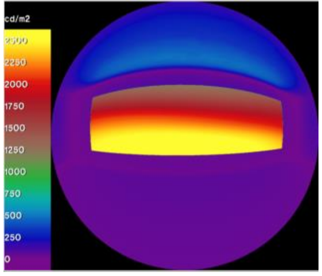
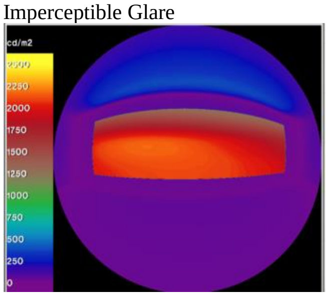
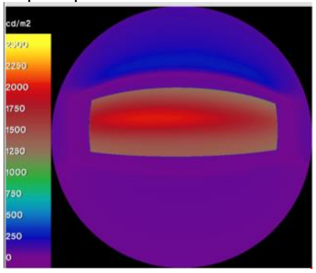
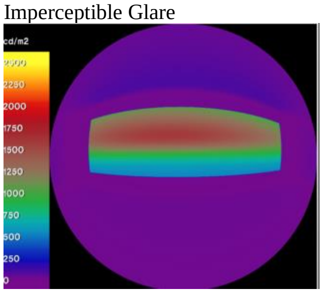
DGP: 1 Intolerable Glare 	DGP:1 Intolerable Glare 	DGP: 0.438 Disturbing Glare 	DGP: 0.432 Disturbing Glare 
7 am	8 am	9 am	10 am
DGP:0.370 Perceptible Glare 	DGP: 0.332 Imperceptible Glare 	DGP: 0.3192 Imperceptible Glare 	DGP: 0.314 Imperceptible Glare 
11 am	12 pm	1 pm	2 pm
DGP: 0.305 Imperceptible Glare 	DGP: 0.289 Imperceptible Glare 	DGP: 0.235 Imperceptible Glare 	DGP: 0.207 Imperceptible Glare 
3 pm	4 pm	5 pm	6 pm

Figure 6-5: Sky Luminance and DGP of Scenario # 4

6.5.1.5 Scenario #5: Double pane: Tinted | Clear glass

In the fifth scenario, the double pane of tinted glass on the outside and clear glass on the inside with a 10 mm air cavity had a VLT and SHGC of 0.44 and 0.48, respectively with a U value of 2.7 W/m2-K. From seven to eight in the morning there was intolerable glare. From 9 to 10 am it decreased to disturbing and further decreased to perceptible glare at 11 am. From noon to 6 pm there was imperceptible glare. Glare occurrence is similar to scenario #5.

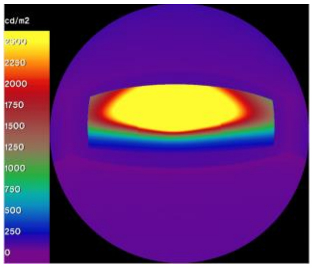
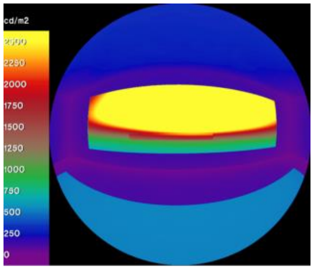
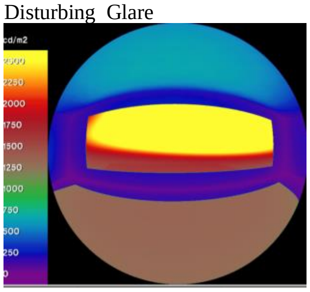
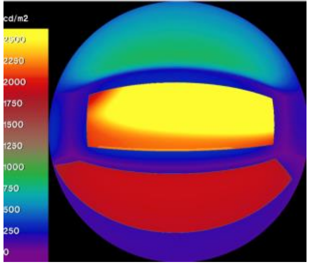
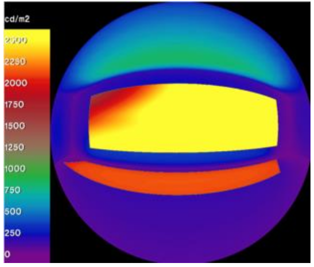
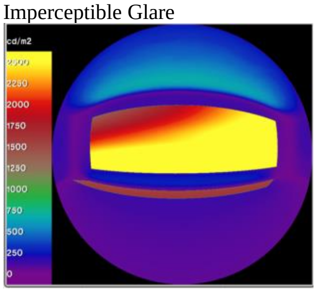
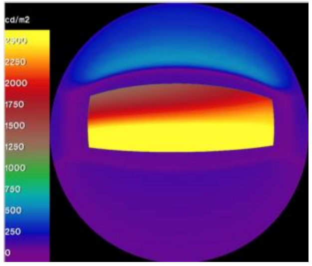
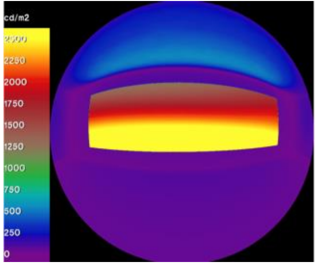
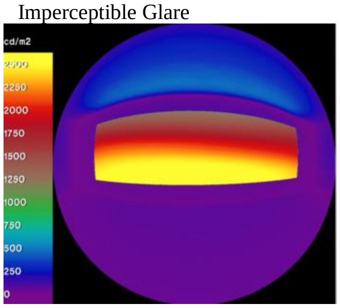
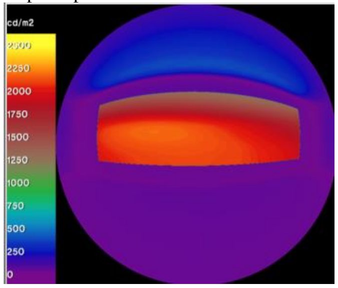
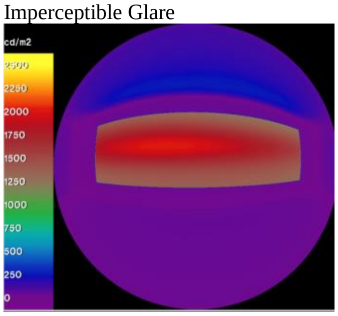
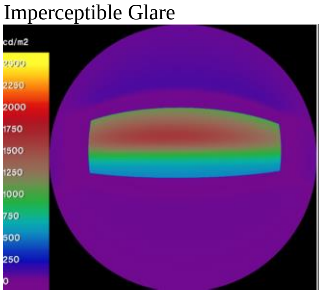
DGP: 1 Intolerable Glare 	DGP: 1 Intolerable Glare 	DGP: 0.438 Disturbing Glare 	DGP: 0.423 Disturbing Glare 
7 am	8 am	9 am	10 am
DGP:0.370 Perceptible Glare 	DGP:0.322 Imperceptible Glare 	DGP: 0.319 Imperceptible Glare 	DGP: 0.314 Imperceptible Glare 
11 am	12 pm	1 pm	2 pm
DGP: 0.305 Imperceptible Glare 	DGP: 0.289 Imperceptible Glare 	DGP: 0.235 Imperceptible Glare 	DGP: 0.207 Imperceptible Glare 
3 pm	4 pm	5 pm	6 pm

Figure 6-6: Sky Luminance and DGP of Scenario # 5

6.5.1.6 Scenario #6: Double pane: Thermal Insulation (TI) Low-E | Clear glass

In the sixth scenario, the double pane of thermally insulated Low-E glass on the outside and clear glass on the inside with a 10 mm air cavity had a VLT and SHGC of 0.73 and 0.61, respectively with a U value of 1.7 W/m2-K. At seven in the morning, there was intolerable glare but at 8 am the glare was again imperceptible and then it turned to perceptible glare at 9 am. Then from 10 am onwards, the glare was imperceptible throughout the day.

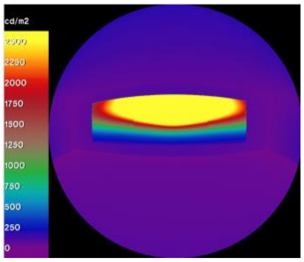
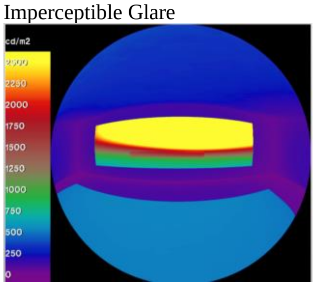
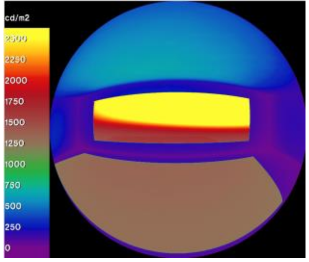
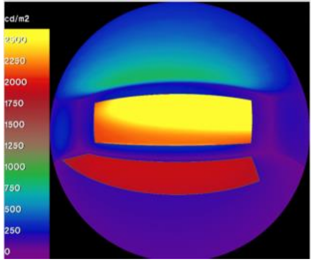
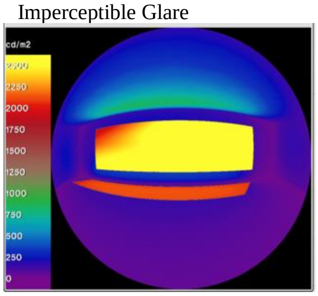
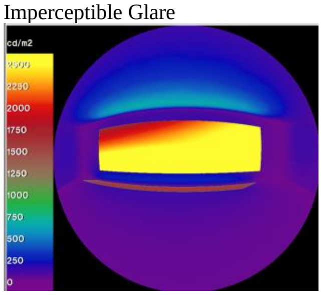
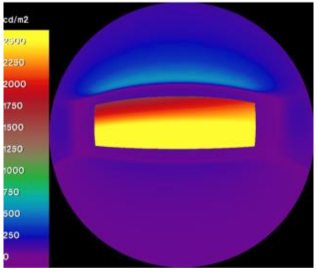
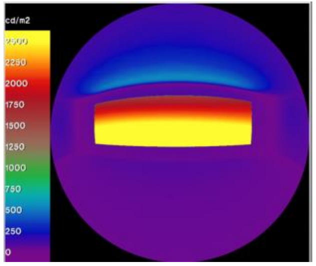
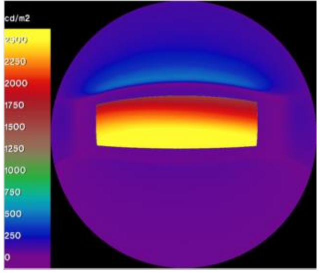
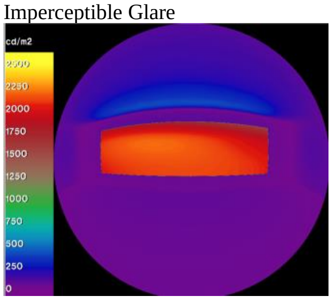
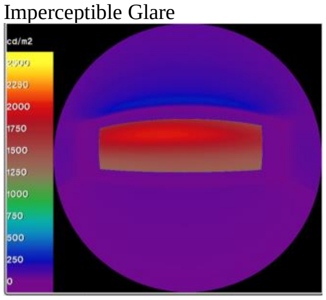
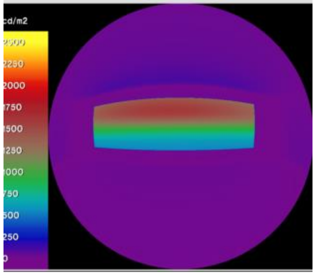
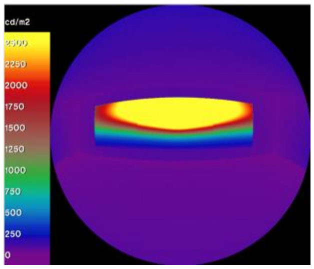
DGP: 1 Intolerable Glare 	DGP: 0.342 Imperceptible Glare 	DGP: 0.399 Perceptible Glare 	DGP: 0.342 Imperceptible Glare 
7 am	8 am	9 am	10 am
DGP:0.326 Imperceptible Glare 	DGP:0.302 Imperceptible Glare 	DGP: 0.296 Imperceptible Glare 	DGP: 0.292 Imperceptible Glare 
11 am	12 pm	1 pm	2 pm
DGP: 0.286 Imperceptible Glare 	DGP: 0.275 Imperceptible Glare 	DGP: 0.214 Imperceptible Glare 	DGP: 0.192 Imperceptible Glare 
3 pm	4 pm	5 pm	6 pm

Figure 6-7: Sky Luminance and DGP of Scenario # 6

6.5.1.7 Scenario #7: Double pane: Solar Control (SC) Low-E | TI Low-e glass

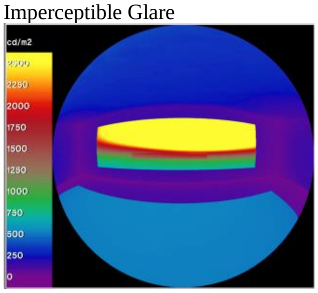
The double pane of solar control Low-E glass on the outside and thermally insulated Low-E glass on the interior of the seventh scenario had a U value of 1.3 W/m2-K, a VLT, and SHGC of 0.53 and 0.34, respectively. At seven in the morning, the glare was awful, but at eight it was once more imperceptible, and at nine it became perceptible. The glare was then undetectable all day starting at 10 a.m. Similar to Scenario 6, there is discomfort from the glare.

DGP: 1
Intolerable Glare



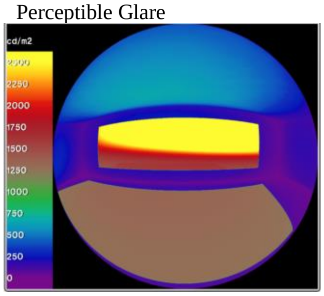
7 am

DGP: 0.342
Imperceptible Glare



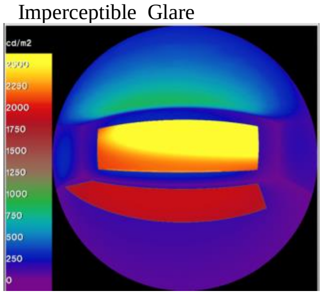
8 am

DGP: 0.379
Perceptible Glare



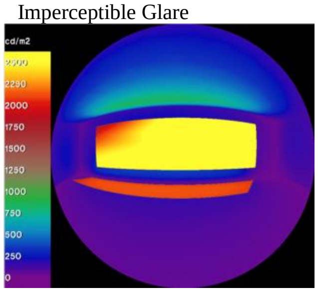
9 am

DGP: 0.342
Imperceptible Glare



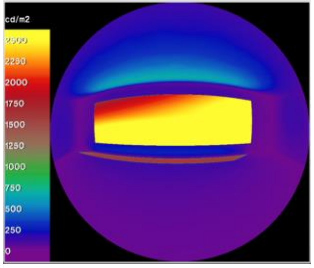
10 am

DGP:0.326
Imperceptible Glare



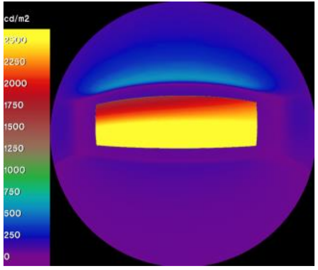
11 am

DGP:0.302
Imperceptible Glare



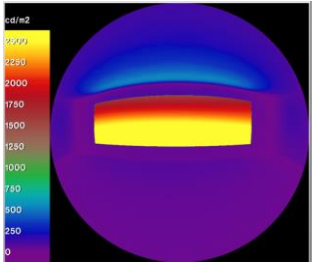
12 pm

DGP: 0.296
Imperceptible Glare



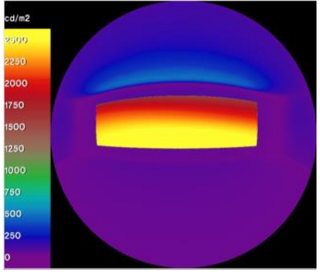
1 pm

DGP: 0.292
Imperceptible Glare



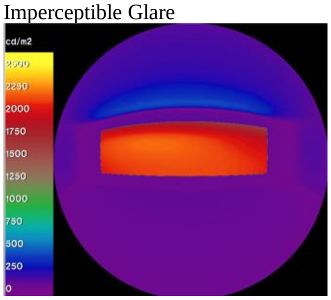
2 pm

DGP: 0.286
Imperceptible Glare



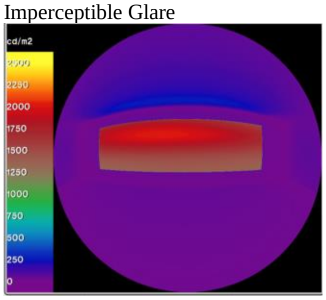
3 pm

DGP: 0.275
Imperceptible Glare



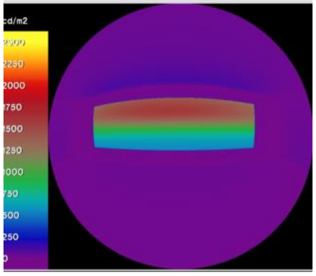
4 pm

DGP: 0.214
Imperceptible Glare



5 pm

DGP: 0.192
Imperceptible Glare

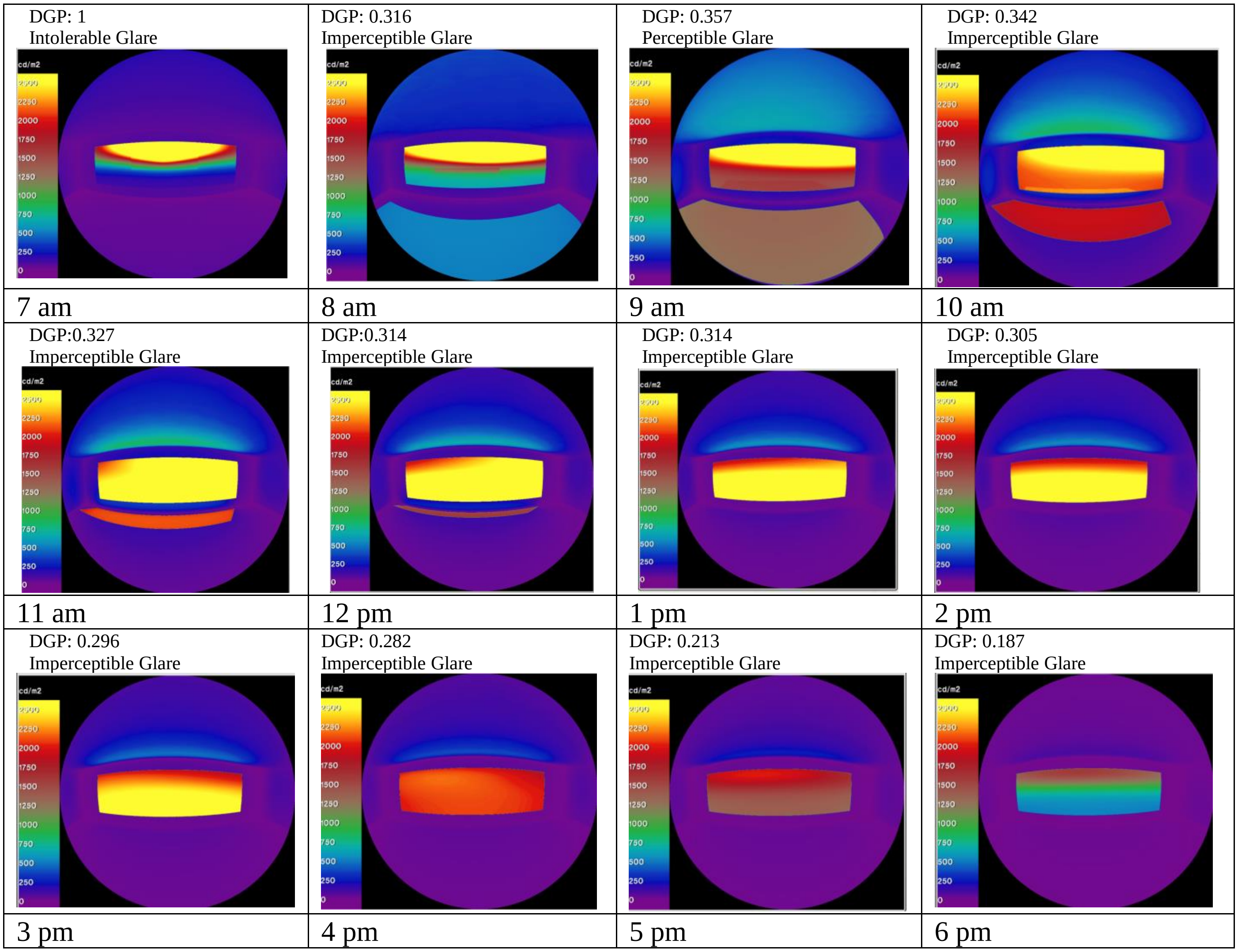


6 pm

Figure 6-8: Sky Luminance and DGP of Scenario # 7

6.5.1.8 Scenario #8: Electrochromic (EC) Glazing

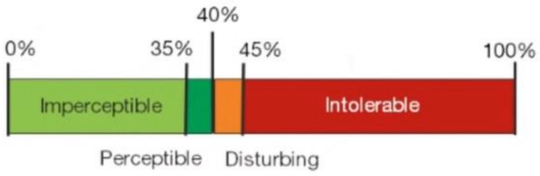
EC glazing was the last test condition. When the window's incident solar irradiation was high, the EC glazing became colored. As a result, the afternoon sky brightness was low, especially between 4 and 5 pm. Sky brightness, however, was just one element of DGP. DGP was imperceptible from 7 to 8 am; it subsequently began to become perceptible at 9 am. The EC glazing shifted from its tinted state and made the glare imperceptible between midday and two o'clock instead of perceptible or intolerable until eleven in the morning. The glare became unpleasant between 3 and 5 pm and finally became unnoticeable at 6 pm.



DGP: 1 Intolerable Glare	DGP: 0.316 Imperceptible Glare	DGP: 0.357 Perceptible Glare	DGP: 0.342 Imperceptible Glare
7 am	8 am	9 am	10 am
DGP:0.327 Imperceptible Glare	DGP:0.314 Imperceptible Glare	DGP: 0.314 Imperceptible Glare	DGP: 0.305 Imperceptible Glare
11 am	12 pm	1 pm	2 pm
DGP: 0.296 Imperceptible Glare	DGP: 0.282 Imperceptible Glare	DGP: 0.213 Imperceptible Glare	DGP: 0.187 Imperceptible Glare
3 pm	4 pm	5 pm	6 pm

Figure 6-9: Sky Luminance and DGP of Scenario # 8

6.6 Comparative Analysis: Daylight Glare Probability (DGP)



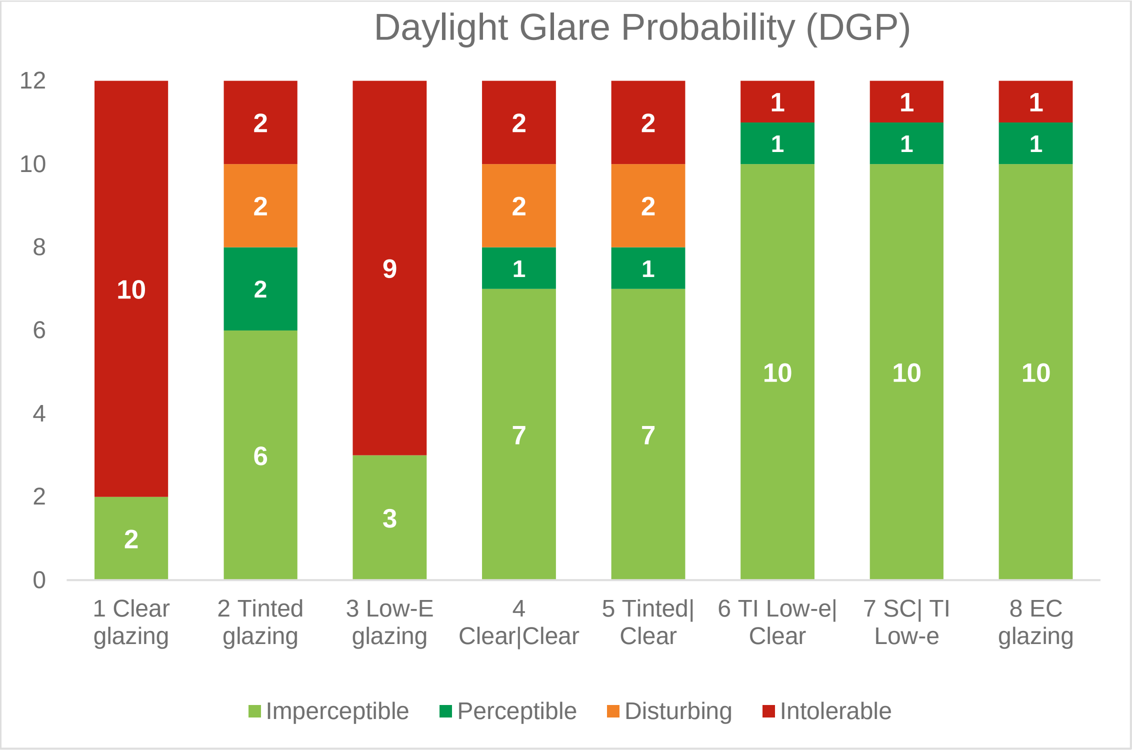


Figure 6-10: Comparative analysis of DGP levels of all 8 scenarios

It can be observed that Scenario # 1 of clear glazing has the worst DGP levels which were quite predictable because of a higher percentage of visible light transmittance. Double-glazed windows have better DGP levels than single-pane windows. Scenarios # 6, 7, and 8 have the best DGP levels and have maximum hours of imperceptible glare.

6.6.1 Energy use

6.6.1.1 Peak Cooling Load

Peak cooling loads were determined by measuring the peak mechanical cooling loads on the summer design day, which in this experiment was June 21. There were non-operable windows and HVAC systems in the space. This section documents and discusses all information on cooling loads for the day and their peak. Watts served as the peak cooling load unit (W).

6.6.1.1.1 Scenario #1: Single pane – Clear glass

13409.46 Watts were required for maximum cooling in scenario 1. The time on June 21st was displayed on the x-axis. At 4:00 p.m., the cooling loads peaked. Cooling loads significantly decreased in the morning and the evening. Given that test condition #1 lacked any specific glazing system to reduce the amount of solar heat entering the space, it ought to have the highest value of all the test conditions. The peak loads' load balance reveals that opaque conduction, followed by solar heat gain, was the primary cause of the majority of the peak loads.

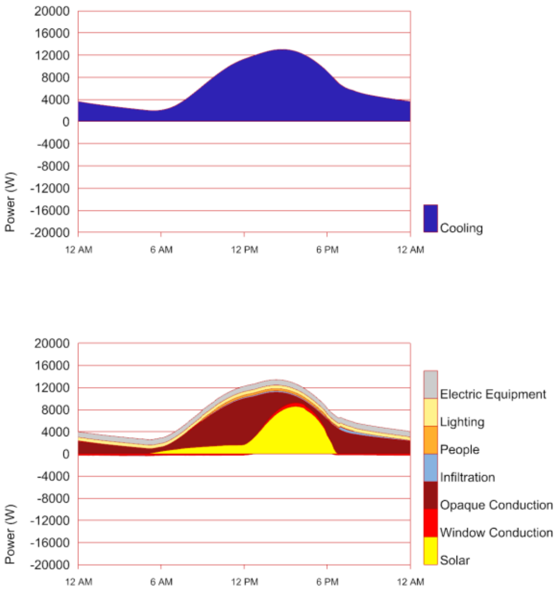


Figure 6-11: Cooling peak loads in Scenario #1

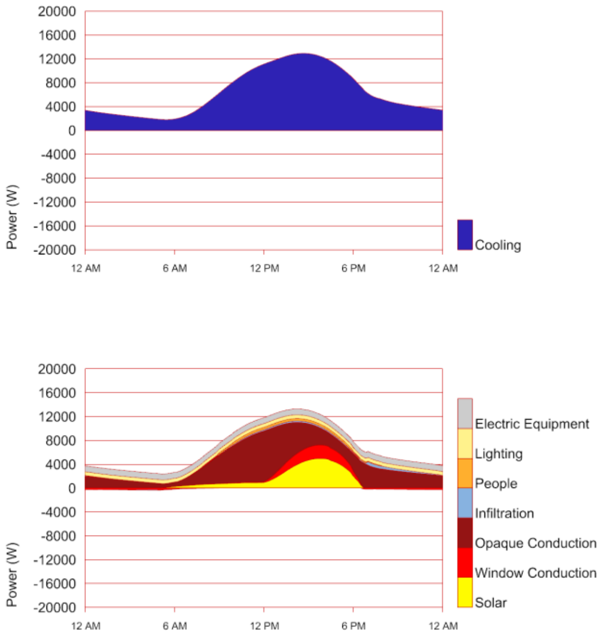


Figure 6-12: Cooling peak loads of Scenario # 2

6.6.1.1.2 Scenario #2: Single pane – Tinted glass

Maximum cooling in case 2 required 12928.061 Watts. On the x-axis, the time on June 21st was shown. The cooling loads peaked around 3:00 pm. Both in the morning and the evening, cooling loads significantly decreased. Test condition #2 should have the lower value of the preceding clear glass scenario since it includes a tinted glazing system to lessen the quantity of solar heat entering the space. According to the load balance of the peak loads, solar heat uptake and opaque conduction were the main causes of most of the peak loads. Window conduction can be seen happening between noon and dusk.

6.6.1.1.3 Scenario #3: Thermal Insulation (TI) Low-e glass

Case 3 required 12671.98 Watts of maximum cooling. The time on June 21st was displayed on the x-axis. Around 3:00 pm, the cooling loads reached their height. Cooling loads significantly decreased in the morning and the evening. Due to the low emissivity coatings on the glass, which significantly reduce the glass's U-value, test condition #3 should consume less energy. Solar heat absorption and opaque conduction were the primary causes of the majority of the peak loads, according to the load balance of the peak loads. Compared to Scenario #2, window conduction is marginally reduced.

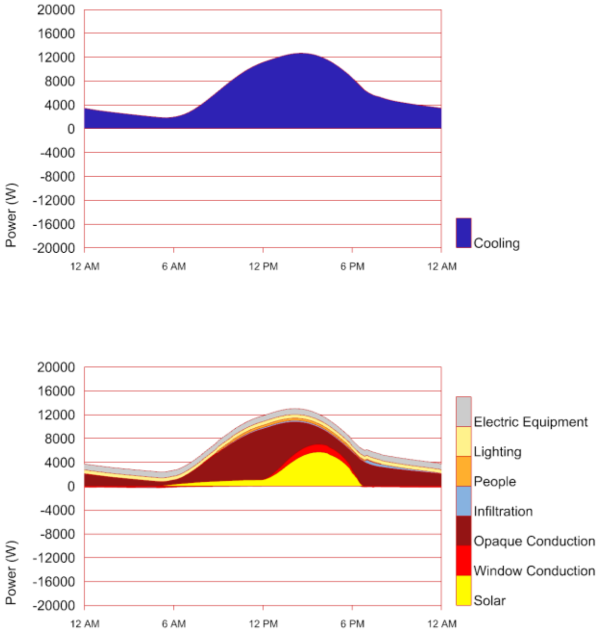


Figure 6-13: Cooling peak loads of Scenario #3

6.6.1.1.4 Scenario #4: Double pane: Clear | Clear glass

12775.54 Watts of maximum cooling were required for Case 4. On the x-axis, the time on June 21st was shown. The cooling loads peaked at about three o'clock in the afternoon. Both in the morning and the evening, cooling loads significantly decreased. There was a small increase in cooling peak loads as a result of the double glazing of two transparent glasses. According to the load balance of the peak loads in earlier instances, solar heat absorption and opaque conduction were the main causes of the majority of the peak loads.

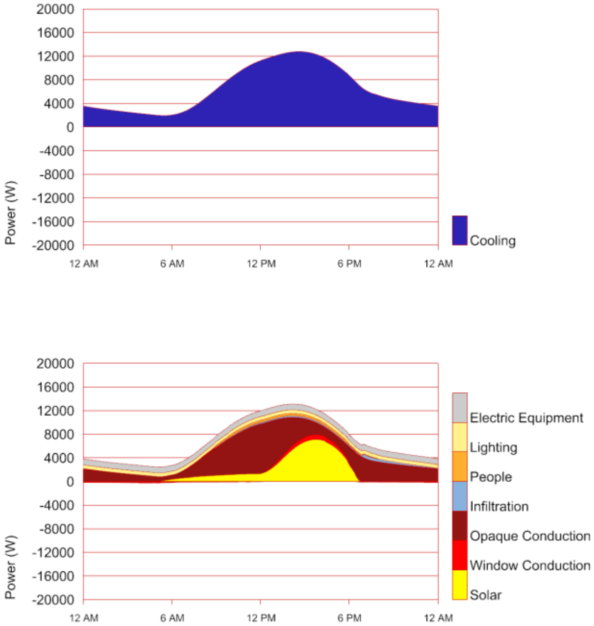


Figure 6-14: Cooling peak loads of Scenario #4

6.6.1.1.5 Scenario #5: Double pane: Tinted | Clear glass

12344.045 Watts of maximum cooling were required for Case 5. On the x-axis, the time on June 21st was shown. The cooling loads peaked at about three o'clock in the afternoon. Both in the morning and the evening, cooling loads significantly decreased. There was a considerable decrease in cooling peak loads in this scenario as compared to the previous double-glazing one.

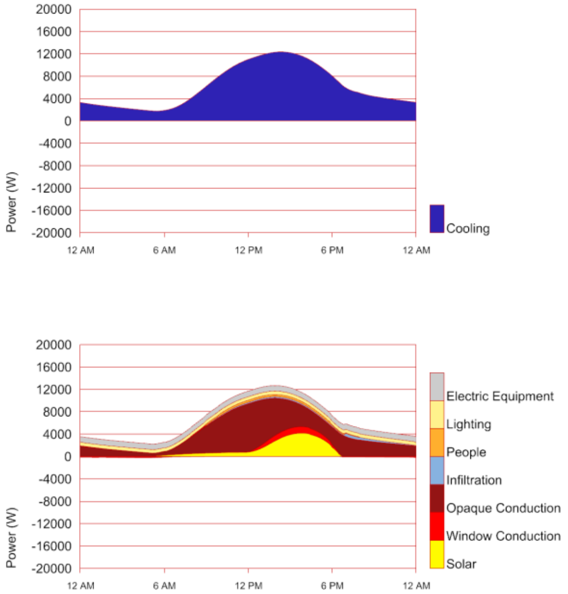


Figure 6-15: Cooling peak loads of Scenario #5

6.6.1.1.6 Scenario #6: Double pane: Thermal Insulation (TI) Low-E | Clear glass

The maximum cooling needed for Case 6 was 12742.42 (Watts), which was more than was needed for scenario 5. The time on June 21st was displayed on the x-axis. At about three o'clock in the afternoon, the cooling loads reached their height. Cooling loads significantly decreased in the morning and the evening. The solar heat has been trapped inside the room or space as evidenced by the rise in cooling peak loads.

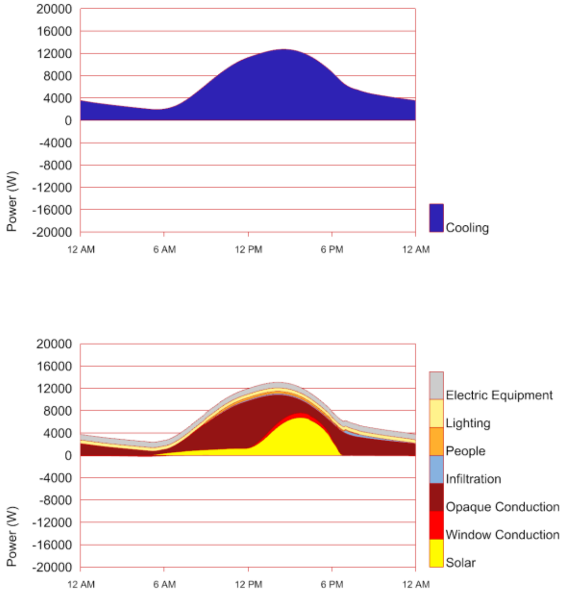


Figure 6-16: Cooling peak loads of Scenario #6

6.6.1.1.7 Scenario #7: Double pane: Solar Control (SC) Low-E | TI Low-e Glass

The maximum cooling needed for Case 7 was 12075.42 (Watts), which was less than all the previous scenarios. The time on June 21st was displayed on the x-axis. At about three o'clock in the afternoon, the cooling loads reached their height. Cooling loads significantly decreased in the morning and the evening. A slight increase in solar heat gain can be seen in the chart.

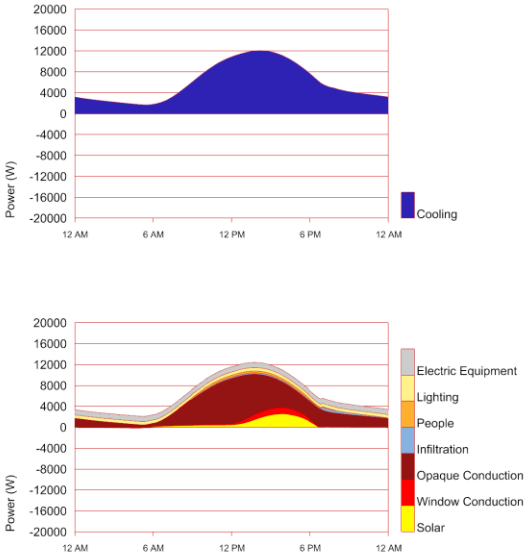


Figure 6-17: cooling peak loads of Scenario #7

6.6.1.1.8 Scenario #8: Electrochromic (EC) Glazing

The maximum cooling needed for Case 8 was 11520 (Watts), which was less than all seven previous scenarios. The dynamic state changes of EC glazing allow it to manage solar heat gain into the building. EC glazing provides an excellent reduction in cooling loads which solves almost half of the HVAC requirements in a particular space/room. As we can see from the chart below is the reduction of cooling loads and in the graph, we can see that there is a significant amount of cut-off from the solar heat gain

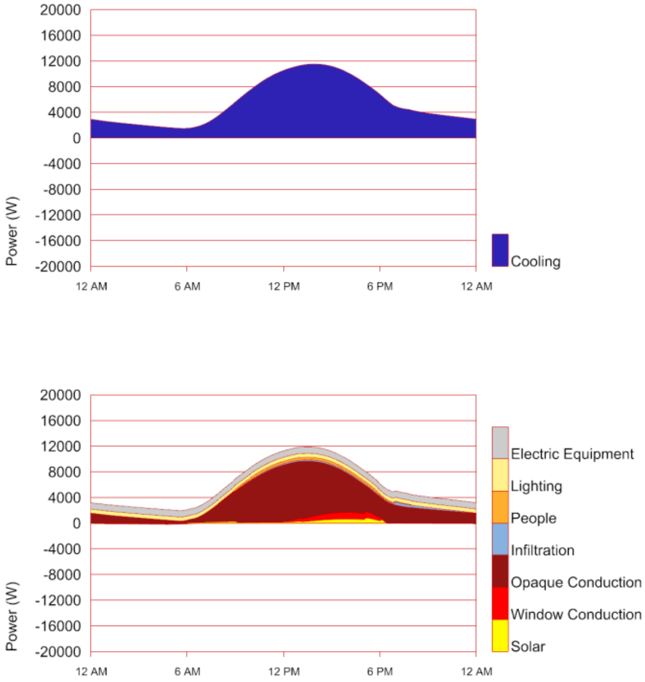


Figure 6-18: Peak cooling loads of EC glazing

6.6.1.2 Energy Use Intensity (EUI)

Another metric used to evaluate the efficiency of energy use was energy use intensity (EUI). It considered more variables. Even if the building were situated in a city with a warm climate, the dynamic glazing systems would raise heating loads even as they screen solar heat and minimize cooling loads.

6.6.1.2.1 Scenario #1: Single pane – Clear glass

Only one clear glazing was present in scenario #1. It was the test condition that accepted the most solar heat without particular glazing solutions. The least amount of energy should be used for heating it each year, but the most for cooling. The total EUI value of the first test condition was 215.25 kWh/m^2.

Table 35: EUI Breakdowns of Scenario #1

Heating (kWh/m^2)	Cooling (kWh/m^2)	Interior Lighting (kWh/m^2)	Interior Equipments (kWh/m^2)	Total EUI (kWh/m^2)
34.71	119.97	19.76	40.79	215.25

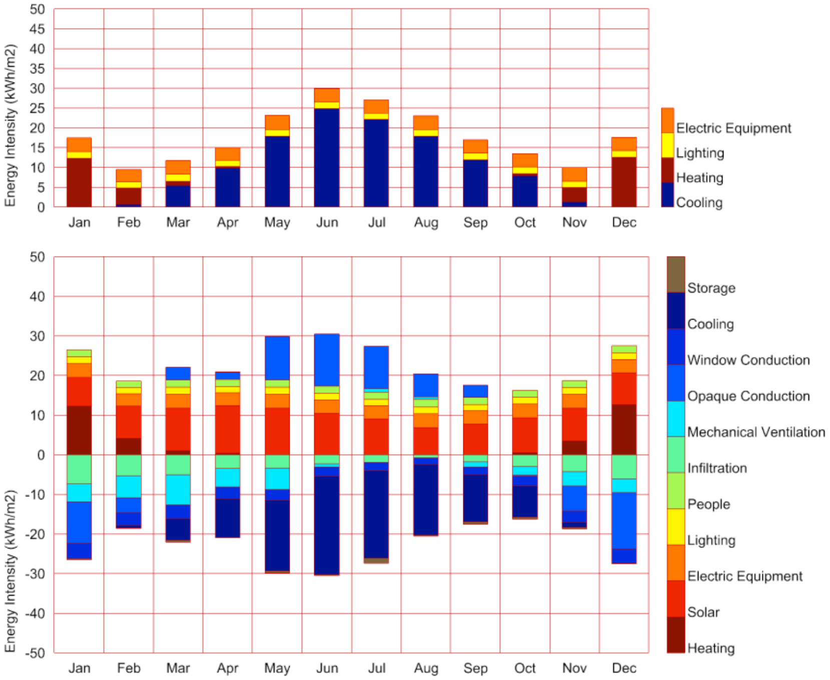


Figure 6-19: Annual Loads Breakdown of Scenario #1

6.6.1.2.2 Scenario #2: Single pane - Tinted glass

Only one tinted glazing was present in scenario #2. It was the test condition that had less VLT and SHGC than the clear glass. The amount of energy for cooling seems to have decreased with a slight increase in heating loads. The total EUI value of the second test condition was 214.127 kWh/m^2.

Table 36: EUI Breakdowns of Scenario #2

Heating (kWh/m^2)	Cooling (kWh/m^2)	Interior Lighting (kWh/m^2)	Interior Equipments (kWh/m^2)	Total EUI (kWh/m^2)
36.89	116.67	19.76	40.79	214.12

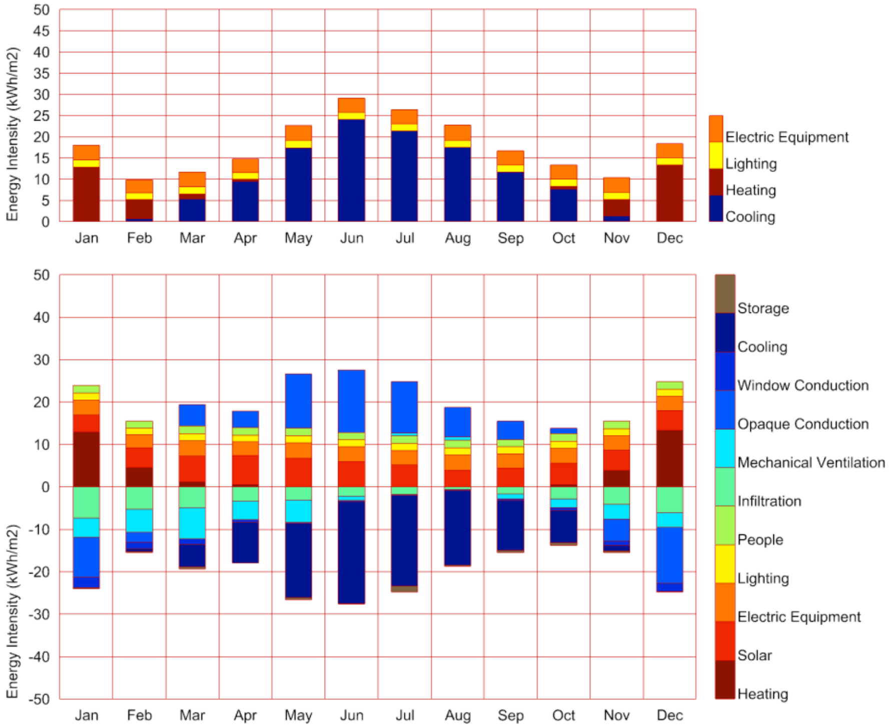


Figure 6-20: Annual Loads Breakdown of Scenario #2

6.6.1.2.3 Scenario #3: Thermal Insulation (TI) Low-e glass

The third scenario had a single pane of thermally insulated Low-e glass. It was the test condition where the glass had a special coating with low emissivity. There is a slight decrease in heating loads but almost no change in cooling loads. The total EUI value of the third test condition was 212.60 kWh/m^2.

Table 37: EUI Breakdowns of Scenario #3

Heating (kWh/m^2)	Cooling (kWh/m^2)	Interior Lighting (kWh/m^2)	Interior Equipments (kWh/m^2)	Total EUI (kWh/m^2)
35.50	116.53	19.76	40.79	212.60

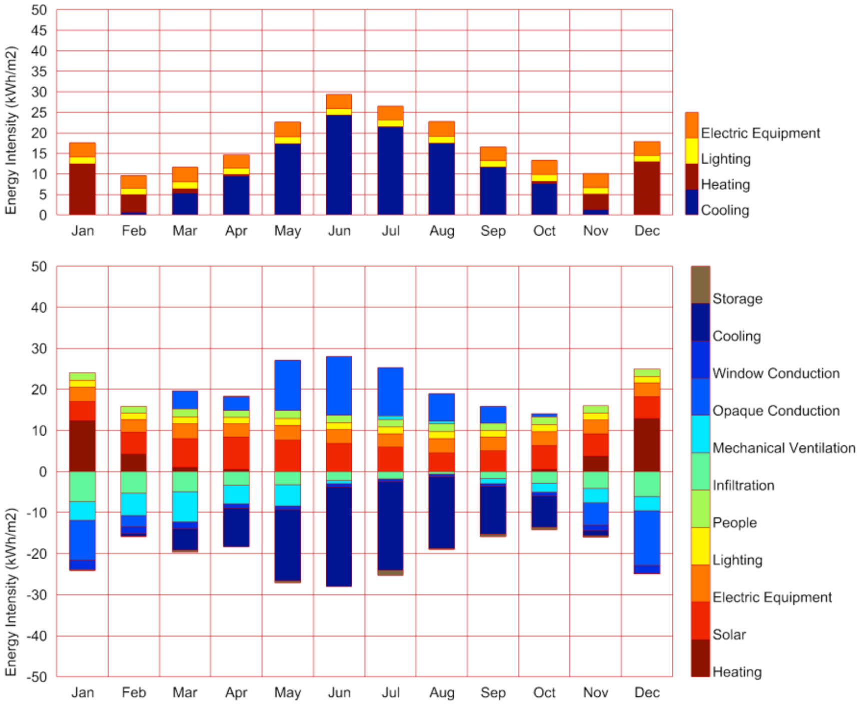


Figure 6-21: Annual Loads Breakdown of Scenario #3

6.6.1.2.4 Scenario #4: Double pane: Clear | Clear glass

The fourth scenario glazing is of a double pane of both clear glasses inside and outside with a 10 mm air cavity in the middle. Double-glazing windows are emerging as energy-efficient windows. However, there is a slight rise in cooling but a decrease in heating loads than the previous scenario of single TI Low-e glass. The total EUI value of the fourth test condition was 213.25 kWh/m2.

Table 38: EUI Breakdowns of Scenario #4

Heating (kWh/m^2)	Cooling (kWh/m^2)	Interior Lighting (kWh/m^2)	Interior Equipments (kWh/m^2)	Total EUI (kWh/m^2)
33.77	118.92	19.76	40.79	213.25

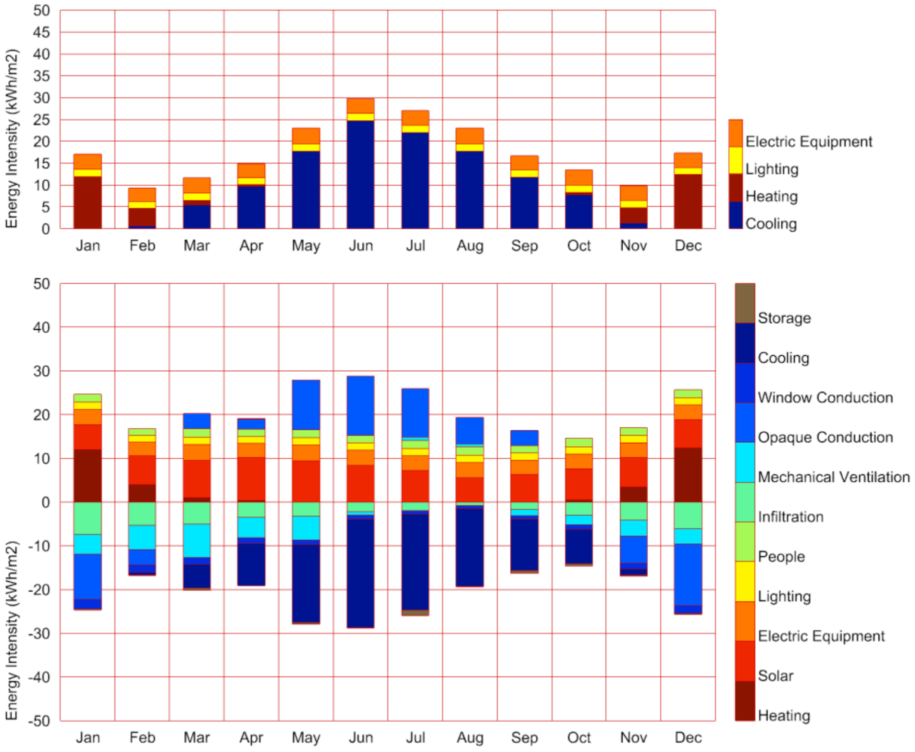


Figure 6-22: Annual Loads Breakdown of Scenario #4

6.6.1.2.5 Scenario #5: Double pane: Tinted | Clear glass

The glazing for the fifth scenario consists of two panes of glass, one of clear glass on the inside and one of colored glass on the exterior, with a 10 mm air cavity in the middle. In this scenario, the EUI of cooling has considerably drooped down with a slight rise in heating loads. A total EUI has been also reduced comparatively against previous scenarios. The total EUI value of the fifth test condition was 209.97 kWh/m2.

Table 39: EUI Breakdowns of Scenario #5

Heating (kWh/m^2)	Cooling (kWh/m^2)	Interior Lighting (kWh/m^2)	Interior Equipments (kWh/m^2)	Total EUI (kWh/m^2)
35.99	113.42	19.76	40.79	209.97

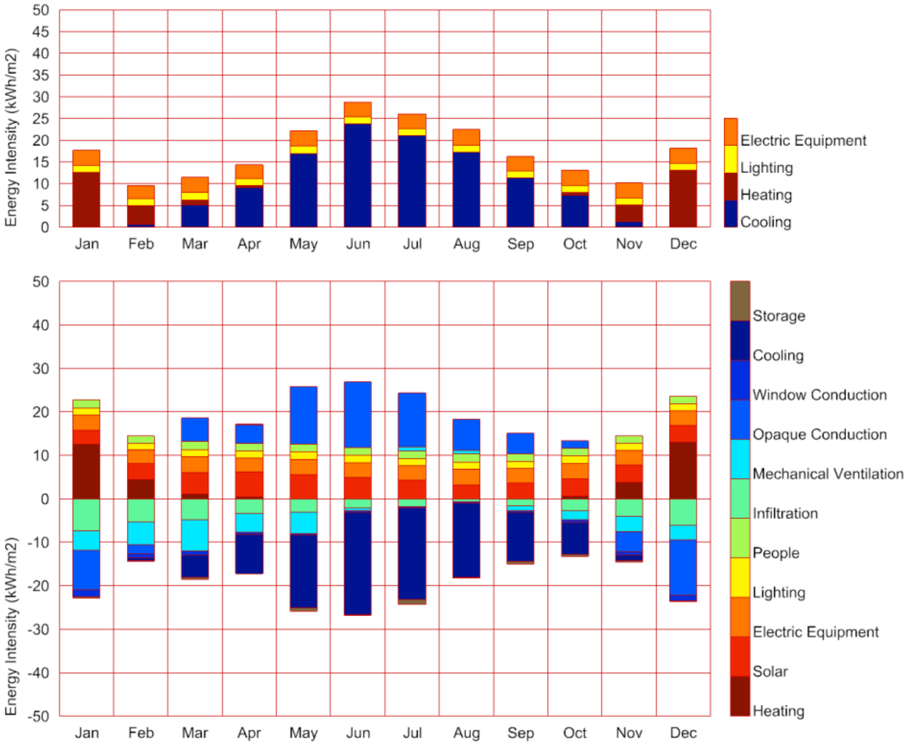


Figure 6-23: Annual Loads Breakdown of Scenario #5

6.6.1.2.6 Scenario #6: Double pane: Thermal Insulation (TI) Low-E | Clear glass

In the sixth case, the glazing consists of two panes of transparent glass with a 10 mm air hole sandwiched between two panes of thermally insulated Low-e glass. In this scenario, the EUI of cooling has considerably raised with a slight decrease in heating loads. A total EUI has been also been increased comparatively against scenario 5. The total EUI value of the sixth test condition was 213.16 kWh/m2.

Table 40: EUI Breakdowns of Scenario #6

Heating (kWh/m^2)	Cooling (kWh/m^2)	Interior Lighting (kWh/m^2)	Interior Equipments (kWh/m^2)	Total EUI (kWh/m^2)
32.63	119.969	19.76	40.79	213.16

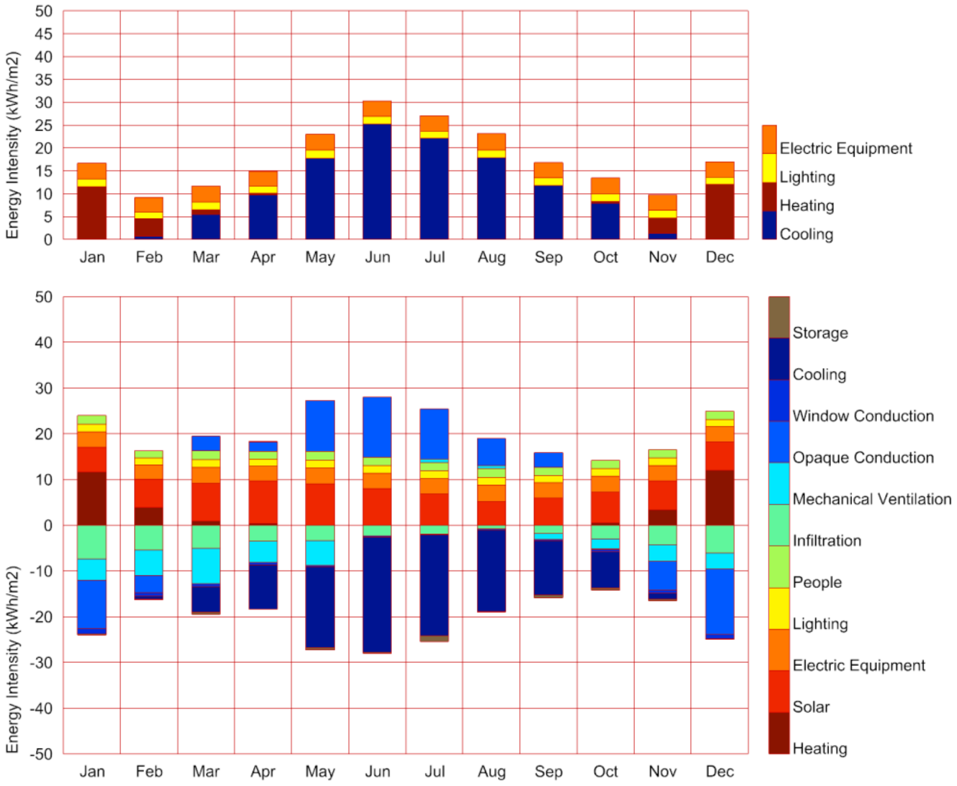


Figure 6-24: Annual Loads Breakdown of Scenario #6

6.6.1.2.7 Scenario #7: Double pane: Solar Control (SC) Low-E | TI Low-e glass

The seventh glazing scenario consists of two panes of Low-e glass with a 10 mm air space in the middle and a double layer of solar control Low-e glass on the outside and a thermally insulated Low-e glass within. High-performance glazing solutions in this situation considerably minimize the EUI of cooling. The total EUI value of the seventh test condition was 207.55 kWh/m2.

Table 41: EUI Breakdowns of Scenario #7

Heating (kWh/m^2)	Cooling (kWh/m^2)	Interior Lighting (kWh/m^2)	Interior Equipments (kWh/m^2)	Total EUI (kWh/m^2)
35.71	111.29	19.76	40.79	207.55

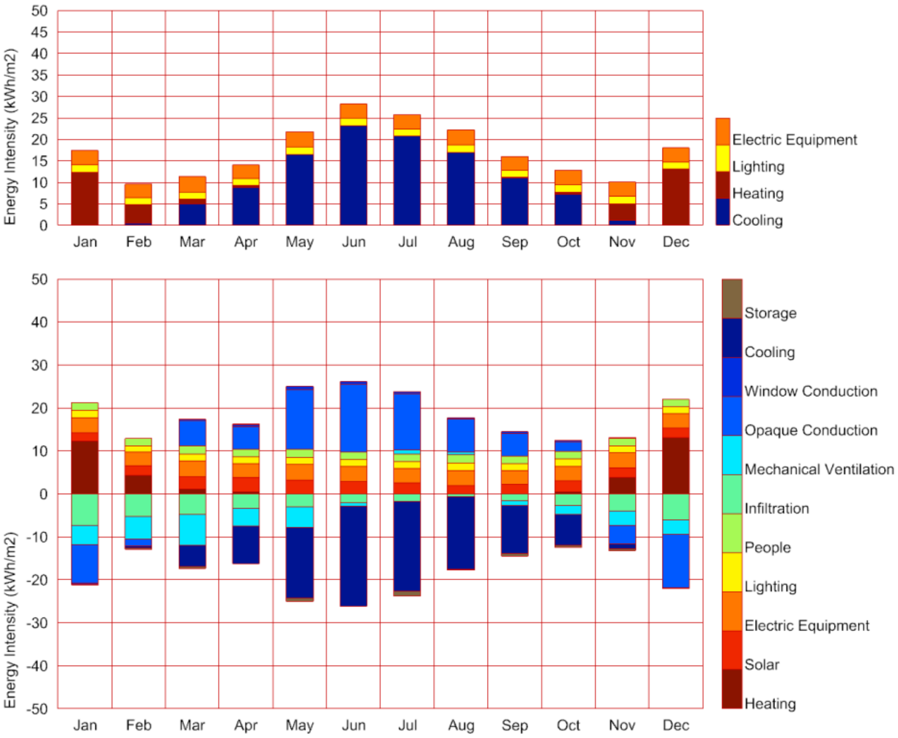


Figure 6-25: Annual Loads Breakdown of Scenario #7

6.6.1.2.8 Scenario #8: Electrochromic (EC) Glazing

The eight-scenario glazing is electrochromic and they change their tint states according to various variables of climatic conditions. In this scenario, the EUI of cooling is greatly reduced due to the high performance of EC glazing. The total EUI value of the last test condition was 204.22 kWh/m2.

Table 42: EUI Breakdowns of Scenario #8

Heating (kWh/m^2)	Cooling (kWh/m^2)	Interior Lighting (kWh/m^2)	Interior Equipments (kWh/m^2)	Total EUI (kWh/m^2)
38.24	105.425	19.76	40.79	204.22

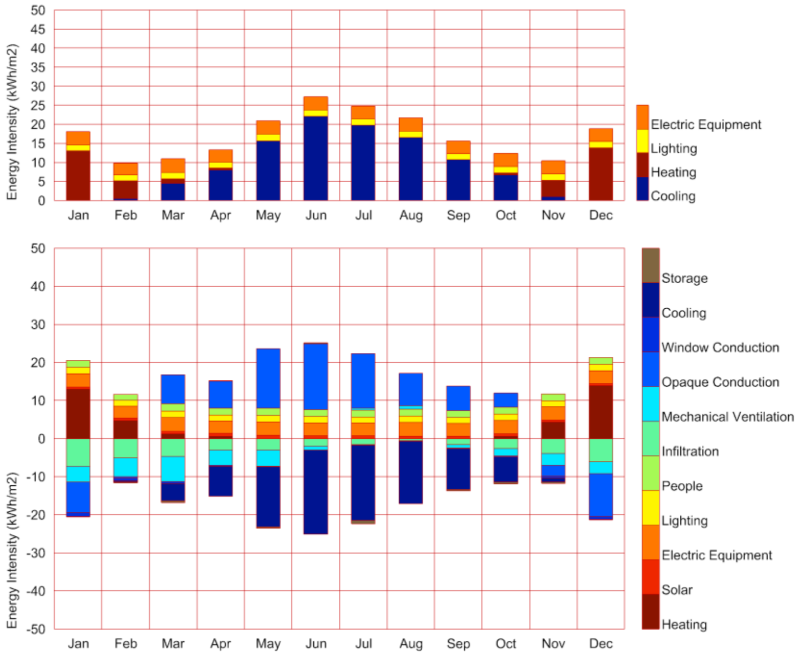
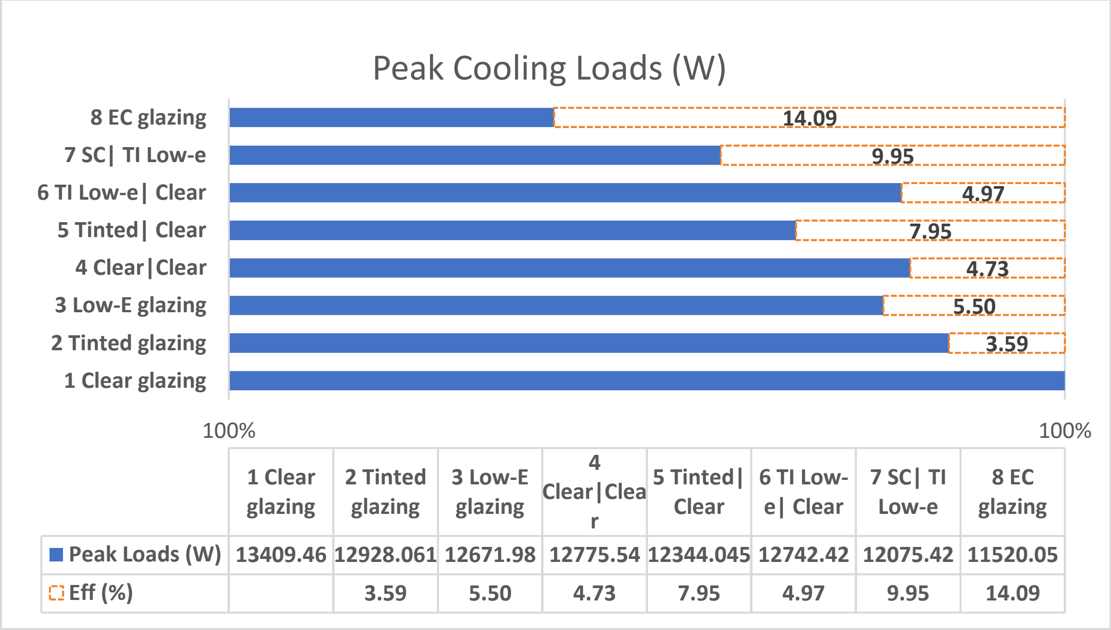


Figure 6-26:Annual Loads Breakdown of Scenario # 8

6.7 Comparative Analysis: Peak Cooling Loads

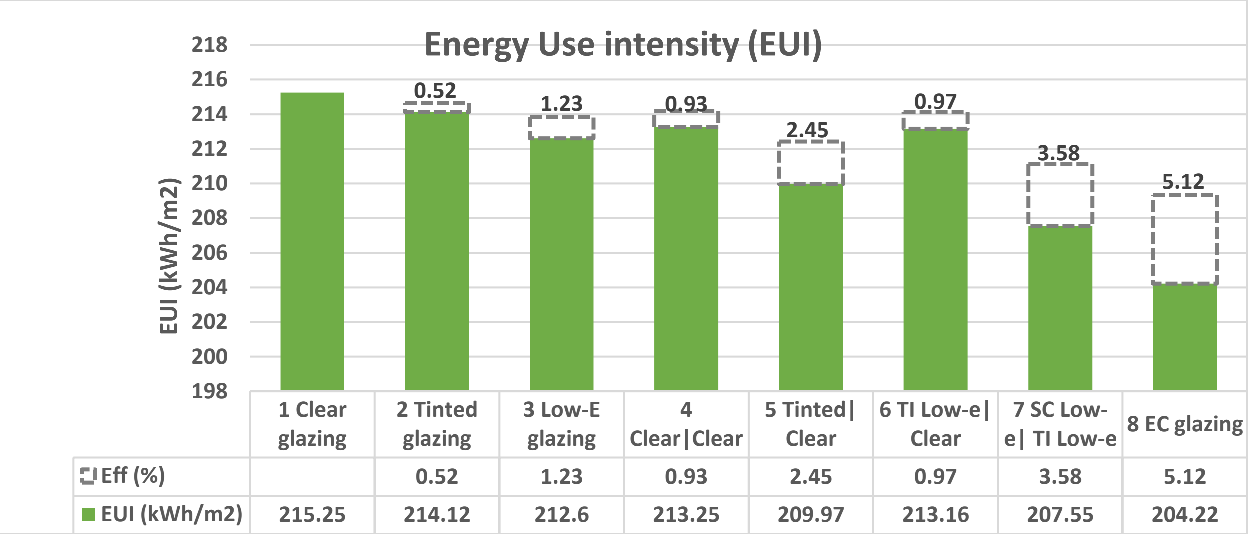


	1 Clear glazing	2 Tinted glazing	3 Low-E glazing	4 Clear|Clear	5 Tinted| Clear	6 TI Low-e| Clear	7 SC| TI Low-e	8 EC glazing
■ Peak Loads (W)	13409.46	12928.061	12671.98	12775.54	12344.045	12742.42	12075.42	11520.05
⬚ Eff (%)		3.59	5.50	4.73	7.95	4.97	9.95	14.09

Figure 6-27: Comparative analysis of peak cooling loads of all 8 scenarios

It can be seen from the chart below that the best performance is shown by scenario #8 which is the Electrochromic glazing with 14.09% of efficiency against the clear glazing. Scenario #7 of Solar control (SC) and Thermally Insulated (TI) Low-e glass also has 9.95% of efficiency in the shoe-box model. Scenario # 5 of Tinted and clear glass also has an efficiency of 7.95 % against the single pane clear glass. The peak loads play a vital role in HVAC sizing and EC glazing shows a promising decrease in peak loads in the shoe box model.

6.8 Comparative Analysis: Energy Use Intensity(EUI)



	1 Clear glazing	2 Tinted glazing	3 Low-E glazing	4 Clear|Clear	5 Tinted| Clear	6 TI Low-e| Clear	7 SC Low-e| TI Low-e	8 EC glazing
⬚ Eff (%)		0.52	1.23	0.93	2.45	0.97	3.58	5.12
🟩 EUI (kWh/m2)	215.25	214.12	212.6	213.25	209.97	213.16	207.55	204.22

Figure 6-28: Comparative analysis of EUI of all 8 scenarios

It can be observed that the best performance is shown by scenario #8 which is the Electrochromic glazing with 5.12% of efficiency against the clear glazing. Scenario #7 of Solar control (SC) and Thermally Insulated (TI) Low-e glass also has 3.58% of efficiency in the shoe-box model. The efficiency percentages have some discrepancies as there is only one window on the western side.

7 Feasibility study

7.1 Operational feasibility

Electricity is needed for the active strategy known as dynamic glazing. To provide adaptive thermal comfort in the absence of an HVAC system but with operable windows, Scenario# 4 of static double-pane glazing was taken into consideration. The diagram's red portion depicts the overheated area when the temperature was 2.5 °C over the month's neutral temperature. The blue portion depicts the chilly conditions, where the temperature was 2.5 °C below the month's neutral temperature. The comfortable conditions are depicted in yellow when the temperature is within the 2.5 °C offset.

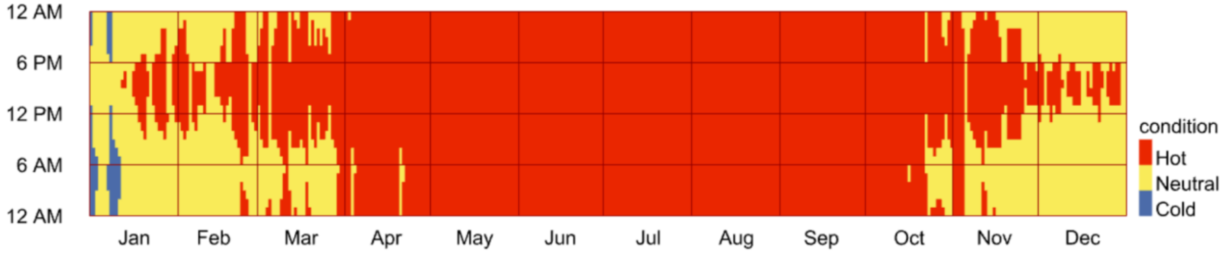


Figure 7-1: Adaptive thermal comfort of Scenario #4

According to ANSI/ASHRAE 2017 standards, ASHRAE 55 governs this activity. Without HVAC, there were 71.83% of times when the room was too hot and 27.28% of times when it was comfortable. 36.49 °C was the maximum temperature recorded indoors. 12.88 °C was the maximum positive departure from the neutral temperature. Although the temperature inside was often uncomfortable, people could nevertheless survive.

% Hot	% Neutral (Comfortable)	% Cold	Lowest Temperature °C	Highest Temperature °C	Lowest Deviation °C	Highest Deviation °C
71.83	27.28	0.89	17.98	36.49	-4.08	12.88

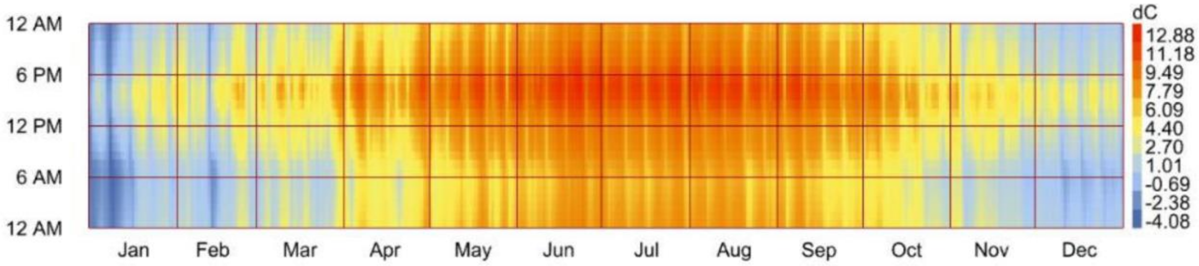


Figure 7-2: Deviation from Neutral Temperatures of Scenario #4

However, the findings indicated that in a genuine workplace situation with plenty of windows, it might be harmful and even fatal to people.

For example, we have 6458.35 ft^2 (600 m^2)of vision glazing per floor = 130 IGUs (5ft x 10 ft)

Peak power needed to tint all 130 IGUs on one floor = 455 Watts

Power needed to hold tint = 130 watt

Power demand during tint transition ~ 3.5 Watts per 5' x 10' IGU
Power for holding tint ~ 1 Watts per 5' x 10' IGU

" Once fully tinted the EC IGU can maintain tint for up to a day without additional power."

7.2 Orientation

For the orientation analysis, the previous shoe box model was chosen with a change in the window’s orientation and EC glazing was compared against clear glazing. It can be observed that the eastern and southern sides have greater efficiency of 7.75% and 5.12% than the northern and southern sides of 2.5%and 0.63%. However, the shoe box model has only one window and it can vary in the real office building model which has many windows.

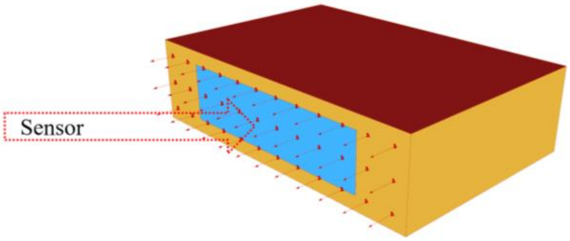


Figure 7-3: Shoe-box model

Table 43: Comparative analysis of the orientation of EC glazing against the clear glass

Orientation	Total EUI (kWh/m2) Clear glazing	Total EUI (kWh/m2) Electrochromic glazing	Efficiency (%)
North	207.55	202.30	2.5%
South	203.79	202.49	0.63%
East	220.54	203.44	7.75%
West	215.25	204.22	5.12%

7.3 Economic Feasibility Analysis

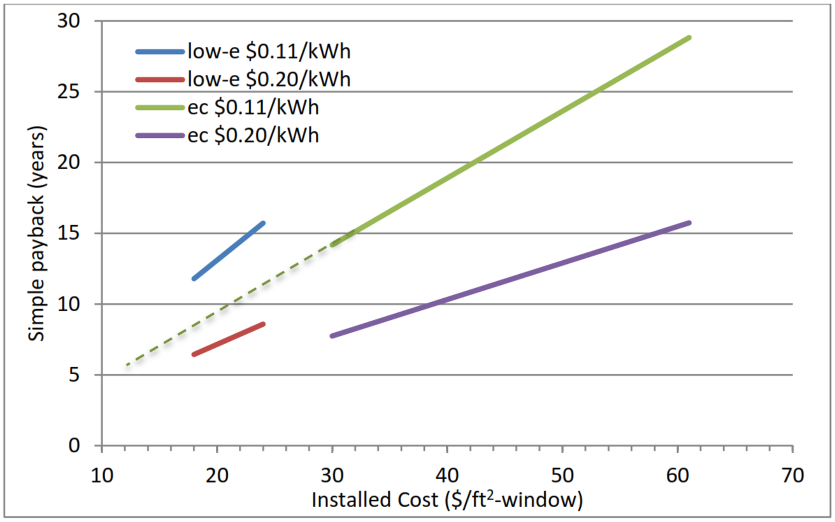


Figure 7-4: Simple payback (years) of a standard Low-E window and an EC window as a function of the installed total cost ($/ft-window) and a flat utility rate for electricity ($/kWh).

Source: (Lawrence Berkeley National Laboratory , 2021)

If the installed total cost is less than $39/ft^2 and the utility rate is $0.20/kWh (which is the average blended rate for metropolitan areas like New York City), or if the installed total cost is less than $21/ft^2 with a utility rate of $0.109/kWh, the simple payback of EC windows can be achieved in less than ten years. These scenarios are not meant to represent a forecast of what the installed cost for EC windows in the future will be; rather, they are meant to give one an idea of what the installed cost would need to be to accomplish a 10-year payback. According to the study's findings, choosing EC windows may also have the following non-energy advantages: (Lawrence Berkeley National Laboratory , 2021)

- More opportunities to view the outdoors
- More sunshine when solar control is unnecessary
- Considerable solar control, and as a result, balancing of loads between internal and north-facing zones and zones exposed to significant solar radiation. If the HVAC system cannot react appropriately to zones with considerable changes in thermal loads, this can enhance thermal comfort throughout the building.
- Possibilities for improved health and productivity as a result of more lighting and access to views outside.

8 Energy Optimization of an Office Building

The performance evaluation showed that electrochromic glazing outperforms EC glazing in terms of energy efficiency and visual comfort when compared to the outcomes of the seven scenarios. One of the goals of this study was to comprehend the many uses and identify the best design strategy to increase an office's energy efficiency. According to its suitability for energy conservation, an actual office building from the field study was selected for this. The following is a description of the simulation's parameters and the building's specifics:

8.1 Model an Actual Office Building

8.1.1 Prabhu Bank (Corporate Building): Building Description

Located on the west side of Dhobi Khola in Babarmahal is the corporate headquarters for Prabhu Bank. The plinth area is 1110 m^2, with a total site area of 2400 m^2. The total built-up area is 8884.96 m^2 and there are eight floors in it. ACP cladding can be seen at the East, North, and South-East corners of the modern building, which has a glass facade in the East. A typical 9" brick wall makes up the remaining other walls.

Figure 8-1: Front View of the Prabhu Bank

Source: Prabhu Bank Limited

For cabins, internal partitions are typically made of 8 mm full-height glass, whereas workstation partitions are made of low-height metal. The structure is stretched in a north-south direction, which is bad for passive solar gain. Only 3 meters separate the south side of the building from the same-story Sagarmatha Television structure, which completely conceals the building's south gain.

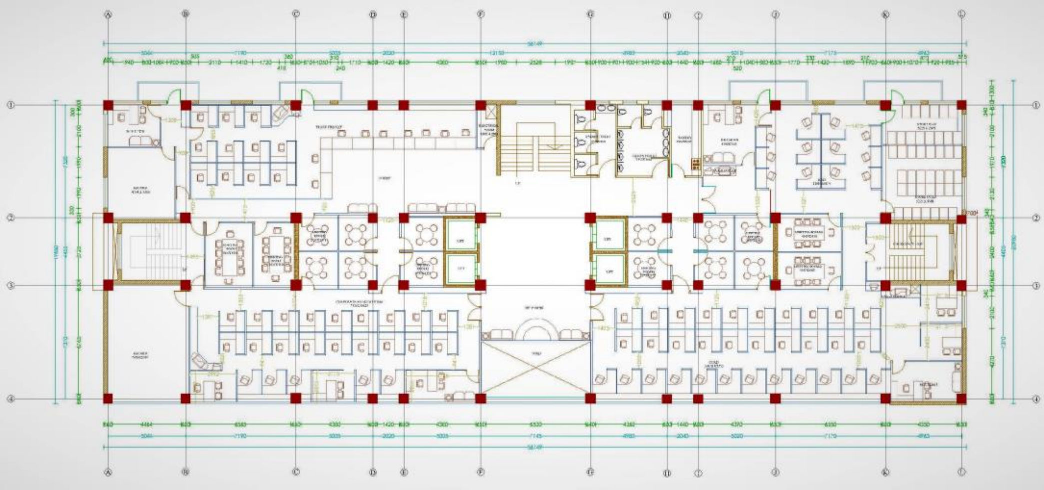


Figure 8-2: Typical Floor Plan of Prabhu Bank

Source: (Paudyal & Bajrachara, 2019)

Table 44: Material in the building case scenario

Building Envelope	**Material**
Outer Wall	230mm brick wall with both side plaster
NE and SW Wall band	6mm ACP cladding with a 50mm air gap
Windows/Openings	6mm Single Glazed with Aluminum Frame
Flooring	Tile/Marble Finishing over Concrete
Roofing	CGI Roof with False Ceiling

In the base case simulation, the case office building is modeled per the floor plans and construction characteristics. Rhino is used to generate the structure model, and Grasshopper plugins are used for the energy simulations. The energy model must use a variety of data types to produce accurate simulation results.

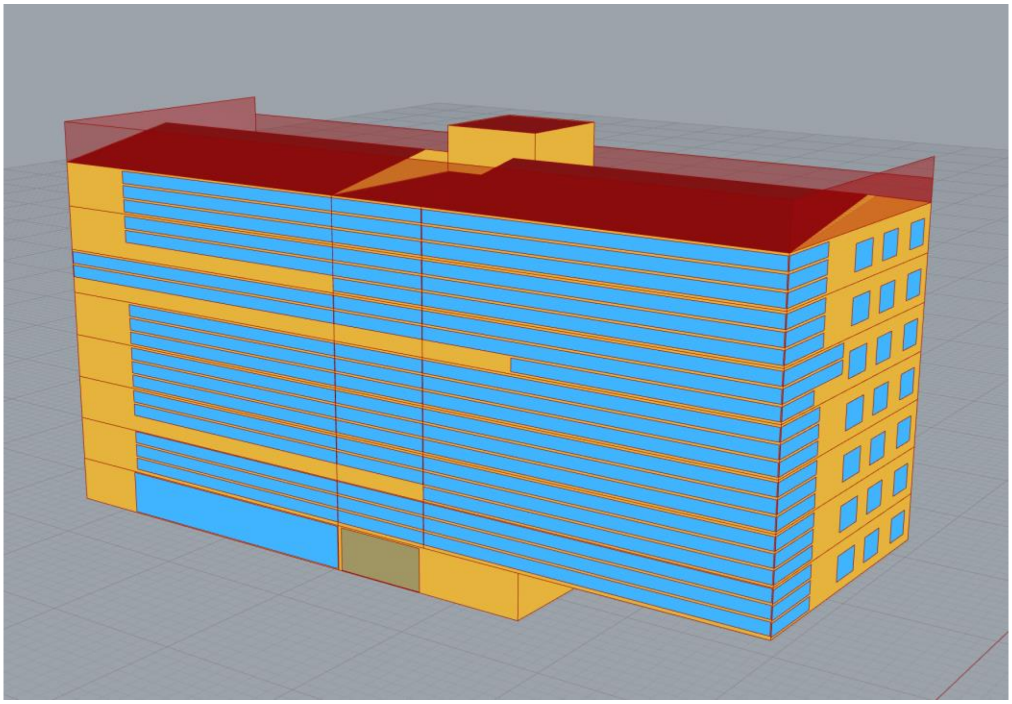


Figure 8-3: 3D Energy model of the actual office building in Rhino

8.1.2 Space Type Breakdown

Before programming the geometry in Grasshopper, the solid rooms are first modeled in Rhino. According to the floor plans, the structure is categorized as a medium scaled building with an open office layout. It is deemed air-conditioned throughout the entire structure.

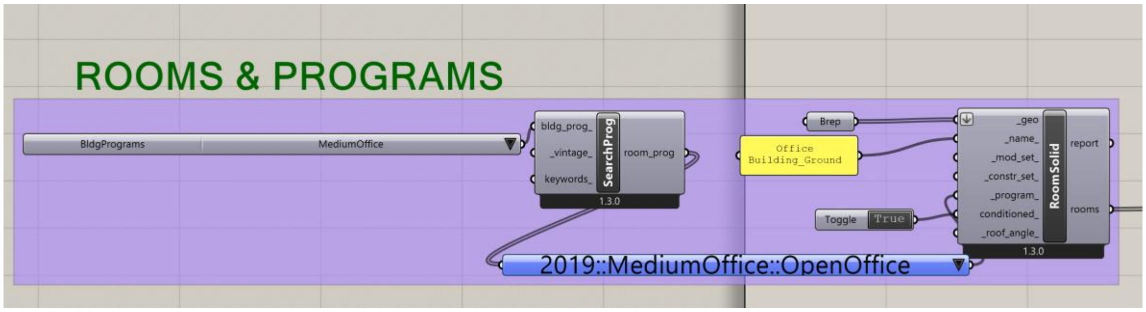


Figure 8-4: Building programs assigned as a medium office building with an open office layout

8.1.3 Space Type Summary

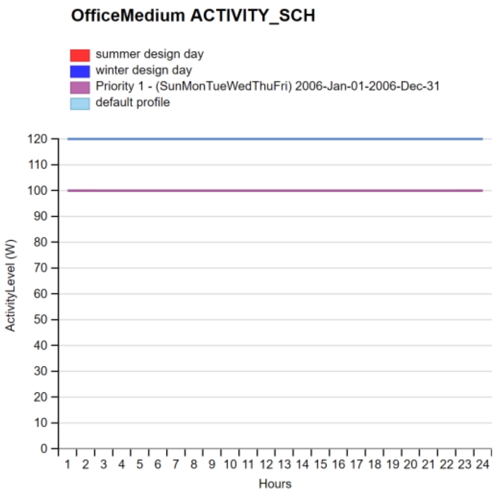
20 areas and 20 thermal zones were determined per the program's allocated open office layout based on the following factors: the number of employees, the amount of electrical equipment, the amount of lighting, the amount of infiltration, and the amount of ventilation.

Table 45: Space Type summary

Definition	Value	Unit	Inst. Multiplier
2019::MediumOffice::OpenOffice_People	0.1076	people/m^2	1.0
2019::MediumOffice::OpenOffice_Electric	7.7535	W/m^2	1.0
2019::MediumOffice::OpenOffice_Lighting	9.04	W/m^2	1.0
2019::MediumOffice::OpenOffice_Infiltration	0.0003	m^3/h/ext surf area m^2	
2019::MediumOffice::OpenOffice_Ventilation (outdoor air method Sum)	8.4950	m^3/h/person	
2019::MediumOffice::OpenOffice_Ventilation (outdoor air method Sum)	0.0003	m^3/h/ floor area m^2	

8.1.4 Operating schedules

According to the priorities established to manage the program, several operational schedules are assigned. Activity, equipment, illumination, occupancy, cooling and heating setpoints, and infiltration loads are just a few of the schedules. Weekday priorities are established, while Saturday is designated as a holiday. The numbers for various schedules that were prioritized are shown below:



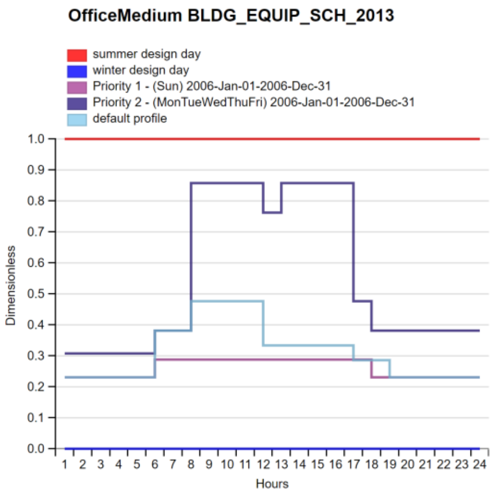


Figure 8-5: (Left) Office medium activity schedule; (Right) Office Medium Building equipment schedule

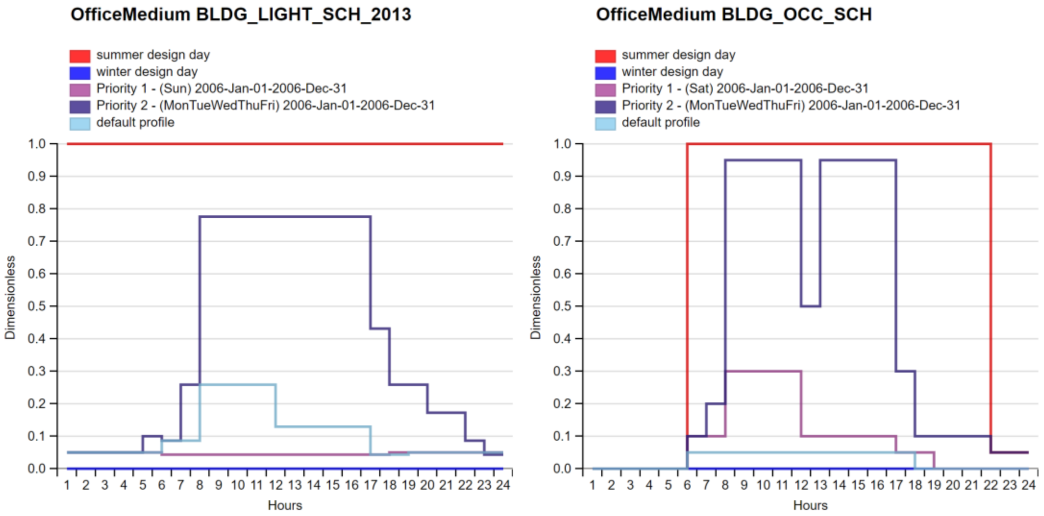


Figure 8-6: (Left) Office medium lighting schedule; (Right) Office Medium Building occupancy schedule

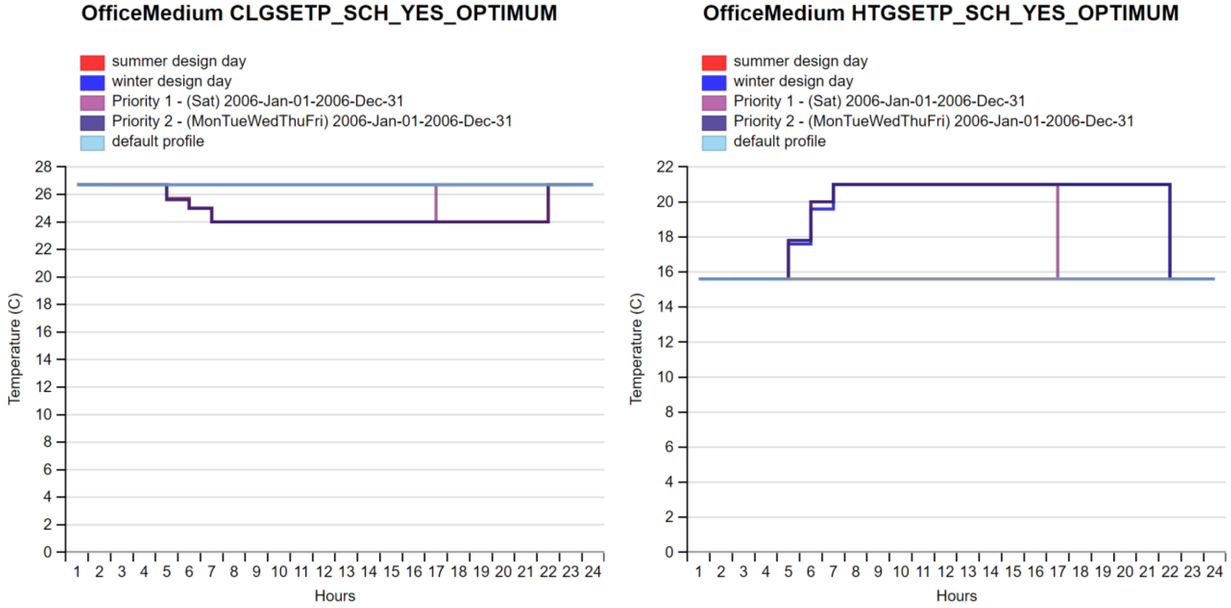


Figure 8-7: (Left) Office medium cooling setpoint schedule; (Right) Office Medium Building heating setpoint schedule

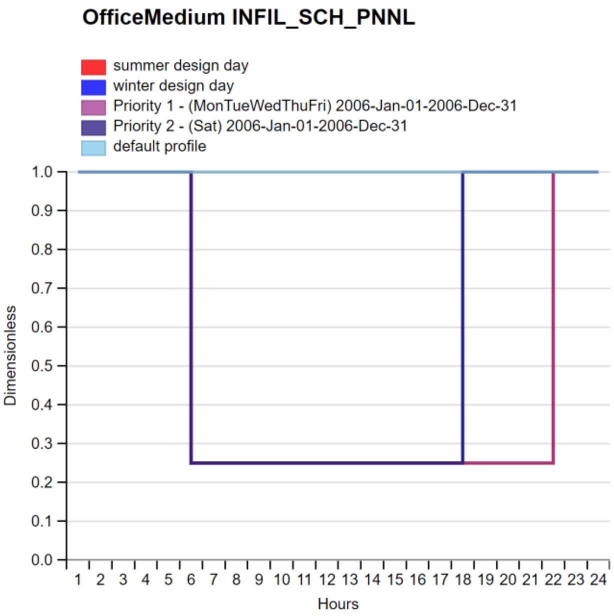


Figure 8-8: Office Medium infiltration schedule

8.1.5 Envelope Summary

Table 46: Base surface Constructions

Construction	Net Area (m^2)	Surface Count	R-Value (m^2*K/W)
CGI Roof	1,273.1	12	0.06
CONCRETE FLOOR	1,257.2	13	0.07
Wall-ACP panels	4,294.8	255	0.38

Table 47: Sub-surface constructions

Construction	Net Area (m^2)	Surface Count	U-factor (W/m^2*K)	SHGC	VLT
Generic Double Pane	147.7	32	1.67	0.43	0.64
Single-glazed tinted glass	1,675.8	238	5.72	0.68	0.72

Table 48: Window-to-Wall area ratios

Description	Total (%)	North (%)	East (%)	South (%)	West (%)
Gross Window-Wall Ratio	29.8	13.73	66.68	8.86	37.76
Gross Window-Wall Ratio (Conditioned)	37.81	19.59	67.89	9.97	42.59

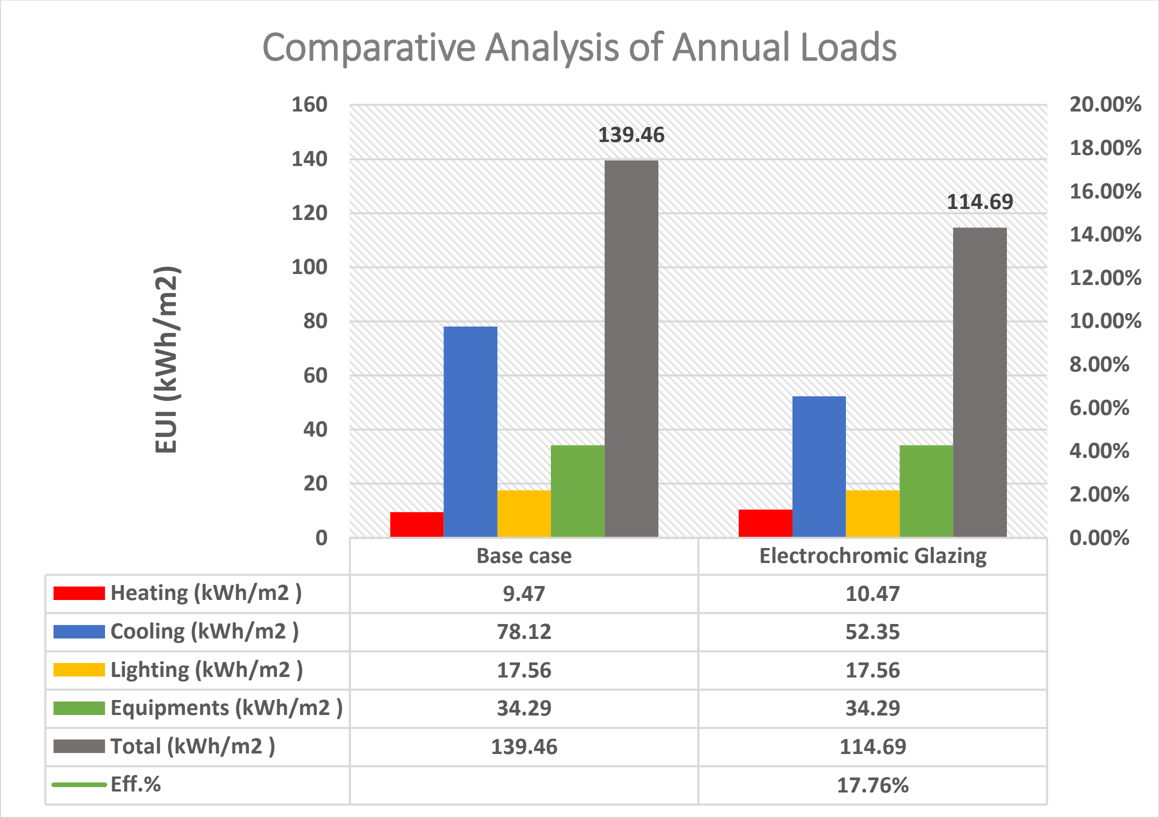
8.2 Simulation results

8.3 End-use Intensity (kWh/m2)

The comparison of all cases' EUI is shown in the table below. The EUI is measured in kWh/m2, which is the standard unit. The breakdown of the annual loads includes heating, cooling, lighting, and equipment loads. The energy efficiency is assessed against the base case scenario.

Table 49: Comparative Analysis of Annual Loads

Scenarios	Heating (kWh/m^2)	Cooling (kWh/m2)	Lighting (kWh/m2)	Equipment (kWh/m2)	Total (kWh/m2)	Eff.%
Base case	11.81	78.47	17.41	28.54	136.24	
Electrochromic Glazing	13.01	52.93	17.41	28.54	111.89	17.76



	Base case	Electrochromic Glazing
🟥 Heating (kWh/m2)	9.47	10.47
🟦 Cooling (kWh/m2)	78.12	52.35
🟨 Lighting (kWh/m2)	17.56	17.56
🟩 Equipments (kWh/m2)	34.29	34.29
⬛ Total (kWh/m2)	139.46	114.69
— Eff.%		17.76%

Chart 24: Comparative Analysis of EUI against a base case

The results suggest that compared to the base case scenario, electrochromic windows may reduce energy consumption by 17.76% without any shading technologies.

8.4 Peak Cooling Loads

A 56.79% reduction in cooling peak loads can be observed in the case of EC glazing against clear glazing. The HVAC load calculation will benefit from a decrease in peak cooling demands. It can reduce electricity expenses for the building owner and contribute to the efficiency and reliability of the electrical power grid. For the power system operator, reducing peak power demand leads to a more predictable load profile and reduces stress on the electric grid system.

Table 50: Comparative Analysis of peak cooling loads

Scenarios	Cooling (W)	Eff%
Base case	1008365.97	
Electrochromic Glazing	435678.34	56.79

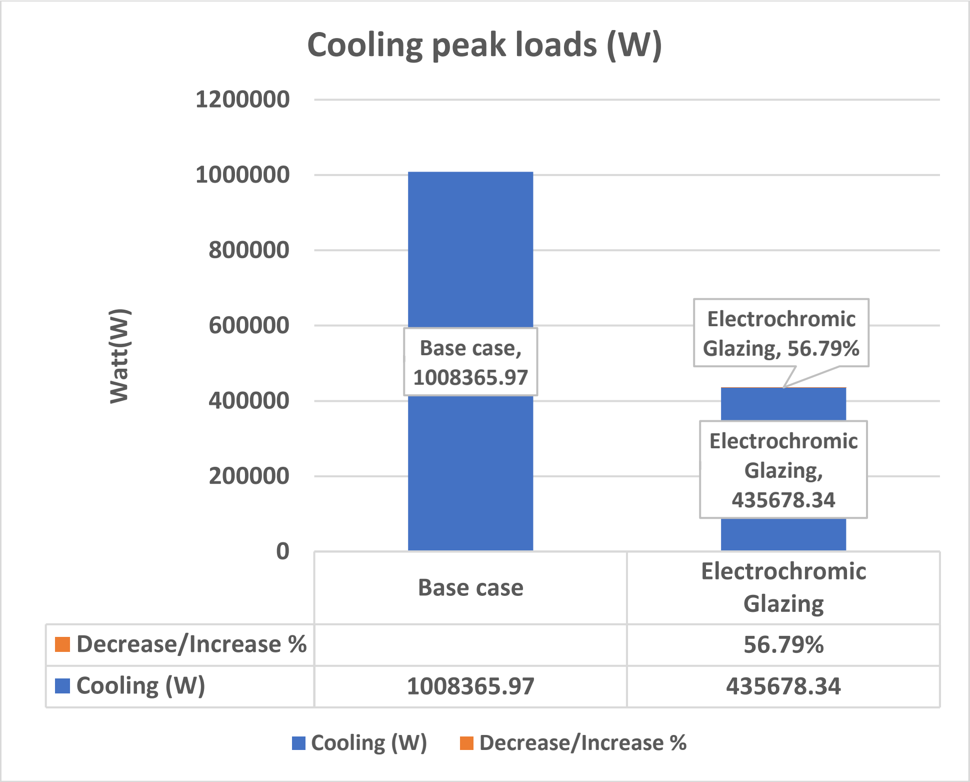
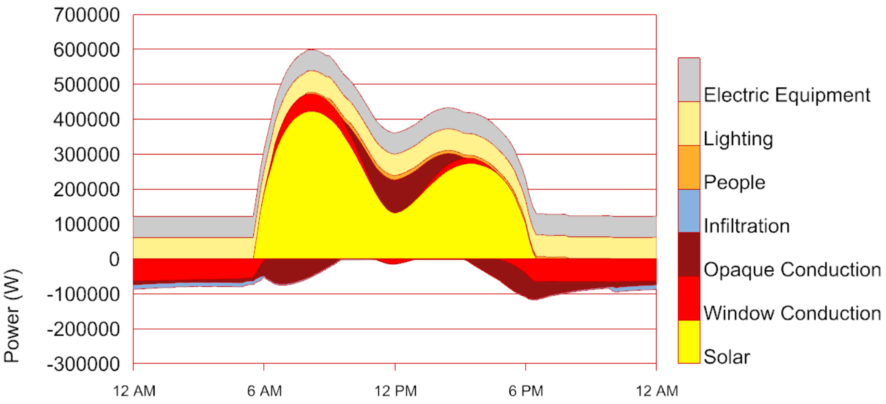
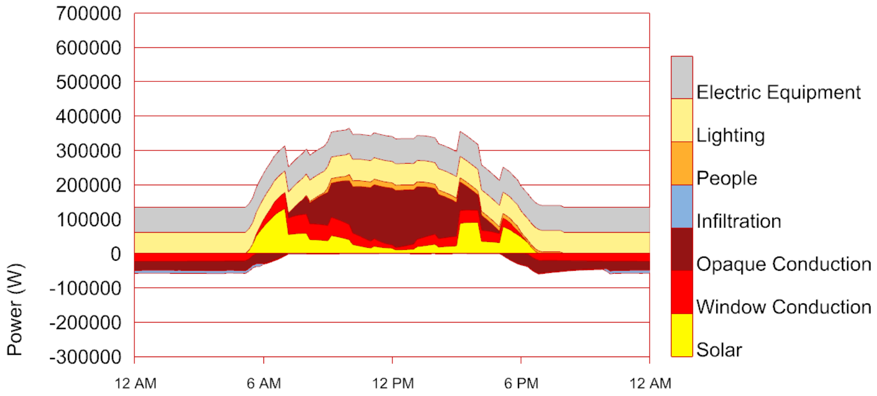


Figure 8-9: Comparative analysis of Cooling Peak loads of all cases

8.4.1 Comparative Analysis: Load Balance



(a) Annual Load balance of Base case



(a) Annual Load balance of EC glazing

Chart 25: Comparative analysis of load balance

The chart shows that there is a significant reduction in solar heat gain when electrochromic windows are used. In the case of the base, there is a significant solar heat gain. This demonstrates how crucial glazing is to a building's energy efficiency.

9 Findings and Discussions

The experiment results for both the shoebox model and the actual model of the office building supported the premise that dynamic glazing would perform best in terms of energy usage and visual comfort. Some of the performance outcomes were inconsistent. The shoebox model's and the office building's actual model's glazing areas' various sizes, orientations, and locations were primarily to blame for the disparity. The hypothesis states that the EC glazing would have the best performance among energy usage, daylight, and glare following the experiment results for both the shoebox model and real office building. The dynamic EC glazing had the best overall performance for both experiments against all seven scenarios of static glazing.

According to research done on a real building, HVAC cooling loads might be decreased in various zones of the building by between 30% and 60%. (Fernandes 2021). In cooling-dominated locations, EC glazing, according to another study, might cut energy use by 52%. (Cannavale 2018). Studies revealed that the potential for energy reduction was between 20% and 30% and that the performance of kinetic shading systems to minimize energy use depended on different shapes and factors (Hosseini 2019). The shoe-box model's findings, however, only indicated a 5.12% reduction in EUI in the case of EC glazing. The rising heating loads resulted in a decrease in the overall EUI. Similar to this, there was only a 10% reduction in peak cooling demand for EC glazing in the shoe-box model, which was insignificant. The single window of the shoe-box model, centered on the west orientation, may have contributed to this result. Other static glazings also lacked good energy efficiency. The strategy of Scenario #7 (Double pane - SC Low-e | TI Low-E) had the second-best performance for the shoe-box model. There were discrepancies in the scores and other performance results. The discrepancy was mostly caused by the different sizes, orientations, and positions of the glazing areas of the shoebox model and the base office model. According to this research, the EC glazing system did have better performance in reducing energy, and thus showed the importance of comparing static glazing strategies in one building setup.

However, in the modeling of the real office model, peak cooling loads were reduced by 56.79%, and the EUI had a reduction of 17.76% without a change in illumination. This study found that the EC glazing system does perform better at lowering energy, demonstrating the value of contrasting it with other static high-performance glazing systems.

9.1 Key Findings

- ❖ For the shoebox model, EC glazing had the overall best performance among all seven test conditions.
- ❖ If daylighting performance was the most important factor to consider, the code-compliant EC glazing provided the most amount of daylighting for the shoe-box model.
    - EC glazing indicated high percentages of dimly lit hours of 43.17%, and only one scenario with 0% higher UDI. The UDI ranged at 56.83%.
- ❖ If glare was the most important issue, Scenario# 6 (TI Low-e|Clear), 7 (SC Low-e|TI Low-e), and EC glazing shielded most of the glare and provided 10 hours of imperceptible glare for the shoe-box model with 1 hour of intolerable glare and perceptible glare each.
- ❖ EC glazing provided the least amount of peak cooling load i.e, 11520 (Watts), and an Energy Use Intensity (EUI) of 204.22 kWh/m2.
- ❖ In the modeling of the real office model, peak cooling loads were reduced by 56.79%, and the EUI had a reduction of 17.78% against the base case model.
- ❖ Nonetheless, all test conditions being analyzed did not represent the performance of the whole glazing type.
- ❖ A single change of parameters would lead to a completely different result.
- ❖ Overall, the research provided a method to evaluate and compare the different performances of various glazing systems.

9.2 Future works

There were topics, elements, and restrictions that the study did not cover but that could be included in subsequent work. These difficulties were brought up here as possible future study subjects. We did not manipulate the dynamic systems in the modeling of EC glazing with particular solar irradiance values. We turned on EC light, heavy, totally tinted states, and dynamic blinds in the shoe-box model using 10%, 20%, 30%, and 40% of the greatest annual solar irradiation value obtained on the window. If different values were used, the results would be largely different The outcomes would also be significantly different if a controller other than solar irradiance had been utilized to activate the dynamic glazing or shading systems. Different combinations of dynamic shading with EC glazing could surpass the single technology of chromogenic facades. We now have a new avenue for future research thanks to the improvement of the Ladybug tools, which could tackle several simulation issues.

Given that many office buildings have glass facades on both the east and west sides, future research may compare the effectiveness of horizontal and vertical blinds. One test scenario may involve placing horizontal louver blinds on the south façade and vertical louver blinds on the west, north, and east sides. The parameters of the test conditions could also be subjected to more controls during the tests. Examples include blinds with the same aspect ratio but different tilt angles, as well as different sun irradiation setpoints or interior result setpoints.

10 Conclusion

The research provided several possible circumstances for designers so that they could have a basic concept of performance in different categories while selecting from those glazing options. For architects and designers considering applying those glazing strategies to buildings, this research may be a useful reference. It is determined that a sizable amount of energy can be saved by merely changing and choosing the correct glazing system. By taking into account the building's aesthetics, it is discovered that up to 17.76% of energy consumption may be cut. The cooling load has greatly decreased, demonstrating the requirement for shading devices and suitable glazing systems to lessen the building's summer heat gain. Similar to Kathmandu, where the environment is generally chilly, passive solar heat uptake is crucial to preserving the degree of comfort.

Electrochromic windows have shown a considerable amount of drop in peak cooling loads which is nearly equal to 56.79%. Reductions in cooling load contribute to energy saving on system sizing, zoning, and most importantly in HVAC load sizing which in turn contributes to better energy efficiency in the long run. Also, there is a huge amount of solar heat gain drop in the case of Electrochromic windows as we can see in the comparative chart against the base case. Again, the results were only based on certain parameters and certain circumstances. The results did not mean EC glazing was generally better than static glazing systems. A small nuance in the selection of parameters or the values obtained could lead to a completely different result in performance. Architects and designers will need to evaluate and make decisions case by case.

10.1 Conclusion Validity

10.1.1 Key findings of the study

- In the modeling of the real office model, peak cooling loads were reduced by 56.79%, and the EUI had a reduction of 17.76% against the base case model.
- EC glazing indicated high percentages of dimly lit hours of 43.17%, and only one scenario with 0% higher UDI. The UDI ranged at 56.79%.

10.1.2 Findings (Other research)

- HVAC cooling loads could be reduced by about 30% to 60% in different zones of the building based on the study done on a physical building (Fernandes 2021).
- Previous studies had used Useful Daylight Illuminance (UDI) which indicated the percentage of areas receiving illuminance from 300 lux to 3000 lux for 50% of the time to evaluate daylight performance of EC glazing, and EC glazing could improve 53.2 % of UDI with 0% of high UDI (Cannavale 2018).
- The strategy of EC glazing reduced 43% peak HVAC cooling load and 24% EUI (Lu, 2022).

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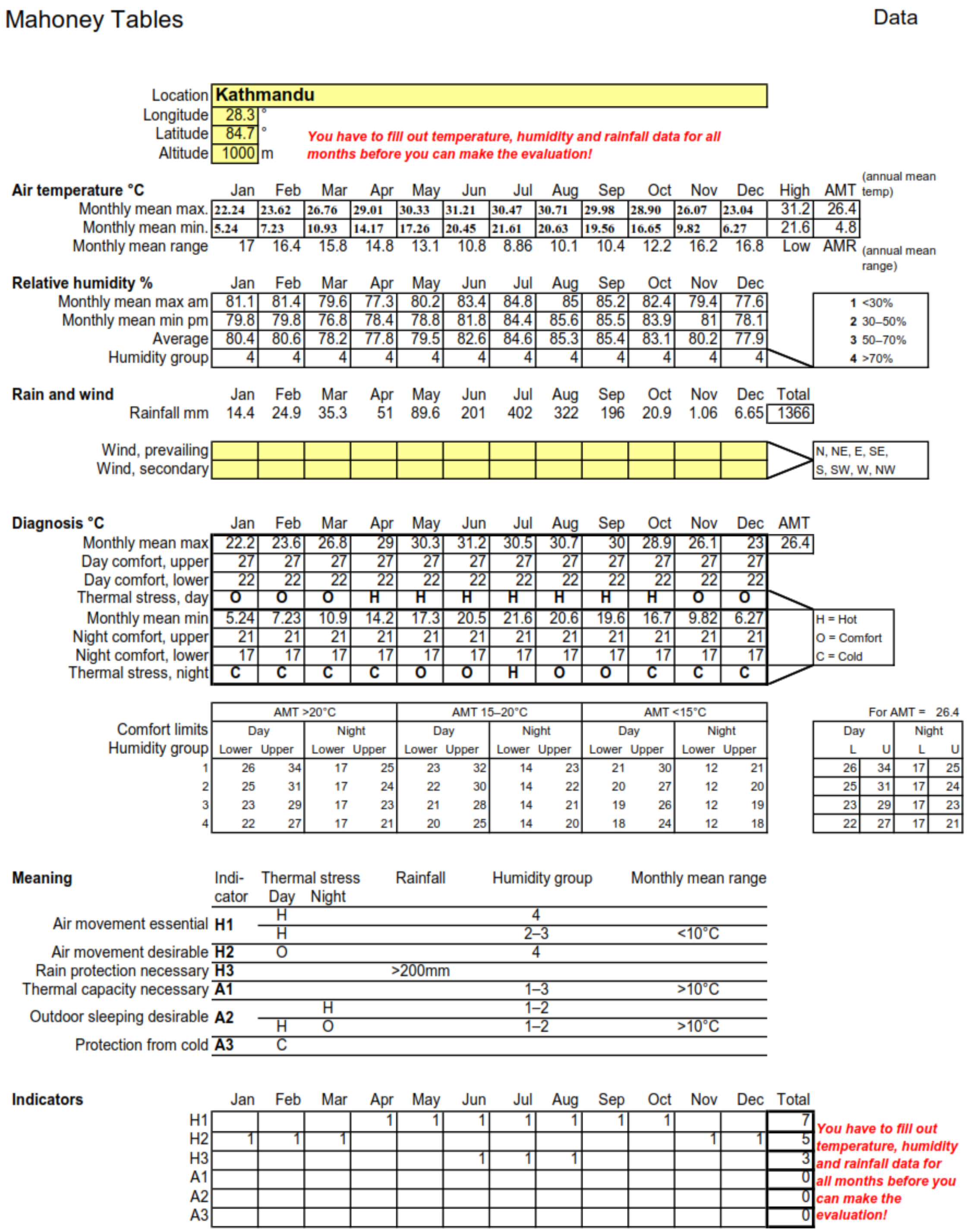
Appendix A



Mahoney Tables

Data

Location	Kathmandu	
Longitude	28.3	°
Latitude	84.7	°
Altitude	1000	m

You have to fill out temperature, humidity and rainfall data for all months before you can make the evaluation!

Air temperature °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	High	AMT	(annual mean temp)
Monthly mean max.	22.24	23.62	26.76	29.01	30.33	31.21	30.47	30.71	29.98	28.90	26.07	23.04	31.2	26.4	
Monthly mean min.	5.24	7.23	10.93	14.17	17.26	20.45	21.61	20.63	19.56	16.65	9.82	6.27	21.6	4.8	
Monthly mean range	17	16.4	15.8	14.8	13.1	10.8	8.86	10.1	10.4	12.2	16.2	16.8	Low	AMR	(annual mean range)

Relative humidity %	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly mean max am	81.1	81.4	79.6	77.3	80.2	83.4	84.8	85	85.2	82.4	79.4	77.6
Monthly mean min pm	79.8	79.8	76.8	78.4	78.8	81.8	84.4	85.6	85.5	83.9	81	78.1
Average	80.4	80.6	78.2	77.8	79.5	82.6	84.6	85.3	85.4	83.1	80.2	77.9
Humidity group	4	4	4	4	4	4	4	4	4	4	4	4

1 <30%
2 30–50%
3 50–70%
4 >70%

Rain and wind	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall mm	14.4	24.9	35.3	51	89.6	201	402	322	196	20.9	1.06	6.65	1366
Wind, prevailing													
Wind, secondary													

N, NE, E, SE,
S, SW, W, NW

Diagnosis °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AMT
Monthly mean max	22.2	23.6	26.8	29	30.3	31.2	30.5	30.7	30	28.9	26.1	23	26.4
Day comfort, upper	27	27	27	27	27	27	27	27	27	27	27	27	
Day comfort, lower	22	22	22	22	22	22	22	22	22	22	22	22	
Thermal stress, day	**O**	**O**	**O**	**H**	**H**	**H**	**H**	**H**	**H**	**H**	**O**	**O**	
Monthly mean min	5.24	7.23	10.9	14.2	17.3	20.5	21.6	20.6	19.6	16.7	9.82	6.27	
Night comfort, upper	21	21	21	21	21	21	21	21	21	21	21	21	
Night comfort, lower	17	17	17	17	17	17	17	17	17	17	17	17	
Thermal stress, night	**C**	**C**	**C**	**C**	**O**	**O**	**H**	**O**	**O**	**C**	**C**	**C**	

H = Hot
O = Comfort
C = Cold

Comfort limits	AMT >20°C				AMT 15–20°C				AMT <15°C			
	Day		Night		Day		Night		Day		Night	
Humidity group	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
1	26	34	17	25	23	32	14	23	21	30	12	21
2	25	31	17	24	22	30	14	22	20	27	12	20
3	23	29	17	23	21	28	14	21	19	26	12	19
4	22	27	17	21	20	25	14	20	18	24	12	18

For AMT = 26.4

Day		Night	
L	U	L	U
26	34	17	25
25	31	17	24
23	29	17	23
22	27	17	21

Meaning	Indicator	Thermal stress Day	Thermal stress Night	Rainfall	Humidity group	Monthly mean range
Air movement essential	**H1**	H			4	
		H			2–3	<10°C
Air movement desirable	**H2**	O			4	
Rain protection necessary	**H3**			>200mm		
Thermal capacity necessary	**A1**				1–3	>10°C
Outdoor sleeping desirable	**A2**		H		1–2	
		H	O		1–2	>10°C
Protection from cold	**A3**	C				

Indicators	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
H1				1	1	1	1	1	1	1			7
H2	1	1	1								1	1	5
H3						1	1	1					3
A1													0
A2													0
A3													0

You have to fill out temperature, humidity and rainfall data for all months before you can make the evaluation!

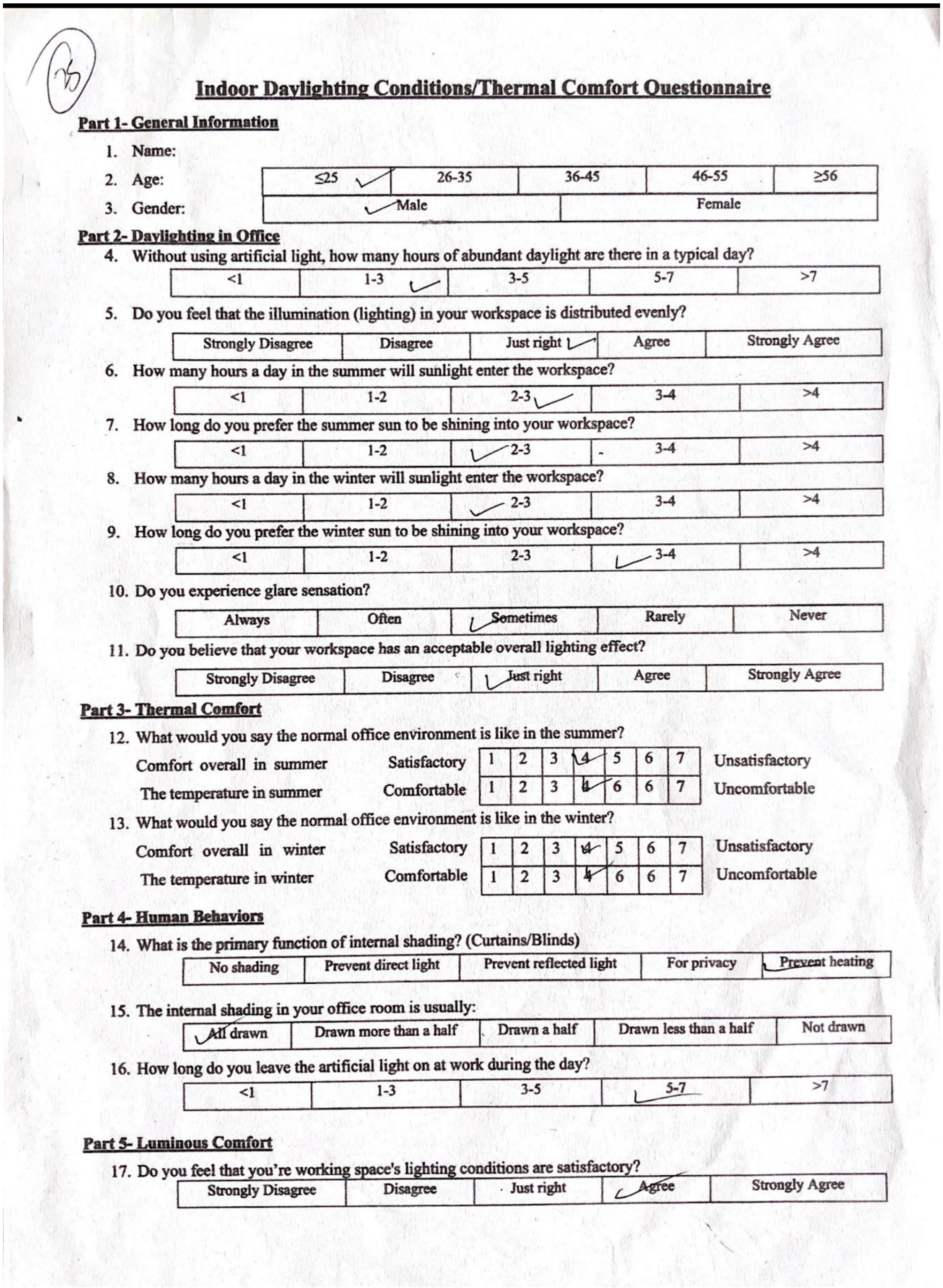
Mahoney Tables

Kathmandu
Latitude 85°N

Indicator totals from data sheet					
H1	H2	H3	A1	A2	A3
7	5	3	0	0	0

							Layout
			0–10			X	Orientation north and south (long axis east–west)
			11–12		5–12		
					0–4		Compact courtyard planning
							Spacing
11–12							Open spacing for breeze penetration
2–10						X	As above, but protection from hot and cold wind
0–1							Compact layout of estates
							Air movement
3–12						X	Rooms single banked, permanent provision for air movement
1–2			0–5				
			6–12				Rooms double banked, temporary provision for air movement
0	2–12						
	0–1						No air movement requirement
							Openings
			0–1		0	X	Large openings, 40–80%
			11–12		0–1		Very small openings, 10–20%
Any other conditions							Medium openings, 20–40%
							Walls
			0–2			X	Light walls, short time-lag
			3–12				Heavy external and internal walls
							Roofs
			0–5			X	Light, insulated roofs
			6–12				Heavy roofs, over 8h time-lag
							Outdoor sleeping
				2–12			Space for outdoor sleeping required
							Rain protection
		3–12				X	Protection from heavy rain necessary
							Size of opening
			0–1		0	X	Large openings, 40–80%
					1–12		Medium openings, 25–40%
			2–5				
			6–10				Small openings, 15–25%
			11–12		0–3		Very small openings, 10–20%
					4–12		Medium openings, 25–40%
							Position of openings
3–12						X	In north and south walls at body height on windward side
1–2			0–5				
			6–12				As above, openings also in internal walls
0	2–12						
							Protection of openings
					0–2	X	Exclude direct sunlight
		2–12				X	Provide protection from rain
							Walls and floors
			0–2			X	Light, low thermal capacity
			3–12				Heavy, over 8h time-lag
							Roofs
10–12			0–2				Light, reflective surface, cavity
			3–12			X	Light, well insulated
0–9			0–5				
			6–12				Heavy, over 8h time-lag
							External features
				1–12			Space for outdoor sleeping
		1–12				X	Adequate rainwater drainage

Appendix B



B

Indoor Daylighting Conditions/Thermal Comfort Questionnaire

Part 1- General Information

1. Name:

2. Age:

[✓ ≤25]	26-35	36-45	46-55	≥56

3. Gender:

[✓ Male]	Female

Part 2- Daylighting in Office

4. Without using artificial light, how many hours of abundant daylight are there in a typical day?

<1	[✓ 1-3]	3-5	5-7	>7

5. Do you feel that the illumination (lighting) in your workspace is distributed evenly?

Strongly Disagree	Disagree	[✓ Just right]	Agree	Strongly Agree

6. How many hours a day in the summer will sunlight enter the workspace?

<1	1-2	[✓ 2-3]	3-4	>4

7. How long do you prefer the summer sun to be shining into your workspace?

<1	1-2	[✓ 2-3]	3-4	>4

8. How many hours a day in the winter will sunlight enter the workspace?

<1	1-2	[✓ 2-3]	3-4	>4

9. How long do you prefer the winter sun to be shining into your workspace?

<1	1-2	2-3	[✓ 3-4]	>4

10. Do you experience glare sensation?

Always	Often	[✓ Sometimes]	Rarely	Never

11. Do you believe that your workspace has an acceptable overall lighting effect?

Strongly Disagree	Disagree	[✓ Just right]	Agree	Strongly Agree

Part 3- Thermal Comfort

12. What would you say the normal office environment is like in the summer?

Comfort overall in summer	Satisfactory	1	2	3	[✓ 4]	5	6	7	Unsatisfactory
The temperature in summer	Comfortable	1	2	3	[✓ 4]	6	6	7	Uncomfortable

13. What would you say the normal office environment is like in the winter?

Comfort overall in winter	Satisfactory	1	2	3	[✓ 4]	5	6	7	Unsatisfactory
The temperature in winter	Comfortable	1	2	3	[✓ 4]	6	6	7	Uncomfortable

Part 4- Human Behaviors

14. What is the primary function of internal shading? (Curtains/Blinds)

No shading	Prevent direct light	Prevent reflected light	For privacy	[✓ Prevent heating]

15. The internal shading in your office room is usually:

[✓ All drawn]	Drawn more than a half	Drawn a half	Drawn less than a half	Not drawn

16. How long do you leave the artificial light on at work during the day?

<1	1-3	3-5	[✓ 5-7]	>7

Part 5- Luminous Comfort

17. Do you feel that you're working space's lighting conditions are satisfactory?

Strongly Disagree	Disagree	Just right	[✓ Agree]	Strongly Agree

Appendix C

Assessment of Visual Comfort of an Office Building in the Kathmandu Valley

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Abstract

Visual comfort is the primary concern for deciding the quantity of illumination required, and each individual responds to light in a variety of ways that differ significantly based on their surroundings and body temperatures. In both the home and the workplace, appropriate daylighting improves people's psychological well-being and productivity. As the trend toward largely glass façades continues throughout the valley, large fenestration regions usually cause excessive solar gains, greatly changing heating and cooling loads, and glare issues. The study aims to assess the glazing performance and visual comfort of an office building in light of the extensive use of coated/tinted glass. The study was conducted using a survey research method using a typical Prabhu Bank Limited bank office structure. A five-part questionnaire used in a random sample survey of 25 participants was created to collect data on the staff's subjective levels of visual comfort as well as their actual working environments. Additionally, measurements of the ambient temperature, humidity, and standard illumination were taken on-site. Using SPSS 25.0, a statistical analysis application, the data were precisely coded, examined, and evaluated. In the studied office setting, the illumination level at the height of the work plane was only 80–95 lux, which is lower than the suggested range of 300–500 lux. The results showed that illumination and behavioral habits both affect visual comfort. Visual comfort is significantly impacted by behavioral characteristics in people who describe their happiness with daylighting as moderately happy. Statistics show no gender or age-related disparities in the desire for daylighting. Long-term usage of artificial lighting during the day—up to 5-7 hours, and even longer than 7 hours—indicates poor daylighting conditions and reduced luminous comfort. The results demonstrate that office workers are more likely to report being bothered by glare regularly and that uncomfortable glare needs the appropriate intervention for an energy-efficient solution.

Keywords

Visual Comfort, Daylighting, Artificial lighting, Luminous comfort, Glare

1. Introduction

With many glass office towers, Kathmandu valley is one of Nepal's most densely populated cities. Even though the Kathmandu Valley receives a lot of sunlight, the amount of light that enters specific building units can vary greatly based on factors including floor level, orientation, glass type, and outside impediments. Energy expenses are impacted by how much daylight is exposed in buildings. The psychological well-being and productivity of people are improved by increased daylight exposure in both homes and workplaces. Because there is a better awareness of comfort, people are paying more attention to their living conditions, including their thermal, acoustic, and luminous comfort[1]. The primary factor in determining lighting requirements is visual comfort. Good lighting is characterized by the right amount and direction of illumination on the work area, accurate color reproduction, and a lack of discomfort. It also offers a pleasing range of lighting intensity and quality. As a result, to obtain great visual performance, there is typically a strong correlation between illumination levels and visual comfort [2].

Traditionally, architects were masters of daylighting design, but in recent years, the quality of daylighting Historically, architects were masters of daylighting design, but recently, because of an increasingly oppressive hand of regulation and standardization, the quality of daylighting design has substantially dropped in the majority of building types. People react to light in very various ways depending on their environment and temperature, and they see it not just as a visible spectrum but also in terms of what is acknowledged and felt [3]. Office workers are confined to their workspace for a sizable portion of the day. For a view of the outdoors and access to daylight, which are crucial for productivity and health, windows are a need in the workplace. An appropriate comfort level is achieved in large part through the design and selection of fenestration systems. As a result, while constructing a fenestration system, a number of physical aspects must be taken into consideration, such as visual contact between the interior and exterior, daylight consumption, solar energy gain, glare reduction, thermal loss, and thermal comfort [4].

The majority of recently constructed office buildings in Kathmandu valley are largely glazed. As the trend of highly glazed façades continues, excessive solar gains and widely fluctuating heating and cooling loads are frequently the results of large fenestration regions. In addition, bright sunlight causes glare issues, particularly for office buildings' south-facing façades. There are significant advantages to office users' greater productivity in terms of a more comfortable working environment. It is challenging to measure their impact, though. As a result, in daylit areas with lighting controls, a thorough awareness of the occupants' requirements, convictions, and preferences is necessary [5].

Due to the widespread use of coated/tinted glass in contemporary commercial buildings around the world, colored glazing systems are now often used (with static photometric qualities and performances).The main purposes of these glazing systems are to statically control exterior solar gains, hence decreasing the excessive solar gain that might have an impact on indoor thermal and visual comfort. However, it has been known for more than 20 years that such coated/tinted glass systems may have greater detrimental effects on human pleasure and visual/color perceptions [6].

Considering the prevailing use of coated/tinted glass, this paper aimed at assessing the visual comfort and glazing performance of an office building in Kathmandu valley.

2. Literature Review

2.1 Glazed Facade in Office Buildings

Architects have observed a rise in the popularity of office structures with glass facades in recent years. Similar to several buildings to enhance the thermal performance of the building envelope, it has evolved into a common element in commercial construction [7]. These days, glass is tinted, polished, laminated, sealed, rubbed, perforated, stitched, wired, tempered, adjusted, and in lots of forms. Modern technologies have made it easier to create a broad variety of unique styles of substances that may be effectively used in building construction, producing greater performance, as compared to earlier materials technology [8].

2.2 Optical and Thermal Performance

A building's windows are essential for ventilation, daylighting, solar heat gain, and aesthetics. The U-value, the Solar Heat Gain Coefficient (SHGC), and visible transmittance are the three main metrics that can be used to analyze the thermal and optical characteristics of a window. The three widely accepted routes of heat transfer—conduction, convection, and radiation—are used to evaluate the aforementioned attributes [9]

Figure 1: The use of new materials in building architecture[8]

2.3 Visual Comfort

Lighting conditions are frequently thought to have a significant impact on how well vision works. Human eyestrain and experience discomfort in both circumstances of excessive brightness and dimness. The desired illuminance can be exactly achieved with artificial illumination, however, measurements of sky/sunlight are subject to fluctuations due to environmental factors. The significant challenge of ensuring acceptable levels of illumination while using daylight as the source of light, as is the case for all metrics of visual comfort, appears to arise from the fluctuation in solar circumstances. Visual comfort is determined by the following parameters [10]:

- Luminance and illuminance
- Reflectance(s)
- Color temperature and color index
- View and daylight
- Frequencies

2.4 Discomfort glare

A significant amount of sunshine entering interior rooms can be used as the primary light source in office buildings with high levels of glazing. As a result, it is now vital to prevent eye strain caused by excessive sunlight exposure. It is customary to take discomfort glare into account when determining visual comfort in interior spaces, and the discomfort glare indices are now being recommended as a method of application [11].

3. Research Methodology

A survey research method was used to carry out the study by taking a typical bank office building. A random sample survey of 25 respondents belonging to Prabhu Bank Limited located at Dhobi Khola, Baabrmahal, Kathmandu was taken between June 26-29th of 2022. The five-part questionnaire was designed to gather information on the staff's subjective levels of visual comfort as well as their objective working conditions. The survey's questions were based on research done by [1]. The survey's objectives, the researchers' presumptions, and other sources were taken into consideration when crafting the questions. The authors received a total of 30 completed surveys and 25 were selected for additional examination. On-site measurements were also done using a light meter (RT-912) to measure standard lighting and a digital thermo-hygrometer was used to measure both the temperature and humidity. With the aid of SPSS 25.0, the data were precisely coded and examined. Before evaluating the general consistency of the psychometric questions, the statistical reliability was assessed.The internal consistency of the two measures, as well as the degree of daylighting satisfaction and people's lighting-related behavior, were all determined using the Cronbach's alpha coefficient.

4. Research Setting

4.1 Selection of study area

With a population of 2.54 million, Kathmandu Valley is one of South Asia's fastest-growing urban areas, rising at a pace of 6.5 percent per year. Numerous business and financial establishments with both formal and informal workforces can be found in the valley. The extensive use of glazing in building facades has increased in Kathmandu Valley in recent years, despite a lack of accurate awareness of such developments in terms of numerous key aspects of structures, such as energy use, demand, and desired comfort level.

4.2 Climatic Study

The Department of Hydrology and Meteorology Nepal's research of meteorological data from 2012 to 2021, revealed that the average minimum temperature for the year is found to be 13.74°C in January. Summertime's yearly average maximum temperature is reported to be 26.04 °C in July. The highest monthly average humidity is 85.20 percent in September, while the lowest monthly average humidity is 76.85 percent in March. July is when the monsoon season often begins. The predominant wind direction in the Kathmandu valley is westerly, with the yearly highest average wind speed occurring in April and the minimum wind speed occurring in January.

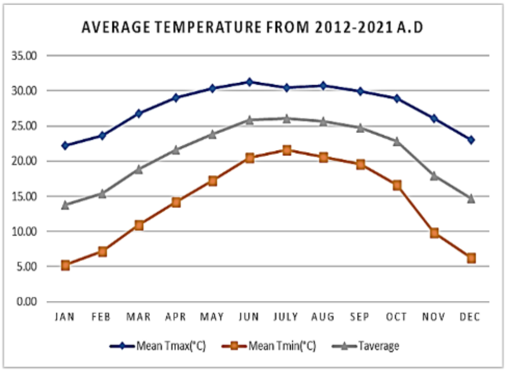

Figure 2: Yearly average maximum and minimum temperature data of the Kathmandu valley from 2012-2021

4.3 Case Study

In Nepal, the number of banking institutions is increasing, along with the number of buildings housing them. A banking office provides the ideal setting for conducting a thorough study with reliable working hours and the ability to assess the visual comfort and glazing performance of office workers.

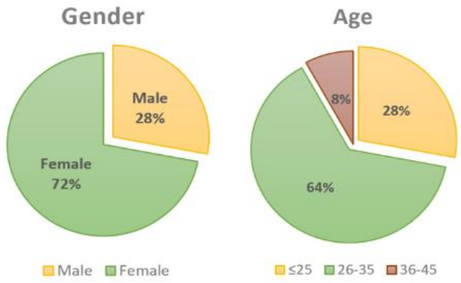

Figure 3: Gender and age based responses

The corporate office of Prabhu Bank, which was chosen for the case study, is situated in Babarmahal on the west side of Dhobi Khola. It is a Nepalese Class A private commercial bank. With a total site area of 2400 m2, the plinth is 1110 m2. There are eight stories and 8884.96 m2 of built-up space overall. The modern structure features a green-tinted glass facade in the East and ACP cladding at the East, North, and South-East corners. The remaining walls are standard 9” brick walls. The flooring is a standard tile/marble finish over a concrete floor, and the roofing is CGI Sheet with a False Ceiling. The floor is 3.15 meters high.

Figure 4: Front View of the Prabhu Bank (Prabhu Bank Limited)

5. Disscusion

5.1 Reliability of the questions - Results

The internal consistency of a survey or questionnaire can be assessed using Cronbach’s Alpha. The reliability of a survey or questionnaire is shown by the range of Cronbach’s Alpha, which is 0 to 1, with higher values. The Cronbach’s Alpha coefficient is determined for the daylighting-related items in Table 1 to assess the internal consistency of respondents’ answers to the questionnaire.

Table 1: Cronbach’s Alpha coefficient (Reliability of the dependent variables)

Daylighting in Office	**Cronbach’s Alpha**
Hours of abundant daylight	0.818
Perception of uniform illumination	
Actual sunlight hours (Summer/Winter)	
Expected sunlight hours (Summer/Winter)	

5.2 Demographic Characteristics of the Respondents

72 percent of the 25 responses received were from women, and 28 percent were from men. The participants’ age ranged; from 28 percent, 64 percent, and 8 percent, respectively, in the age groups of greater than or equals to 25, 26 to 35, and 36 to 45. Figures 4 and 5 below show the split in answers according to gender and age groups.

5.3 Satisfaction with Daylighting – Gender

There was a cross-tabulation done between gender and daylighting satisfaction. Gender-based variation in the replies was investigated. Figure 6 shows how the replies varied from one another.

In comparison to male respondents, female respondents reported considerably higher satisfaction levels. In contrast to the 20 percent of female respondents who disagreed, just 4 percent of the male respondents out of the total answers strongly disagreed. 24 percent of the female respondents and 16 percent of the male respondents expressed satisfaction with daylighting. Only 4 percent of the respondents who identified themself as female

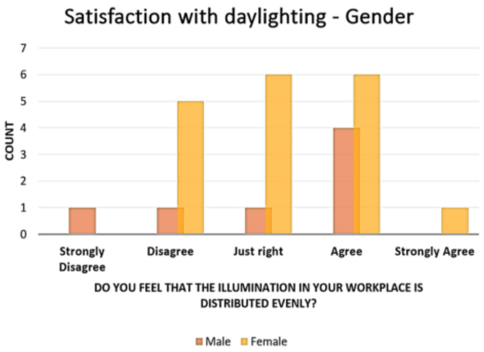

Figure 5: Satisfaction with Daylighting - Gender

strongly agreed with how well-lit the area was.

5.4 Satisfaction with Daylighting – Age

A cross-tabulation between the age group and daylighting satisfaction was conducted. The responses' variance by age group was examined. Figure 7 demonstrates how the responses varied from one another. From 4 percent strongly disagreeing to 16 percent disagreeing and neutral, to a whopping increase of 28 percent agreement in daytime satisfaction, the percentage increases for the age group of 26 to 35. Responses from the 25–44 age range were 4 percent disagree, 12 percent indifferent, 8 percent agree, and ultimately, 45 percent strongly disagree. In the elder age range of 36 to 45, there is an equal percentage of disagreement and agreement (4 percent).

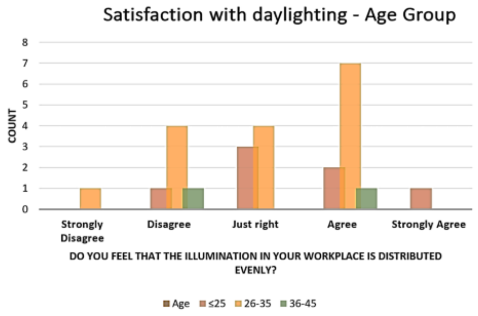

Figure 6: Satisfaction with Daylighting - Age group

Another crucial element is the amount of sunlight, as this has a big impact on how satisfied people are with daylighting. The actual summer sunlight hours and the expected winter hours are a key determinant of how satisfied a person will be with daylighting. The participants would have experienced less daylight hours in winter because in actuality there are fewer daylight hours in winter than there are in summer[1]

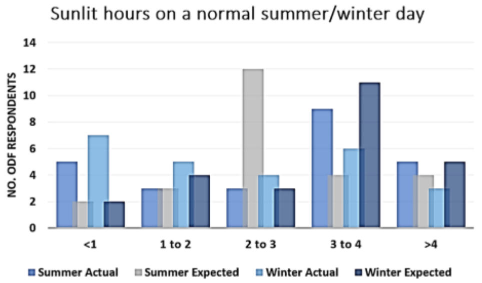

Figure 7: Sunlit hours on a normal summer/winter day

On a warm day, most office workers wanted to enjoy more than two or three hours of sunlight. They hoped for 3 to 4 hours of sunlight per day, and occasionally even more, during the winter. We can attest that our participants chose winter months over summer ones to get as much sunlight as possible. This outcome might be a result of how office spaces can be heated effectively during the winter by sunshine.

5.5 Human Behavior

To change or enhance their indoor lighting environment, people frequently use internal shading and artificial lighting. However, different tasks require various types of illumination, and various lamps offer various color temperatures. The usage of artificial illumination should therefore be considered when evaluating human behavior and luminous comfort. 16 percent responded that the hours of artificial lighting needed in the office ranged from 1-3 and less than an hour.

However, 24 percent, 28 percent, and 16 percent of respondents responded that 16 percent of respondents said that between 1-3 and less than an hour's worth of artificial lighting was required in the workplace. However, a greater rise in the number of hours of artificial lighting from 3-5, 5-7, and more than 7 hours was indicated by 24 percent, 28 percent, and 16 percent of respondents, respectively.

To examine the connection between the two, a cross-tabulation between the perception of glare in the office area and the employment of interior shading tools such

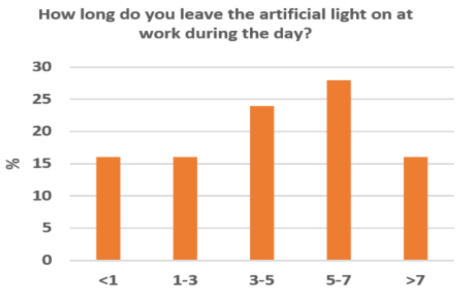

Figure 8: The number of hours of artificial lighting

as curtains and blinds was conducted. Figure 10's findings make it clear that respondents are more likely to report experiencing glare in an office setting.

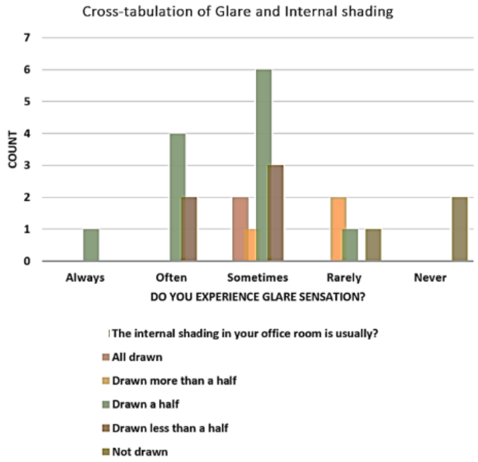

Figure 9: Cross-tabulation between Glare sensation and the use of internal shading device

The cross-tabulation results reveal that the internal shading device is often drawn to half when glare is present. Shade is not necessary when there is no glare sensation. This demonstrates how crucial it is to minimize excessive sun radiation in the workplace for optimal visual comfort. This can be done with the proper installation of energy-efficient glazings and ideal shading components.

6. Findings

Statistics show no gender or age-related disparities in the desire for daylighting. We can confirm that participants chose the winter months over the summer months to receive the greatest sunlight. The findings show that office workers are more likely to claim that glare bothers them frequently. It was discovered that the maximum number of hours for artificial lights was 5-7 hours, and some people responded even longer.

The on-site measurements revealed that the illumination level at the height of the work plane was only 80–95 lux, which is less than the recommended range of 300–500 lux for office work. Table 2 lists the results of the on-site measurements made with a thermohygrometer and light meter:

Table 2: On-site measurements of standard illuminance, temperature and humidity of office building

Features	**Prabhu Bank Limited**
Location	Babarmahal, Kathmandu
Date of Measurement	11th July 2022
Time	12:45 to 1 pm
Sky Conditions	Partly Cloudy/Partly Sunny
Standard Illuminance	West - At the height of the work plane - (80-95 lux) Light source -(300-350 lux) Main façade east side Green tinted window-(890-900 lux)
Temperature	29.6 degree Celsius
Humidity	59 Percent

7. Conclusion

This investigation's primary goal is to evaluate the glazing performance and visual comfort of a Kathmandu Valley office building. The study, which was conducted using a typical bank office structure in the Kathmandu valley, involved a survey research approach and on-site measurements. The data analysis allows for the following conclusions to be drawn regarding the elements that enhance visual comfort.

- People who believe themselves to be relatively satisfied with daylighting say that behavioral aspects have a significant impact on their visual comfort.
- We can confirm that participants preferred winter months to summer months to acquire the maximum sunlight, which may be related to the

fact that sunlight can efficiently heat offices in the winter.

- The findings show that office workers are more likely to report being affected by glare frequently and that this problem calls for the right kind of intervention to find an energy-efficient solution.
- People routinely enhance the indoor lighting environment with internal shading and artificial lighting, and these various actions have an impact on their comfort levels.
- The length of time spent using artificial lighting is the behavior that has the biggest impact on comfort levels in the light. Long-term usage of artificial illumination is associated with decreasing luminous comfort and poor daylighting conditions.

The limitation of this study is that it only examines the glazing performance of the case building that was chosen for examination, which has tinted windows. It does not consider the daylighting and behavioral consequences of other types of glazing. Only under specified climatic conditions are the on-site measurements that were made during the above-mentioned survey dates applicable.

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