

Investigating the functionality of permanent sun shading devices on high-rise buildings of Addis Ababa using custom-made Heliodon



Amanuel Tesfaw

A Thesis Submitted to the department of Architecture

School of Civil Engineering and Architecture

Presented in partial fulfillment of the requirement for the Degree of Master's in
Environmental Architecture

Office of Graduate Studies

Adama Science and Technology University

October, 2022

Adama, Ethiopia

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Approval Page of M.Sc. Thesis

I, the advisor of the thesis entitled “**Investigating the functionality of permanent sun shading devices on high rise buildings of Addis Ababa using custom made Heliodon**” and developed by **Amanuel Tesfaw** hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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RECOMMENDATION

I, the advisor(s) of this thesis, hereby certify that I have read the revised version of the thesis entitled “**Investigating the functionality of permanent sun shading devices on high rise buildings of Addis Ababa using custom-made Heliodon**” prepared under my guidance by **Amanuel Tesfaw** submitted in partial fulfillment of the requirements for the degree of Master’s of Science in Environmental Architecture. Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedures.

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LIST OF ACRONYMS AND ABBREVIATIONS

CIBSE - Chartered Institution of Building Services Engineers

CNC – Computer numerical control

IWEC - International Weather for Energy Calculations

MAPE - Mean absolute percentage error

MDF – Medium-density fiberboard

MTSE – Maritime transit shipping enterprise

SWERA - Solar and Wind Energy Resource Assessment

TM – Technical Memorandum

TMY- Typical Meteorological Year

US NOAA - US National Oceanic and Atmospheric Administration

WWR – Window-to-wall ratio

ABSTRACT

The application of shading devices on buildings goes far back in history and it is being a necessary design element in the modern age as a method of achieving certain aspects of sustainability in buildings. These design features are essential elements in a step forward toward sustainable buildings. In the current state of the use of shading elements, particularly external permanent devices are recurring elements in the modern high-rise building of Addis Ababa. In addition to its fundamental purpose of providing shading against undesired solar exposure the elements also provide an esthetic quality to the general appearance. This paper investigates the effectiveness of these devices in terms of shading capability during overheated seasons. The overheated season is determined by identifying periods of the year exceeding a temperature threshold of 24 °c for 2% or more time of the month. To conduct this investigation, a custom-made heliodon which is a device that can simulate the position of the sun in terms of azimuth and altitude on a particular location throughout the year is developed and used. The design basis is a conceptually clear model of heliodon first developed by Robert Lechner which intern is inspired by a geo-centric view of solar geometry. As such the custom-made heliodon with a 1:40 scaled model of selected high-rise buildings' shading elements is used to determine the shaded fraction cast on the window glazing surface. Among various shading devices selected for this analysis, a horizontal louver on a vertical plane performs the best with 90% average shading. The lowers shading performance was recorded by vertical fins facing southeast at 45% shading. Combined shading system of vertical overhang with horizontal louvers sowed above 70% of shading in their respective orientations. A result verification conducted using a mean absolute percent error resulted in a 13% error margin. A computer simulation result was used as an accepted value to compare the results against. Finally, It is recommended that a thorough understanding of solar geometry be established while designing shading devices. Also, solar analysis using tools such as heliodons, solar charts, or computer simulation be conducted early in the design phase as these devices can play a crucial role in a stape towards sustainable architecture.

Keywords: Heliodon, shading devices, solar geometry, solar path tracking, sun's position

CHAPTER ONE

INTRODUCTION

Maintaining favorable indoor conditions through various design strategies is becoming a vital concept in modern buildings. Shading devices are one of the passive approaches that enable architects to achieve sustainable designs in terms of preventing solar heat gain. These design elements are implemented in different building typologies throughout the world. Several buildings in Ethiopia and Addis Ababa also feature shading devices of various sorts. This research focuses on external shading devices on high-rise buildings because of their high-glazed surface areas that necessitate the use of shading elements during overheated seasons. The motivation behind the research is the desire to promote the use of proper shading devices as sustainable design features and understand the extent of the shading element's effectivity besides being an aesthetical feature. This study investigates the functionality of external shading devices in terms of respective shaded fractions using a custom-made Heliodon.

The background of the study, statement of the problem, objectives, research questions, scope, significance, and limitations of the study are discussed below in this chapter.

1.1. Background of the study

As a result of growing urbanization and a rapidly growing population, high-rise buildings have become more prevalent in many cities. According to (Ibrahim, 2007) Tall structures are erected due to the lack of other alternatives for achieving dense development in the urban fabric. The rising demand for buildings was resolved by the development of new construction which required lightweight materials that resulted in the wide use of frame constructions and glass envelopes (Abbood, Weli, & et.al., 2021). However, glass presented the problem of indoor overheating and paved the path for the invention of air conditioning systems as an active measure and the integration of shading systems as a passive measure (Ray & Roy, 2019).

Owing to high solar heat intake, today's buildings are often found excessively hot on sunny days (R Ruparthna, 2016). Summer overheating issues, on the other hand, appear to be increasing as a result of the growing tendency toward greater glass envelop as part of western aesthetic considerations, culminating in the entirely glazed facades in commercial and office

buildings (Abdoli & Bakhsh, 2014). Huge windows provide numerous benefits in terms of visual comfort with the surrounding environment, and good psychological reaction linked with the sense of openness and freedom that large glass exteriors create (Cellai G, 2014). According to Laura, et.al, (2014), Extensive glazing necessitates practical solutions for the reduction of solar heat penetration during the hot season is the primary focus in reducing solar heat penetration (Laura, Concetta, & et.al, 2014).

The indoor thermal comfort of a building depends on several factors which include the prevailing climatic conditions, site location, building orientation, and building materials used (Ngungui, 2018). Solar radiation is one of the main factors that impose a significant influence on indoor temperature and consequently cooling loads (Mingfang, 2001). This can translate to being the main driving factor to indoor thermal gain. It was evaluated that solar radiation increases cooling requirements by as much as 25% (Elasfour AS, 1991). There is a growing demand for strategies to combat excessive solar gains in buildings (Mingfang, 2001). The inclusion of effective shading has the potential to improve the indoor thermal environment, it can reduce summertime overheating, regulate swings in temperature and reduce cooling load (R Ruparthna, 2016). Furthermore, shading devices help to limit the amount of light that enters a structure, reducing thermal overheating, glare, and other unpleasant effects (Brotas & Nicol, 2016). External shading devices are considered by several works of literature to be the most effective barrier against the sun and to have the greatest impact on the building's appearance (Brotas & Nicol, 2016). When used in appropriate circumstances solar shading elements help mitigates overheating conditions which otherwise lead to thermal discomfort, reduced performance, and health issues (Szokolay S. , 2008). Also, architectural shading systems have proven to be an important part of architectural expression. They are often found on the building's exterior and play a significant role in its look (Brotas & Nicol, 2016). They form an outside skin that, in addition to aesthetics, regulates the internal climatic conditions of the building based on technical criteria (Mandalaki & Tsoutsos, 2020).

In comparison to low-rise or medium-rise structures, which can be easily shaded by the roof and vegetation, high-rise building envelopes are exposed to the entire impact of global solar radiation and the ambient temperature due to their height (Cellai G, 2014). The area of the façade and fenestration of high-rise buildings is much larger than that of low-rise buildings (Ossen, Ahmad, & et.al., 2005). Incoming solar radiation in buildings has strong implications both in visual and thermal aspects. To mitigate this concern passive architecture

can be applied. The basic principle of passive solar architecture is to take advantage of environmental situations by strategically placing, orienting, and sizing building components with minimal mechanical or artificial thermal control (Szokolay S. , 2008). Solar shading systems control daylight levels in buildings and the view to the outer environment by reducing annual solar gains and modifying heat exchanges via the glass building envelope (Laura, Concetta, & et.al, 2014).

High-rise buildings have been rapidly increasing worldwide due to limited land availability in populated areas and their primary role as essential buildings in modern cities and capitals (Abbood, Weli, & et.al., 2021). Addis Ababa, the capital of Ethiopia is no exception to this international phenomenon. Tall buildings generally, as a built form consume more material and energy resources in their construction, operation, and demolition than low-rise or mid-rise buildings, making them environmentally demanding. According to (Tsfahunegn, 2020) the most common design parameters employed in the passive design of buildings in Ethiopia include orientation, shading, ventilation, glazing, and thermal properties of materials. Shading devices, which are a component of a building envelope, perform a crucial role to give positive influences towards energy efficiency in buildings (Nielsen MV, 2011).

A solid grasp of solar geometry and its influence on the design of buildings or locations is required for successful solar-responsive designs (Szokolay S. V., 2007). According to Conrado-Lizbeth (2022) Sun path diagrams, heliodon devices, and software programs are the three primary tools that can be used to analyze shadows and shading performance. Using Heliodons, shading devices can be tested to determine their effectiveness in their respective building envelopes (Lechner, 2015). Heliodons are developed for testing sunlight effects on physical building models, aiming at reproducing the actual direction of sunlight in relation to a building (Cheung & Lam, 2015). Using this tool effectiveness of shading devices can be demonstrated.

1.2. Problem Statement

Newly emerging high-rise buildings in Addis Ababa have various design styles and approaches. The buildings use diverse design elements which can potentially add to the visual appeal of high-rise buildings by allowing architects to merge functionality and aesthetics. One of the notable features of these buildings is their tendency to have a high area of glazed envelop exposed to solar radiation. Window glazing is usually the weakest thermal

element in the building envelope, and one of the most common causes of overheating is excessive solar gain through windows. Designers typically dismiss data regarding the significance of shading devices. But design considerations for shading devices are crucial, especially for facades with a high window-to-wall ratio. This can significantly reduce solar gain through windows. Which is an important consideration in maintaining comfortable indoor temperatures and implementing low-energy building design. As indicated by various scholars, external shading devices on a building's façade are effective passive design solutions due to their potential to reduce the direct incidence of solar radiation. High-rise buildings in Addis Ababa feature these design trends of integrating external permanent sun shading components. A preliminary survey showed that 41% of buildings identified as high-rise incorporate permanent solar shading devices. This study inquires whether the permanent sun-shading elements of high-rise buildings are aesthetical appendages or a practical solution for one of the root causes of indoor discomfort due to overheating. And if these devices are functional, to what extent are they effective? Identifying the current practice of shading elements helps us evaluate the level of understanding about solar architecture in the city. Moreover, this can help identify exemplary practices and adapt to future projects.

Previously conducted international research has assessed the performance of shading devices, direct solar shading, illuminance, daylight factor, glare, and outdoor visual. This study primarily employed computer simulations. Local research conducted about assessing the performance of external shading is highly limited. A research paper by Fitsum (2021), assessed context-based design and performance of fixed exterior shading devices in multiple buildings in Addis Ababa. Using a software simulation, this research assessed the performance of fixed exterior shading devices in blocking incident solar radiation as well as optimizing indoor thermal comfort. However, the selection of buildings was not inclusive of all orientations despite including various shading types. However, from a methodology aspect, no research has been conducted locally using Heliodon. Hence this research expands on previous studies by introducing Heliodon as an analysis tool and outlining specific methods.

1.3. Objectives of the study

General Objective

To investigate the shading performance of external permanent sun shading devices installed in high-rise buildings of Addis Ababa during the overheated season.

Specific objective

- To identify the overheated time for which sun shading devices are needed
- To analyze the performance of the respective sun-shading device
- To Validate the findings against the computational model of solar shading analysis

1.4. Research question

1. What is the overheated season in Addis Ababa?
2. How effective are these shading devices against direct solar radiation during the overheated season of Addis Ababa?
3. To what extent are the findings reliable?

1.5. Significance of the study

The study aims to contribute by bridging the gap between the theoretical and the practice of sustainable and passive solar architecture by analyzing the current application of sun shading designs integrated into high-rise buildings and assessing their effectiveness. Furthermore, the research lays out a method and constructs a Heliodon as a reintroduction of analysis and demonstration tool that is used to conduct sunlight emulation throughout the year, and time of day in the specific study location, which will be a significant contribution to the department as learning and teaching instrument that can aid in the understanding of solar geometry and the impact it can have on the design of buildings or project locations.

1.6. Limitations of the study

Due to the nature of the study being dictated by the measuring instrument used, some known limitations are acknowledged from the start. One of the major limitations is the lack of already established procedures to conduct the analysis and the lack of pre-existing validation

method for use. The measuring device (i.e. Heliodon) can only emulate the direction of the solar rays and not their thermal intensity. Furthermore, the limitation arises from accumulated inaccuracy of both instrument and measurement error. To reduce this limitation, repeated measurements were taken. Another important limiting factor is the complex building and shading device geometries. This limitation is mitigated by simplifying façade details such as inclinations and curvatures of large diameters.

1.7. Scope of the study

In the recent development of high-rise buildings in Addis Ababa, the application of shading devices has been increasing. Hence, this study focuses on investigating the performance of permanent shading devices installed on the exterior envelope of high-rise buildings located in Addis Ababa, the capital of Ethiopia. Parameters of investigations are the effectiveness of the respective external permanent shading devices shielding short wave radiation from the sun in the given location and during the overheated period. All buildings that satisfy the prior criteria in cardinal and ordinal directions are included in the study. Even though solar radiation is responsible for the provision of natural daylight in the building space, this particular study focuses mainly on solar incidence which can result in indoor overheating.

For ease of analysis, the selected shading devices are simplified and placed in a uniform scaled model. And the analysis focused on direct solar radiation excluding the property of glazing material, effects of ambient refraction, and self-shadowing. The study investigated the shading device in and on their merits in their respective orientations. Further analysis was conducted in a hypothetical scenario where the selected shading device has the same orientation.

1.8. Definition of key terms

Conceptual definition

Heliodon: (HEE-leo_don) is a device for adjusting the angle between a flat surface and a beam of light to match the angle between a horizontal plane at a specific latitude and the solar beam.

Sun path: refers to the apparent significant seasonal and hourly positional changes of the sun (and length of daylight) as the Earth rotates, and orbits around the sun.

Solar azimuth: position of the sun measured in the horizontal plane from north or south.

Solar altitude: position of the sun measured upwards from the horizon where the observer's location is at the center of the sky dome.

Solar declination: the angular distance of the sun's rays north (or south) of the equator.

Shading mask: a representation of the sky as viewed from a reference point, indicating the portion of the sky that is visible and obstructed.

Sky Dome: refers to the sum of the components for the entire sky from horizon to zenith, and in all azimuthal directions

Operational definitions

External fixed shading devices: immovable shading elements constructed as sun breakers in the outer perimeter of a building as part of the façade or the building structure.

High-rise buildings: buildings that have 13 or more floors.

Overheating periods: periods when the average temperature surpasses 24 °C for 2 % or more of the time.

shadow analysis: describes the process by which the shadow profiles of an object and its surroundings are studied at a particular time of day or for certain days of the year.

Shading performance: the extent of functionality of shading devices in terms of providing a barrier against the incidence of direct solar radiation.

Solar altitude: position of the sun measured in degrees upwards from the horizon where the observer's location is at the center of the horizontal plane, this changes gradually with the month of the year.

Solar azimuth: The angle between the line that points to the sun and the south. This angle changes with the hours of the day. 15° represents 1 hour and 90 ° represents midday.

1.9. Organization of the research

This thesis consists of Five chapters. The study's material and data are thoroughly examined in each chapter. The following provides an additional description of the thesis's key chapters.

Chapter one: Introduction, consists of the background of the study, statement of the problem, objectives, hypotheses, and research questions, significance of the study, delimitations, and limitations of the study.

Chapter two: Literature review, this chapter is used to maintain a clear connection to the current study. It offers a thorough overview of the problem's background. It reveals what other researchers have previously investigated and how it relates to the current study. The formulation of the problem statement and development of measurement tools is the focus of the review chapter.

Chapter three: Material and Method, this chapter outlines the study's methodology, population, and sample are covered in the first half of the analysis, while the instruments and methods used in the research are covered in the second section. Additionally, the study's methodology is presented. In this chapter, the entire study's design is covered in depth. The systematic reporting of tool administration and scoring methodology. Here, the structure and presentation of the data are also discussed.

Chapter four: Results and Discussions, following the methods described in the previous chapter results are obtained and this chapter outlines the results uncovered by the research. And also in this chapter results of the research are briefly discussed to draw a conclusion and summarize the analysis.

Conclusion and recommendations, the results are addressed to make them more relevant.

The final section of this research is the conclusion and recommendations. Based on the findings and discussions of various metrics, this chapter came to certain conclusions. In this chapter, concrete measures that should be implemented by stakeholders in light of the research's results were also advised.

CHAPTER TWO

2. LITERATURE REVIEW

Using case-related scientific publications, databases, and web searches, a thorough review of the literature is conducted. This chapter focuses on bringing clarity to defining high-rise buildings, building shading device types, moreover the theoretical and practical use of Heliadons to assess the effect of the sun on buildings and their shading elements. The literature explores the technical factors that need to be considered while constructing a heliaden to better understand the relationships between the physical world and the simulated environment. Also, the chapter explains the notion of overheating seasons concerning the study area.

2.1. Theoretical review

Defining High rise buildings

High-rise buildings have become a more common occurrence, particularly in metropolitan regions. Tall buildings, as a building type, are a 19th-century technological invention in reaction to economic, industrial, and social changes. Several scholars explain that beginning in the late 19th and early 20th centuries, Chicago and then New York were the birthplaces of commercial tall buildings. During the 1980s and 1990s, this building type became popular due to globalization, population growth, and rapid economic development in Asian and African countries (Challinger, 2008).

The utilization of mass-produced industrial materials - primarily steel, concrete, and glass - was critical in allowing the types of construction necessary to accommodate modern functions. Furthermore, the use of mass-produced (and occasionally prefabricated) materials had the potential to be constructed more efficiently and inexpensively than craft-based, traditional materials, thus serving as practical and symbolic proof of modern invention and progress.

Buildings are defined as an enclosed structure that has walls, floors, a roof, and usually windows. Nonetheless the term 'high-rise building' does not have internationally agreed-upon definitions. However, there are some definitions put forth by different works of literature, Among these descriptions of what a high-rise building is a definition by

(Challinger, 2008) which states high rise building (tall building) is a multi-story structure in which most occupants depend on elevators to reach their destinations.

Various countries have different criteria for this issue. The accessibility of firefighting equipment is a crucial factor in determining the height of a high-rise structure. The urban planning standard book (Hall, 2005) recommends that the cut-off point for high-rise buildings is around seven stories. Sometimes, seven stories or higher define a high rise although the height can sometimes be described in linear meters. On the other hand, Multifamily and commercial high-rise buildings are structures that share common walls with the units that are laterally and vertically adjacent. The typical height cut-off for these structures is considered to be 12 to 50 levels or more (Steiner & Butler, 2007).

In the Ethiopian context, there are different approaches to classifying building types. Building height classification was established in Ethiopia in 1986, 2002, and 2010. Building heights are now classified into building height zones under the new building height rule. The zones are broken down as follows:

- Building Height Zone 1: - has 70m minimum height and adds no limit on the maximum height.
- Building Height Zone 2: - Maximum building height of 70m.
- Building Height Zone 3: - Maximum Building height is 35m.
- Building Height Zone 4: - Maximum Building height is 35m but the floor area ratio is different from zone 3

The 2011 amended building height regulation of Addis Ababa delineates high-rise buildings as buildings that have 13 or more stories with an average recommended plot size of 24 m by 26 m (Report on Building Height Regulation updating study for Addis Ababa, 2011). Therefore, the study includes buildings in zone 2 which have a height above 35, and zone 1 which includes buildings heights of 70 m and above.

Overheating in buildings

Defining overheating

At the present, there is no definitive, unassailable, and universally accepted definition of overheating (Lomas & Porritt, 2017). Nonetheless, there are different definitions by different scholars, among the explanations is that 'overheating' refers to discomfort to occupants

caused by the accumulation of warmth within a building. Another definition by (Szokolay S. V., 2007) states that overheating occurs when the monthly mean temperature is higher than the lower comfort limit which requires shading to be provided. Szokolay notes that daily temperature profiles should be referred to determine hours when shading is necessary.

A professor and an advocate of sustainable design (Lechner, 2015) define overheating in terms of Balance point temperature (BPT) which is defined as the outdoor air temperature required for the indoor temperature to be comfortable without the use of any mechanical heating or cooling. Furthermore, the balancing point is a critical indication that indicates the relationship between a building's climate, occupancy, architectural design, and energy flow patterns. This is the external air temperature at which heat gains from electric lighting and equipment, body heat, and solar radiation are balanced by heat losses owing to temperature variations through the building envelope (Michael & James, 1997).

Cause and Impact of overheating

Overheating is a concern for most new buildings, as well as several existing structures, and will certainly grow more so as our climate warms. This is because the climate of the earth is largely influenced by the energy input from the sun. The solar heating effect is determined by the intensity of solar radiation reaching the earth's surface, as well as its angle (Lechner, 2015). The internationally renowned (Passivhaus Trust, 2021) describes that an overheating condition will develop if the amount of heat entering the building (gains) exceeds the amount lost by passive or active cooling (losses), and the interior temperature will begin to increase. Therefore the primary overheating driver is typically solar energy transmitted through glazing as shown below in Figure 1.

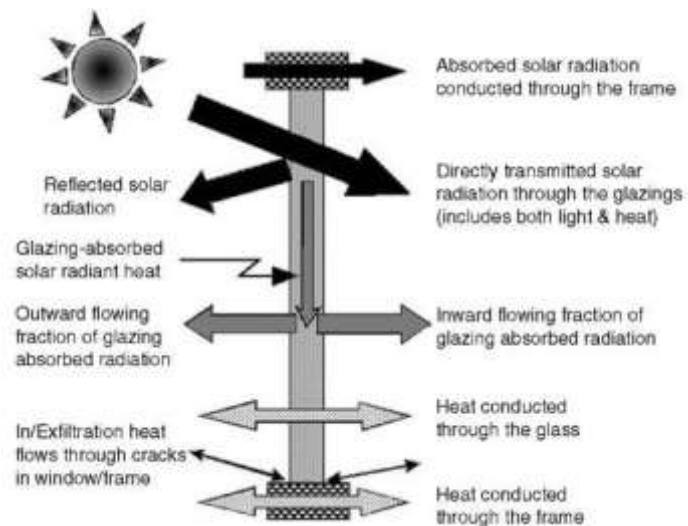


Figure 1 Transmission of solar energy through glazing

Solar energy is transported indoors through the building envelope's transparent components. This energy raises the temperature within the indoor space (Cellai G, 2014). Some of the diffuse solar radiation impinging on the outside surface of the glazing is transported within and diffusely reflected on the interior surface. A part of the incoming radiation is absorbed by the opaque walls and the inside surface of the glazing after several diffuse reflections between walls and glazing, raising the indoor temperature (Hernández & Moreno, 2018). (Szokolay S. , 2008) Posit that architects have to take into consideration of the apparent movement of the sun i.e. solar geometry and energy flows from the sun and how to respond to it i.e. exclude it or take advantage of the energy as an input.

Over the last century, the proportion of high-rise buildings' envelope that is transparent has increased significantly. Among several factors, the nature of transparent building facades is the leading cause of overheating in buildings which are becoming a problem in buildings in the city centers (Etheridge, 2010). This situation is further exacerbated by the Urban Heat Island phenomena and by climate change (Brotas & Nicol, 2016). Due to the low thermal insulation property of glass, in comparison to mass opaque building materials (Cellai G, 2014). The larger the transparent portion of the building's envelope, the more the building is susceptible to overheating hence, necessitating the control of solar energy inflow, to keep thermal and visual conditions indoors at acceptable levels. Transparent facades require an extra management mechanism to assist prevent sun radiation during overheated time (Mandalaki & Tsoutsos, 2020)

The impact of overheating in the built environment has been a topic of discussion for many researchers. Most reviews conducted on the impact of overheating suggest that high temperatures are a potential cause of various physical and psychological indispositions, which include cardiovascular and respiratory ailments. As summarized by (Zero Carbon Hub, 2015) The physiological responses to heat are continuous functions and there is a multi-stage transition from thermal discomfort to heat stress. Moreover, a large burden of adverse heat-related effects on health may occur in the absence of clearly identifiable heat stress and affect a wide range of clinical conditions. Thus, heat-related illness consists of a spectrum that includes heat rash, heat oedema, heat cramps, heat syncope, heat exhaustion, heat stroke, and even death (Lomas & Porritt, 2017).

Overheating standards

There is no universally accepted starting point for overheating to occur, however, Patidar et.al. (2012) State that defining any specific threshold for measuring overheating in the context of buildings is a complex issue as such thresholds should be linked to the thermal comfort of the occupants.

According to Lechner, a typical internally dominated building has a balance point temperature of 15 °C. And 10 °C for envelop-dominated buildings. The overheated range starts at 5 °C above the BPT, similarly the underheated period has a threshold below 5 °C of the BPT (Lechner, 2015).

The ASHRAE standard on overheating ISO 7730 does not put forward a definite threshold for overheating periods but rather defines thermal comfort based on the responses of the occupants. Figure 2 shows ASHRAE's range of acceptable temperatures for free-running buildings.

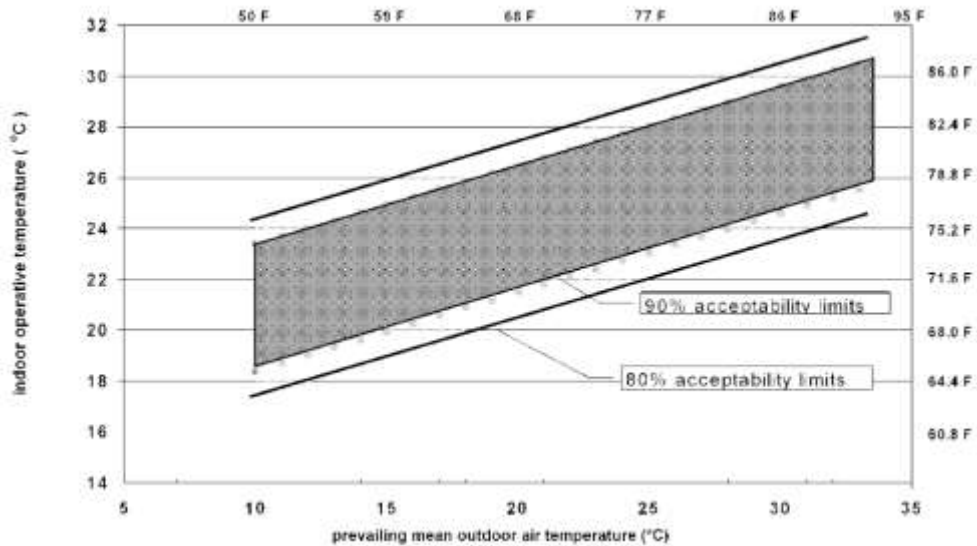


Figure 2 ASHRAE acceptable indoor temperature for free-running buildings

According to the documentation of overheating simulations (BB101 2018, TM52, TM59) criteria are used to assess the performance of naturally and mechanically ventilated buildings during periods of hot weather. Design criteria can differ in complexity from the number of hours for which a particular temperature is exceeded to a sophisticated comfort prediction. The overheating criteria are mainly defined to investigate the influence of persistent overheating of the building over a specified period on the occupants. The Chartered Institution of Building Services Engineers (CIBSE) defines overheating as the exceedance of 28 °C for more than 1% of occupied hours, based on simulations using weather files from a ‘design summer year’ (DSY).

According to the passive house standards overheating is dependent on the level of occupancy and activity. As a comfort-driven approach, the standard defines overheating in terms of internal temperature levels, as such summer overheating criterion is that indoor temperature shall not exceed 25 °C for more than 10% of the year. The threat of a building overheating is often greatly reliant on actions taken by the occupants most commonly encouraging occupants to deploy shading or initiate ventilation (Passivhaus Trust, 2021).

The Standard Assessment Procedure (SAP) (BRE 2012) provides a simplified check of whether the space will have an overheating problem. If the calculation shows monthly mean internal temperatures lower than 20.5°C the risk of the space overheating is predicted to be not significant. If the calculation estimates internal temperatures between 20.5°C and 22°C, then there is predicted to be a ‘slight risk’ of overheating, (see Table 1).

Table 1 SAP overheating threshold

Threshold temperatures (°C)	Likelihood of high internal temperatures during hot weather
< 20.5 °C	Not significant
≥ 20.5 °C and < 22.0 °C	Slight
≥ 22.0 °C and < 23.5 °C	Medium
≥ 23.5 °C	High

Risk of overheating in Ethiopia

A report by the World bank group on Climate risk profile (2019) assesses the impact of climate change under different scenarios. Under a high-emission scenario, East Africa, notably Ethiopia, will see increased temperatures, with mean monthly temperature variations anticipated to rise by 1.8°C by the 2050s and 3.7°C by the end of the century. In expected future climates, the frequency of 'hot' days and nights will significantly rise. According to annual forecasts, 'hot' days will occur 19–40% of the time in the 2060s, and 26–69% of the time in the 2090s (see Figure 3).

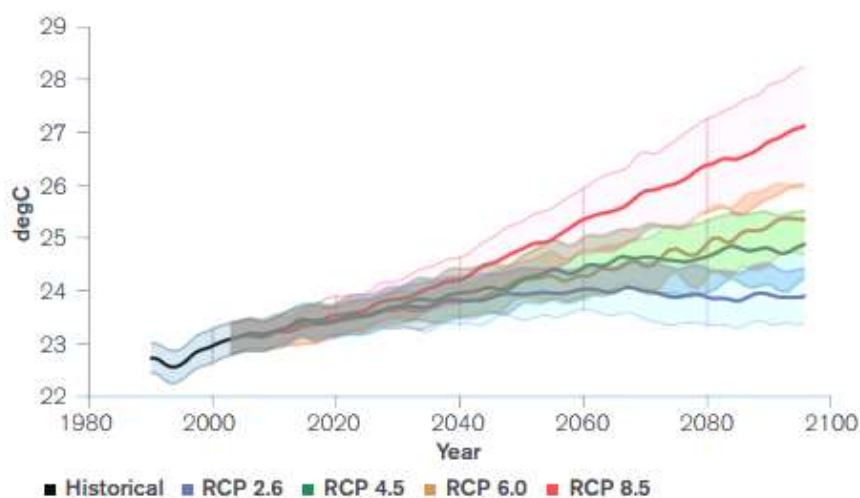


Figure 3 Projection of heat increase in different scenarios

WHO report (2018) indicates that the temperature in Ethiopia will continue to rise through the end of the century, regardless of emission scenarios. Average temperatures will rise substantially by mid-century in a high-emission scenario. Temperatures will rise sharply and be felt throughout the entire cycle, from June to January. Increased heat, especially intense heat, will have serious consequences for human and animal health, agriculture, water supplies, and ecosystems. In general, the mean annual temperature is set to increase by 1⁰ to 3⁰ in Ethiopia.

Principles of solar overheating control

Sunlight is often welcome in buildings but the sun can also have an adverse effect, excessive solar gain can lead to overheating during sunny seasons or high air conditioning loads to compensate for the excessive heat gain. As portrayed by the CIBSE TM37 and by various scholars, overheating can be prevented through appropriate building design among which, Solar shading measures including external, internal, or mid-pane shading devices or solar control glazing are often incorporated on building envelopes as passive design measures.

Lecher's (2015) principles of sustainable design suggest planning the layout of buildings and rooms to maximize the benefits of sunlight and minimize the disadvantages such as solar heat gains is of paramount importance. The other important measures linked with building envelop is limiting window area since solar heat gain is roughly proportional to the window area. Additional techniques include exposing heavyweight structures with high thermal mass, providing good ventilation, and reducing internal gains because of equipment and appliance. As an active measure using mechanical cooling or air conditioning can prevent overheating in an indoor environment (CIBSE, 2006).

2.2. Sun shading devices

Historical background

Sun shading devices overall allow designers to manage natural lighting, ventilation, and solar gain, all of which provide a benefit to the overall building performance (Laura, Concetta, & et.al, An Overview on Solar Shading Systems for Buildings, 2014). Historically massive shading systems serve two purposes: they shade the inside space and provide a shaded outside area. The portico and colonnades of ancient Greek and Roman structures may provide both shading and protection for the facade. Shadowed outdoor areas Aside from its symbolic and aesthetic value, which is adapted as neoclassical style in hot and humid conditions (Mandalaki & Tsoutsos, 2020).

Shading systems play a vital role in the energy performance of buildings as well as serve to be strong architectural expression elements. This is due to their placement in the exterior of the building hence greatly influencing the appearance of the building. Especially in the modern era where construction has transitioned from masonry walls to skeleton systems, the possibilities of expressiveness in building facades have increased (Laura, Concetta, & et.al,

2014). Shading devices have been in use in one form or another, therefore there is a diverse range of typologies and styles which have inspired modern shading strategies.



Figure 4 Illustration by Le Corbusier

During the 1930s, as one of the pioneers of modern architecture, Le Corbusier was working largely in hot countries, and the invention of the brise-soleil seemed to be the answer to problems of heat gain. As illustrated by his artwork (Figure 4), Le Corbusier realized the dual nature of the sun—‘our friend in the winter and our enemy in the summer. After coming to this conclusion, shading started to play a major role in his architecture. He valued the potential for artistic expression just as highly as solar protection. As a result, the sunshade is a prominent visual aspect in many of his buildings (Lechner, 2015).

Modern architectural preferences in elevations and general appearance resulted in an increased transparent portion of building facades. Consequently, the requirement for shade has grown, and shading systems have become increasingly crucial for the building's overall aesthetics (Mandalaki & Tsoutsos, 2020).

According to (Mandalaki & Tsoutsos, 2020) and Lechner (2015) Historically, the necessity of larger windows to facilitate ventilation, reduce interior humidity and admit more natural light into the interior of the spaces has long been understood, this is evident in some vernacular practices, especially in classical architecture. But also the exposure to solar radiation through these windows has been a challenge. Classical architecture which echoes through neoclassical architecture has addressed these issues through the use of external shading elements (Laura, Concetta, & et.al, 2014).

Purpose of solar shading devices

The ASHRAE Handbook describes Shading as an element that can be placed outside or within the building, and in some situations; it can even be built into the glazing system (between the glass). Metal, wood, plastic, and fabric are among the materials employed.

Shading devices come in a variety of shapes and sizes, each with its appearance and energy efficiency. Indoor and outdoor blinds, integrated blinds, indoor and outdoor screens, shutters, draperies, and roller shades are just a few of the options. Outdoor shading devices are more effective than indoor shading systems at reducing solar heat gain. Indoor gadgets, on the other hand, are simpler to use and adapt (ASHRAE, 2009).

The primary purpose of solar shading systems is to reduce the fractional range of transmittance of solar radiation so that it does not penetrate inside structures. External shading performs well on the envelope's glazed surfaces, allowing for good shade management in hot and humid circumstances. In such environments, an efficient shading strategy should not only reduce but also optimize solar gains throughout the year, as well as compensate for other solar energy-related criteria linked with its availability in the built environment, such as adequate daylight inside the environment. (Dalumo & Lim, 2021). Fixed external shading devices, such as louvers, are widely used to combat solar gains that can lead to excessive overheating (Kenneth Ip, 2019).

An application of a sun-shading device is one of the decisions to elevate the exterior façade appearance while keeping the thermal performance at the best for indoor environments. Passive design strategies for cooling, such as fixed sun-shading devices on the external surface of buildings, can create a comfortable and favorable thermal environment. Because the absorbed heat is dispersed externally, these sun-shading devices are the most effective of all for lowering solar radiation. Their ability to obscure the sun's rays before it reaches the building is quite valuable (Saifelnasr, 2015). The sun-shading device system affects energy demands and enables significant control of indoor thermal performance, visual comfort, and space conditions while allowing occupants to control their privacy and view of the outside (Gimat & Sulaiman, 2020).

Solar shading devices and sustainability

As stated by (Lechner, 2015), the three-tier design strategy (Figure 5) is a sensible and environmentally sustainable way to provide summertime thermal comfort. Shade and heat avoidance are included in tier one.

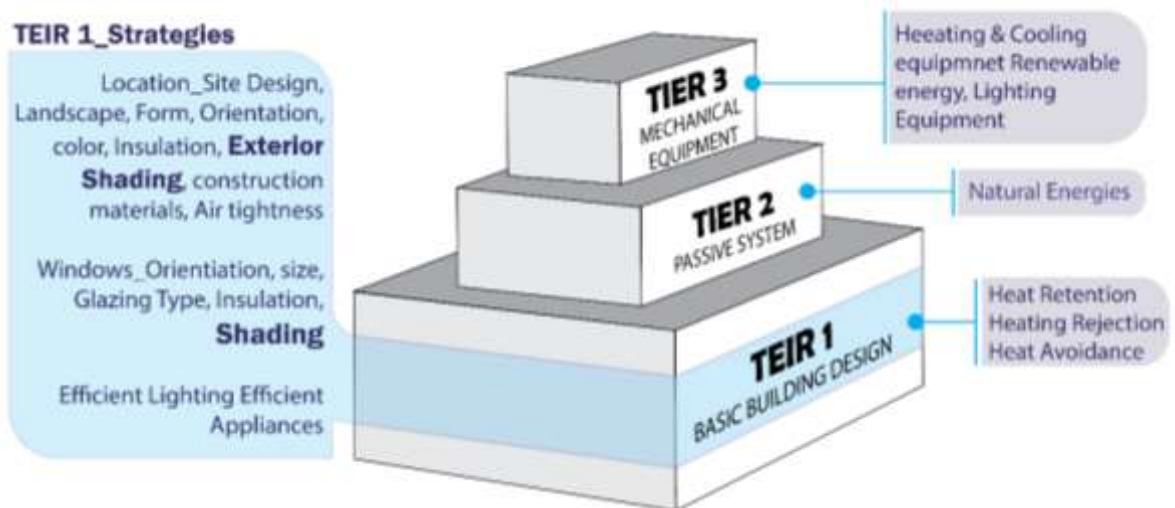


Figure 5 The three-tier sustainable design approach

Leading researchers in the concept of bioclimatic design such as Lechner explain that Exterior sun-shading devices are often employed in the design of contemporary buildings to reduce solar heat gain during cooling months and prevent glare from disrupting the occupants' visual comfort. As shown in Figure 6, Adopted from Geovanni's structural bioclimatic chart, Shading is a passive measure that can be applied to modify the temperature of a space to keep it within the thermal zone.

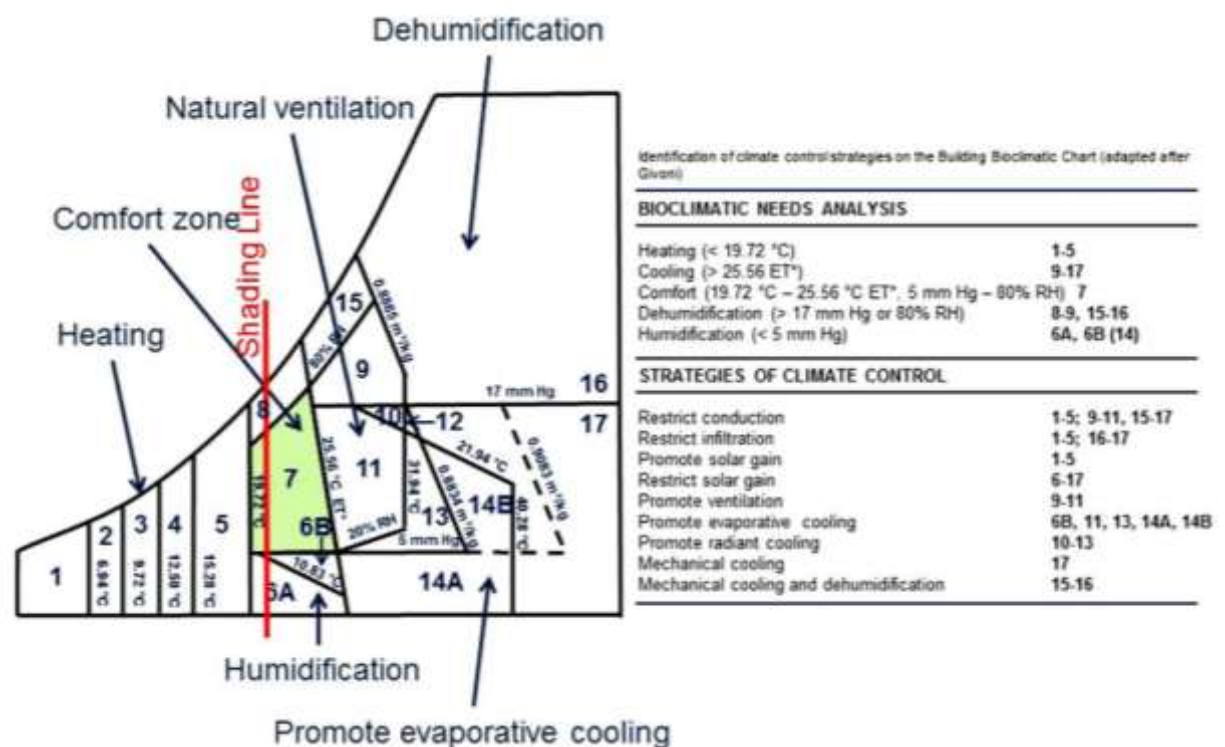


Figure 6 Strategies of climate control overlaid on a psychrometric chart (After Watson and Labs)

Shading with regards to Solar Radiation

The sun protection effect for glass surfaces depends on several factors, among this factors the most significant are; the reflectivity of solar radiation of the applied material and its coating color, the location of the shade protection which influences the reradiating and convection heat impact, and the specific arrangement of the applied shading method. The interplay of these factors can help us conclude the effectiveness of shading elements (Olgyay, 2015).

Generally, solar radiation is divided into two types; direct and diffuse. Diffuse radiation does not have a directional beaming property it is the sum of scattered sky radiation and reflected direct radiation and is not significant in terms of heat gain. On the other hand, solar radiation that reaches the Earth's surface without being diffused is called direct beam solar radiation which can cause an increase in temperature in an environment (Brotas & Nicol, 2016). The most effective way to regulate solar heat gain is to intercept it before it reaches the building exterior, as long as this does not interfere with solar gain arrival in the winter when it is needed (Laura, Concetta, & et.al, 2014). A shade system's primary function is to shield a structure from direct solar radiation, but it also serves two other functions in its designated place as a regulator: creating a healthy atmosphere and improving building performance. Shading devices operate by breaking direct sunlight and dispersing it into diffuse light (Al-Masrani & et.al, 2018). Solar shading devices diminish the sunlight loads by 20% of the load that would otherwise be received by none shaded window (Mandalaki & Tsoutsos, 2020)

Design factors for shading devices

Shading design is linked to two major environmental factors which are the overheated period which constitutes the time of year when shading is required and the geographical location of the building site which determines the sun path angles which intern establish the required vertical and horizontal shadow angles (Lechner, 2015). According to (Szokolay S. V., 2007) by taking these design factors into account, a successful shading device can be designed and implemented and further evaluate the effectiveness of existing shading elements. Other design considerations that influence the effectiveness of shading devices are surrounding site conditions and design objectives (Gimat & Sulaiman, 2020).

Types of shading

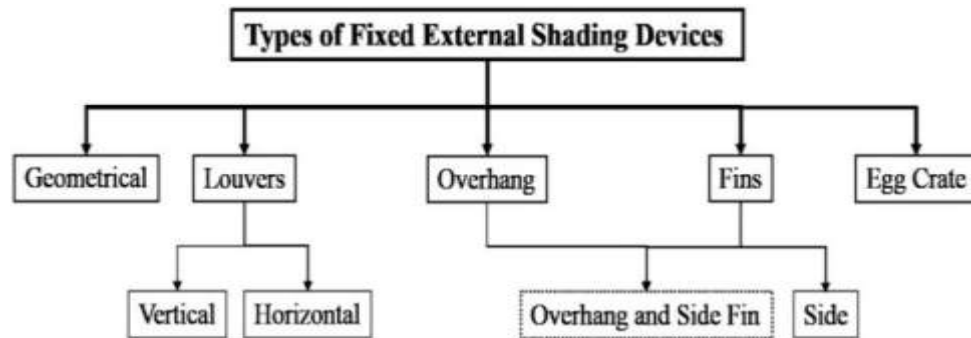
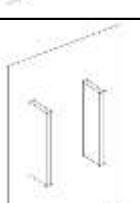
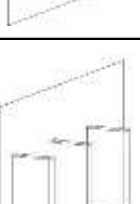
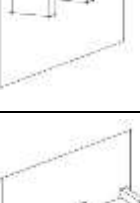


Figure 7 Types of shading devices

Passive design strategies include shading devices that follow the passive design approach that contributes to the creation of an ideal indoor environment. The primary idea behind this method is that no energy source is used. As shown in Figure 7, Fixed and adjustable shading devices are the two types of shading devices in this category (Laura, Concetta, & et.al., 2014). Furthermore, Shading can be accomplished by exterior devices, glazing, or by indoor shading devices. Although indoor shading is almost always movable, exterior shading can and often should be movable (Lechner, 2015). Typical shading exterior devices are shown in Table 2 with their orientation where it can be most effective.

Table 2 Shading types and their description

		Descriptive Name	Best orientation	Description
1		Overhang Horizontal Panel or awning	South, East, West	Traps hot air, can be be loaded snow and wind, can be slanted
2		Overhang Horizontal louvers in horizontal plane	South, East, West	Free air movement, snow or wind load is small, small scale
3		Overhang horizontal louvers in vertical plane	South, East, West	Reduce length of overhang, view restricted also available with miniature louvers
4		Overhang vertical panel	South, East, West	Free air movement, No snow load, view restricted
5		Vertical fins	North	Restricts view if used on east and west orientation
6		Vertical fin slanted	East, West	Slanted towards north in hot climates and south in cold climates, restricts view significantly, generally not recommended
7		Eggcrate	East, West	For very hot climates, view very restricted, traps hot air, Generally not recommended

Shading periods of the year

Building glazed facades and fenestrations require shading throughout the overheated period of the year, which is a function of both climate and building type (Lechner, 2015). Both during the hot period and when the weather is comfortable, shading is essential. The reason for this is that allowing solar gain at pleasant times might result in excessive heat, which can be uncomfortable. As a result, the lower comfort limit is utilized to determine when shading should begin.

Olgyay proposed using a threshold outside temperature of roughly 21 °C (70 °F) as a criterion for identifying when shade would be necessary throughout the year. On the bioclimatic chart, this threshold temperature corresponds to the shading line as the bottom boundary of the comfort zone. The threshold temperature is used in Olgyays' shading design approach to defining the "overheated period," which is defined as the number of hours during the year when the threshold temperature is surpassed outside. The contour of the overheated period on a sun path diagram reflects the shading requirements and may be directly connected to the geometry of particular forms of shading devices. (Yannas, 2015)

The indoor overheating threshold is debatable, but it is likely to be between 24 and 29 degrees Celsius, depending on space functions, occupant activities, clothing level, and acclimatization, with a midpoint of 26-27 degrees Celsius as a more commonly accepted limit for summer conditions in non-air conditioned spaces. In every scenario, different values of threshold temperature, internal gains, and heat loss coefficient should be assessed to determine the balancing point temperature. Internal gains will likely vary according to space functions, whereas heat loss coefficient values are influenced by design factors (glazing areas, insulation, and airtightness requirements), as well as building typology (for example, low-rise detached, high-rise attached, and so on) (Yannas, 2015).

Shading analysis methods

A more recent review by Conrado-Lizbeth (2022) dives into shading analysis. Practically, shadow analysis entails the task by which the shadow profiles of an object and its surroundings are examined at a specific time of day or for a certain duration of the year to utilize available solar radiation or obstruct it when it is in excess.

According to Conrado-Lizbeth (2022) shadow analysis methods can be classified into three fundamental techniques; sun path diagrams, heliodon devices, and software packages. As

noted by (Ralegaonkar & Gupta, 2010) Sun path diagrams are visual tools that illustrate the apparent changes in the sun's position at any given time of day throughout the year. On the other hand, a heliodon is a mechanical device that uses an artificial light source and a positioning mechanism to simulate the seasonal and hourly positional changes of the sun (Lechner, 2015). Though durable, heliodons are expensive to manufacture and as a result, various software packages have been introduced to handle a wide range of simulations and energy studies of buildings. These tools are proving to have dramatic improvements in the designer's workflow (Conrado-Lizbeth & et.al, 2022).

2.3. Heliodon and its application

As stated in the review on Heliodons by (Conrado-Lizbeth & et.al, 2022), Heliodons are tools that aid in the visualization of the movement and direction of sunlight around the building and the impact on insolation to make effective use of daylighting and reduce the use of artificial lighting, also optimize energy demand for heating and cooling systems. Using this device informs the design process involving building form, optimal building orientation, shading system, solar systems, and daylighting.

Heliodons are three-dimensional models of the sun path diagram which is especially helpful in understanding the complex geometry of sun angles throughout the year (Lechner, 2015). In general, a heliodon is any device that can physically (i.e., using models) recreate the effects of the Earth's yearly and daily rotation around the Sun. Regardless of their construction and design, all of these devices show the Sun-Earth geometric relationship using a loco-centric view, in which the observed position is fixed and the Sun revolves around it. They are emulators rather than simulators because they portray the impact of the Sun-Earth geometric relationship rather than the physical process that underpins it (Szokolay S. V., 2007).

To maximize energy efficiency for heating, ventilation, and air conditioning (HVAC) systems and user comfort, a heliodon can be used to visualize the change in the direction of sunlight around a building and the related effect on insolation. This will allow for the effective use of daylighting and a reduction in the need for supplemental electric lighting (Conrado-Lizbeth & et.al, 2022).

Historical development

The earliest known design and application of heliodon (Figure 8) goes as back as 1932, a publication by Dufton and Beckett entitled “The heliodon: an instrument for demonstrating the apparent motion of the sun” defined heliodon and described its working principles. In the Heliodon system, the representation of the motion of the sun is simplified by the disjunction of the rotation of the earth about its axis from the apparent oscillation of the ecliptic relative to the earth (Dufton & Becket, 1932). One of the most widely accepted descriptions of Heliodon is ‘machines or devices that mimic the sun’s path as it travels through the celestial sphere’ (Fernando & et.al., 2016).

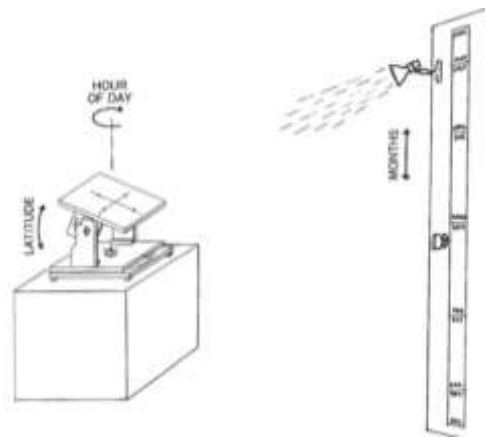


Figure 8 Dufton and Becket's Tabletop Heliodon

A modern heliodon (Figure 9), also known as a sun-emulator, is made up of physical components that represent the variables for studying the sun's position with reference to a location and time (Dalumo & Lim, 2021). The use of modern heliodon for solar shading predictions is proven to offer quite accurate results and effective solar shading design solutions in practice (Mostafa & Maged, 2017).



Figure 9 Sun emulator Heliodon

According to (Conrado-Lizbeth & et.al, 2022) the design of Heliodons was gradually iterated from 1932 to 2007 (as shown in Table 3), owing to the increased interest in the scientific community in the device's application. However, no heliodon design was recorded between 2007 and 2011. It might be because of the advancement and application of computational technologies. It's worth noting that there was interest in using the heliodon from 2011 to 2015, during which period various automatic and semi-automatic Heliodons were developed. Table 3 summarizes major literature and design iteration by different scholars throughout the years.

Table 3 Timeline of Heliodon designs

1932	1996	2000	2002
Dufton & Beckett Heliodon made of acrylic	Cheung et al. Heliodon with a mobile light source.	Cheung et al. Multi-lamp heliodon.	Cheung et al. Heliodon with two-time rings, Orange heliodon, Tulip Heliodon.
2005	2006	2007	2011
Mansy et al. Heliodon with a distribution of light source Galvan and Bortot Heliodon based on solar graph	Bodart et al. Heliodon with single-patch sky Ljubici et al. Heliodon with an octagonal structure	Maristany et al. Heliodon with the mobile light source through a metal arch Heliodon of analemmas	Cheung et al. Heliodon mounted on a camera tripod. Szokolay et al. Heliodon based on an inverted pendulum
2014	2015	2016	2017
Mendoza et al. Heliodon with semi-circular Mechanical arm Monroya et al. Heliodon based on arc-shaped structure	Dolan et al. Heliodon with a point-view camera	Lopez et al. Heliodon based on traditional solar charts	Sun emulator heliodon Heliodon made by Faculty in Thailand

Working principles

The earth is a spherical body in space continually intercepting a cylinder of parallel solar energy rays (Figure 10). Hence the angle of any earthly site to the solar beam is determined by;

- i. The site's latitude, which gives its position on the curve of the earth between the equator and one of the poles.
- ii. The time of day at the site, measured by its progress eastwards around the earth's axis from sunrise to sunset.
- iii. The date, which locates the earth on its annual orbit of the sun

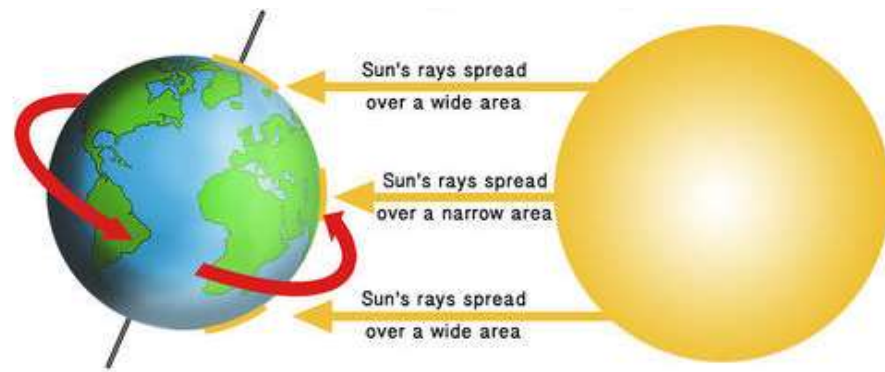


Figure 10 Earth and the sun

Throughout the study of solar geometry, various sun emulators have been developed. As stated by (Cheung & Lam, 2015), regardless of the type, Heliodons use three variables to simulate sunlight direction with respect to the building model,

- The latitude variable, which defines the sun's paths in relation to the geographical location.
- The seasonal variation, which relates to the declination of the sun on a given day, &
- Hourly change of the sun from East to West.

Since Heliodons are a physical representation of the sun's path, it is highly dependent on the solar geometry of a particular location or they can be adjusted to assume the sun's path in the desired location. Therefore the geometry of a heliodon is based apparent movement of the sun which can be determined on the solar path diagram and months that are represented with arms and sunlight is emulated using light fixtures on the arms (Cheung & Lam, 2015).

(Maged G, 2018) Explains the concept of the design is to use the conversion of the Altitude and Azimuth angles to their corresponding measurements on the (X, Y, and Z) coordinates (with relation to the observer's location) to determine the position of the sun.

Solar Geometry

Solar geometry is a result of tracking the sun in the sky. Tracking the point where the sun's rays penetrate an imaginary sky dome every hour, and connecting these points for one-day results in the sun's path for that particular day (Lechner, 2015). As shown in Figure 11 below the sky dome can be simplified to show the path of the sun at a specific time of year.

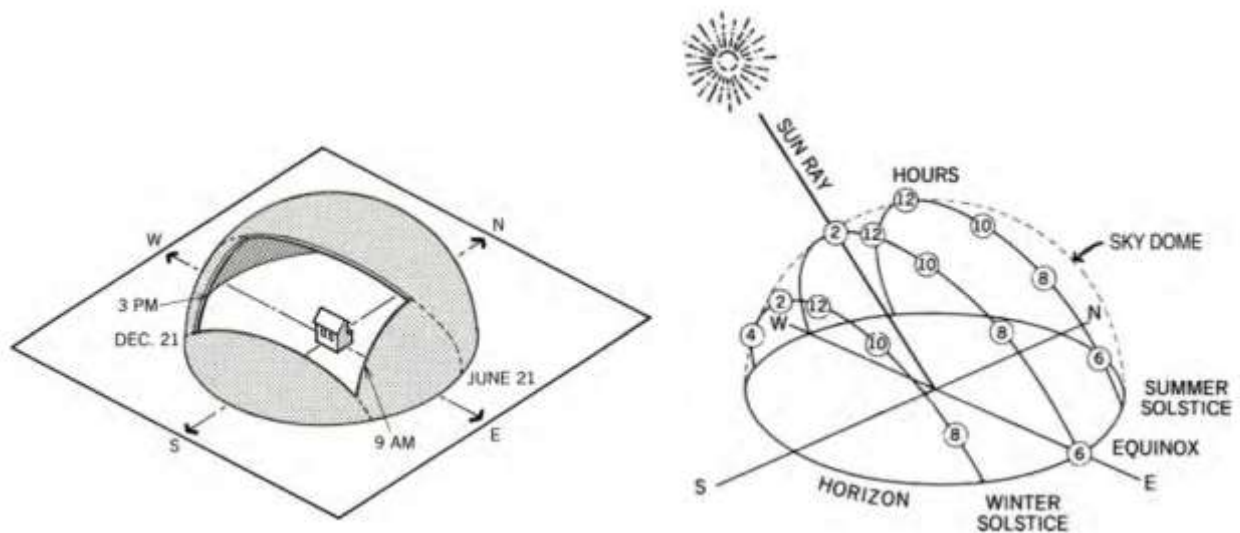


Figure 11 Solar window on Sky dome (left) and simplified sunpath (Right)

.Azimuth and altitude angles

The position of the sun can be described by two different angles, Azimuth and Altitude (Figure 12). The angle of the sun's beams measured in the horizontal plane from due south (true south) for the northern hemisphere or due north for the southern hemisphere is known as the solar azimuth angle. The vertical angle at which the sun's rays strike the earth is called the altitude angle and is a function of the latitude, time of year, and time of day (Lechner, 2015).

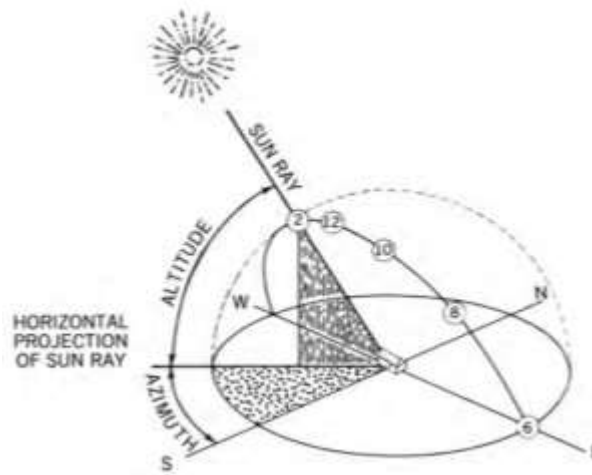


Figure 12 Solar azimuth and solar altitude

Solstice and Equinox

On the equinox, the sun's altitude at solar noon at any place on earth is equal to 90° minus the altitude. Due to the symmetry of solar motion about the ecliptic, the position of the sun is symmetrical on both sides of its maximum/minimum positions, that is, the solstices. Thus,

the sun's position on May 21 is the same as on July 21. As shown in Figure 13 The sun has the highest orbit and will appear to be on the zenith at noon on June 22 along the Tropic of Cancer (LAT= + 23.45°) (Lechner, 2015).

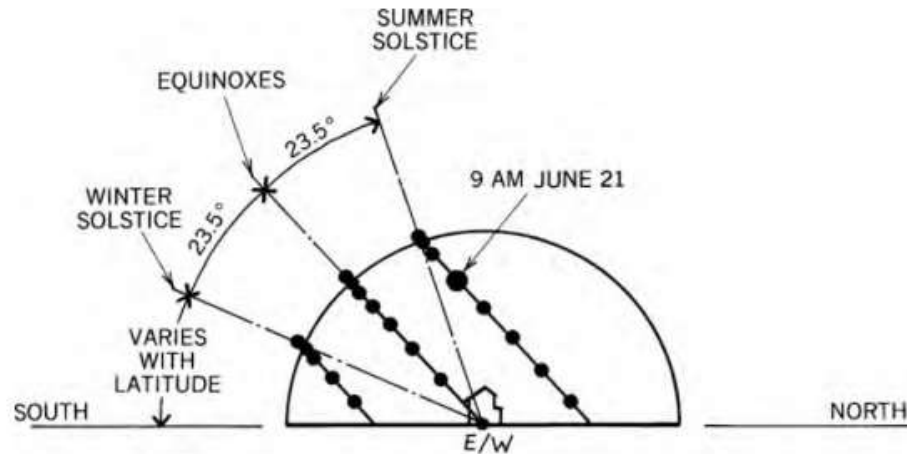


Figure 13 East elevation of the sky dome with Equinox & Solstice paths

Types of Heliodon

Heliodons are now available in a variety of shapes and sizes, depending on their intended usage and application. Despite the many forms, they all serve the same purpose: to analyze the patterns of sunshine at various times and locations. According to (Barrantes, 2021) the two designs in which Heliodons can be found today are Virtual Heliodons and Physical-annular Heliodons. A virtual heliodon is created and executed using software programs that digitally imitate the angles and patterns of sunlight, while a Physical heliodon is a physical model that most closely simulates our experience on Earth. The trajectory of the sun's movement is simulated by the use of lamps that are placed in circular paths (Conrado-Lizbeth & et.al, 2022).

Different works of literature have posited varied classifications for physical Heliodons. In general, Heliodons are developed to simulate the direction of sunlight in relation to a building model (Cheung, 2001). Accordingly, they can be classified as to how the model is placed on the heliodon. In one category, the model is rotated as well as slanted. In the second category, the model is positioned horizontally and is typically stationary.

Movable Flat Surface and Fixed Light Source

As shown in Figure 14, movable base heliodons are tilted to adjust for the degree of latitude of a particular site. While the light source remains fixed. This particular device is portable and can work with both artificial and natural sunlight (Cheung, 2001).

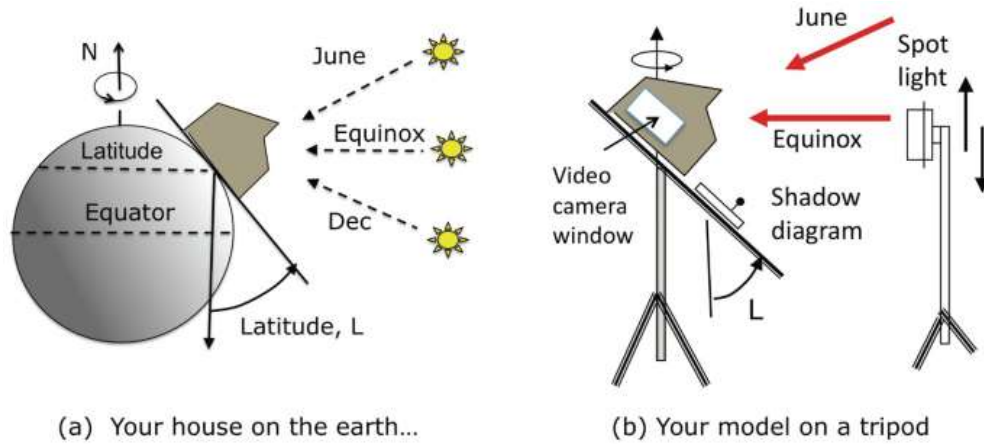


Figure 14 Movable base Heliodon

This system, however, has a few drawbacks. (Salgado-Conrado & et.al., 2022) Points out, when the model is moving, or even when it is set at a non-horizontal position, shadows are challenging to see (Figure 15). To prevent drawbacks in the analysis, the building model must be set up securely. When the building model moves or is positioned in a specific tilt, the design makes it difficult to see shadows.

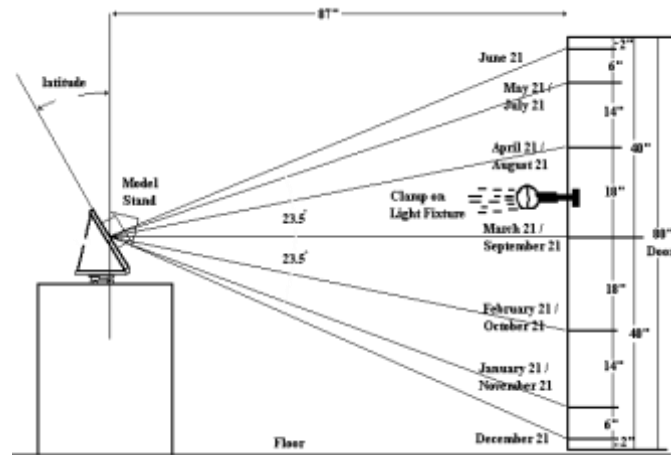


Figure 15 Table top heliodon

Stationary Flat Surface and Movable Light Source Heliodon

In this configuration, the object being studied remains stationary while the light source rotates around it to mimic sun motion and the shadows the sun casts on the model. This model follows the principle explained by Lechner (2015) as a loco-centric view of the sky,

As depicted in Figure 17, a building model is set up on the flat surface of a heliodon and light follows the supposed sun path as the heliodon's operational principle. With the help of the positioning mechanism, the light source trajectory is locked at a particular latitude. The light source is then changed to reflect the user's desired analysis time and date. The effects of one building's shading on another reveal issues or openings for addressing climate change that favor solar-responsive architecture for energy savings, glare reduction, and improved occupant comfort (Conrado-Lizbeth & et.al, 2022).



31

An in-depth classification is given by (Khorasgni, Proshasky, & et.al., 2014) and (Cheung & Lam, 2015) beyond the positioning of the study model. In their classification, Heliodons are categorized based on their ability to simulate light and sky conditions.

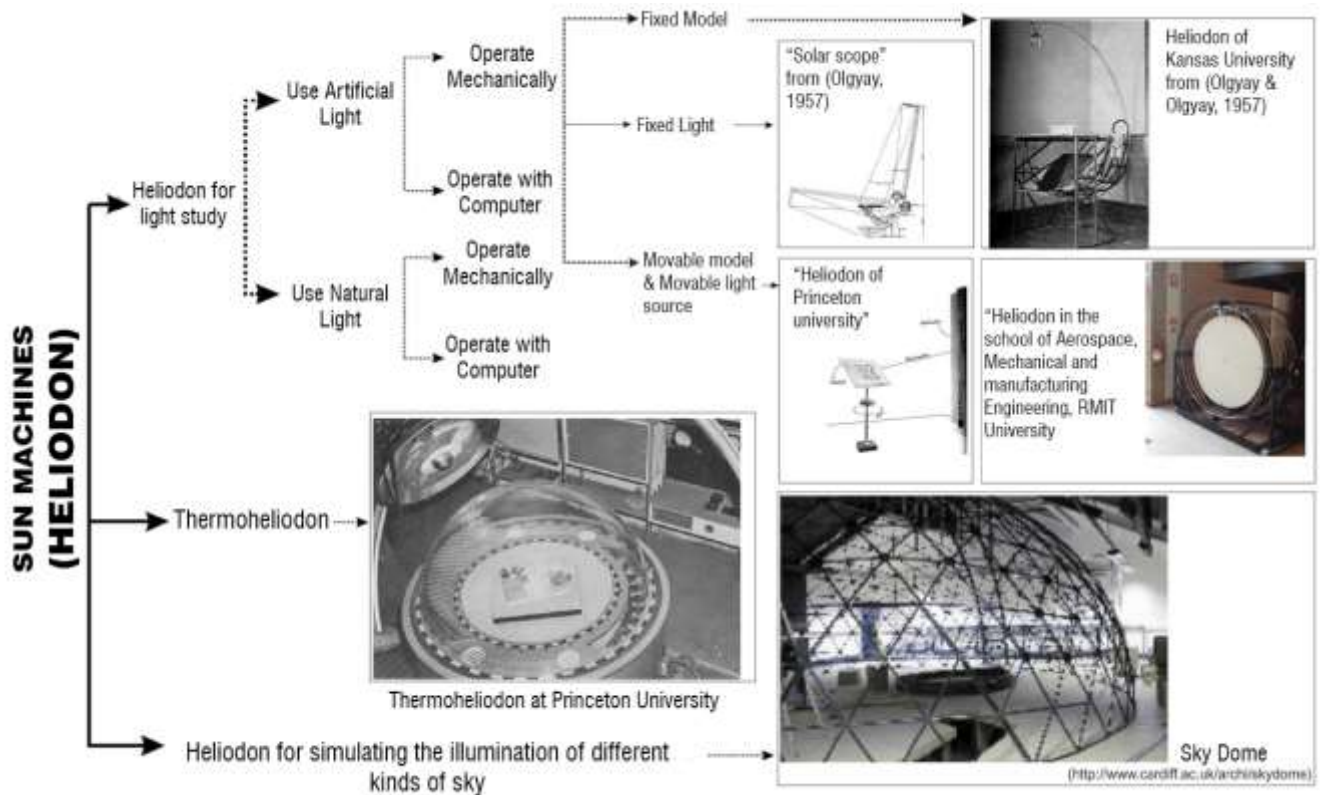


Figure 18 Classification of Heliodons based on general function (Khorasgni, Proshasky, & et.al., 2014)

(Conrado-Lizbeth & et.al, 2022) Also presented a similar classification with an addition of more recent developments such as robotic arms with sophisticated software yielding high precision (Figure 19).

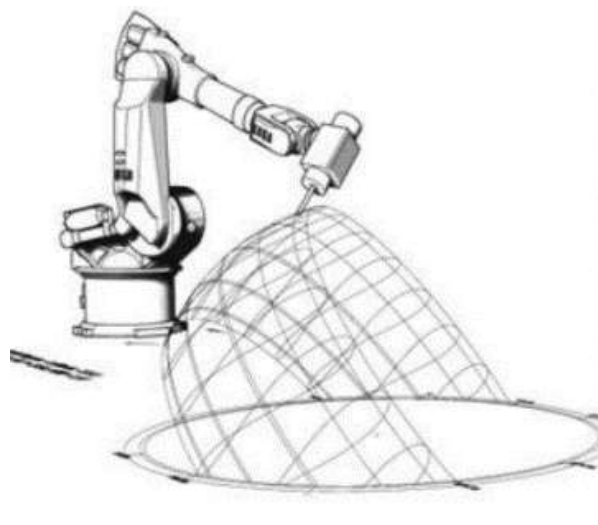


Figure 19 Robothermodon by Khorasgani, et al. at Royal Melbourne Institute of Technology

Conceptually clear Heliodon

As the name implies this particular device is seemingly simple in design. Norbert Lechner developed this type of Heliodon at Auburn University. The conceptually clear Heliodons are three-dimensional models of the solar window and the sky dome, in which each month's sun path is represented by an arch hence physically representing the actual path of the sun throughout the year (Lechner, 2015).

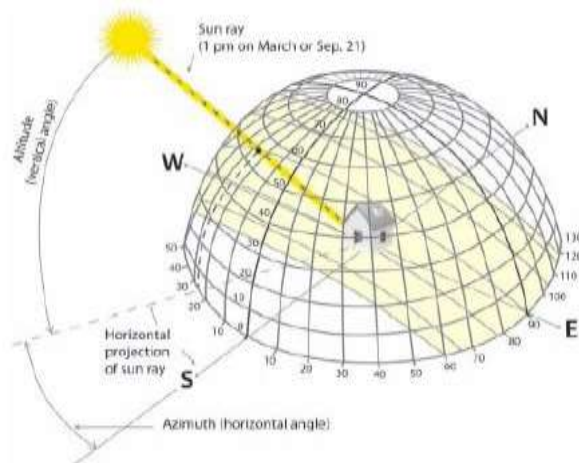


Figure 20 Sky dome

Furthermore, the clarity of the concept arises from the fact that the ground plane is always horizontal hence simulating the daily experience of the sun's path revolving over the building site (Figure 19). This developed out of necessity, particularly for architecture schools and firms that lack the space to accommodate a permanently installed fixed heliodon such as the sun simulator (Lechner, 2015). Lechner further bases this approach on a geo-centric rather than a geocentric approach to viewing the solar path.

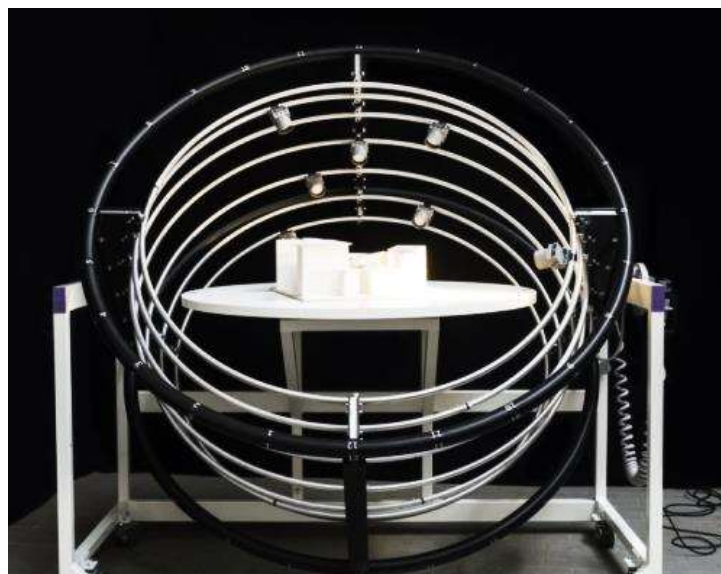


Figure 21 Sun emulator Heliodon

Heliodon vs Computer simulations

In the age of computers and automated analysis, the use of mechanical device can be perceived as an outdated practice. But using physical models has its advantages. According to (Lechner, 2015) Physical models will always be exceptionally easy to understand for the brain because people evolved to understand the physical reality around them.

Comparative studies on physical heliodon and computer simulation have been conducted, one of these studies by (Pajek & et.al., 2018) the potential accuracy error of the heliodon was assessed by comparing insolation data acquired by computer software with those obtained by heliodon. The results revealed that the heliodon with the highest accuracy was at a scale of 1:400. (Average error of 7 percent on the equinox and 20 percent on the winter solstice). Furthermore, their research has revealed that physical heliodon is preferred by the majority of students (83.3%) to be user-friendly and conceptually understandable to grasp bioclimatic design concepts.

Limitations of Heliodon

Even though the physical model of heliodon is a valuable analysis instrument, (Dalumo & Lim, 2021) have compared the results of heliodon with that of a computer simulation and found it to be lacking in certain aspects. One of the major limitations revealed by their experiment was that; Heliodon does not precisely depict the relative distance of the sun to the earth's surface consequently creating more shading effect on the surface being studied. Generally, when compared to computer simulation methods, the adopted physical method of determining shaded areas using the heliodon is limited in precision, resulting in underestimation or overestimation of results.

Limitations and advantages of Heliodons and their use have been investigated by (Salgado-Conrado & et.al., 2022), the major drawback of using Heliodons as an analysis tool is the lack of standardized procedures for calibration and the use of it. Hence different pieces of literature consider using computational tools or/and field verification to validate the findings of a Heliodon analysis. The drawback and advantages are summarized in Table 3 as shown below.

Table 4 Advantage and limitation of Heliodons

Advantages	Challenges/ Limitations
• Their use is instinctive due to the resemblance of our experience of the sun's movement across the real sky	• Some Heliodons require large spaces to operate and store
• They encourage working in groups	• The size of the area to be analyzed depends on the light source area
• Automatic Heliodons are more accurate, however, their cost is high	• Methods of data collection and analysis lack definite standards
• They are excellent teaching and designing tools	• Calibration methods and procedures are not put in place
• Low maintenance	• Difficulty in data collection
• They are crucial tools to visualize and calculate solar properties.	• It is time-consuming

Validation of results of Heliodon

Almost every paper that has been written on heliodon mentions the lack of an established validation method as a major drawback. Similarly, in his analysis Salgado-Conrado (2022) reiterated this issue in a recent paper that attempted to validate and verify results from heliodon measurements. However, by contrasting the outputs of the physical experiment's evaluation of shade performance in a computer simulation with those produced on a scale model using a heliodon, the validity of the evaluation can be established (Dalumo & Lim, 2021). (Osser, 2007) Lays out an assessment method to validate findings from different analysis methods which is based on the concepts of comparative analysis. To determine the degree of validity, Osser (2007) proposed a percentage error analysis. This method requires a measurement from heliodon and an accepted value (real value) generated from verified simulation (Dalumo & Lim, 2021).

2.4. Empirical review

International practices in shading analysis

An in-depth review by Conrado-Lizbeth et.al.(2022) identified sun path diagrams, heliodon devices, and software programs are the three main categories of tools for shadow analysis. Sun path diagrams are visual aids that show the apparent changes in the sun's position at any given time of day throughout the year. In contrast, Heliodons are mechanical devices that use an artificial light source and a positioning mechanism to mimic the seasonal and hourly positional changes of the sun. Despite being costly to produce, these tools are sturdy. In comparison to physical experiment approaches, which were constrained by the mechanical design of the components, the computational assessment approach offered a more effective

means of conducting the performance simulations (Dalumo & Lim, 2021). Even though the type and working principles of various heliodon types have been explored by different researchers, no definitive procedural record was found as a method of empirical analysis. On the other hand, a study by Dalumo & Lim (2021) assessed the shading prediction of SunCast; a virtual solar shading calculation tool, and RadianceIES for measuring daylight availability in a tropical climate region.

Shading analysis in Ethiopia

The availability of shading analysis research in the local context is found to be lacking. Only one study has been found that undertook a case study on multiple buildings with external shading devices. (Fitsum, 2021) adopted a computer simulation to assess the performance of existing shading devices. Particularly the research used Ecotect's solar incident solar radiation to determine the shading capability of respective shading devices. Meanwhile, no research was conducted using a physical Helion.

2.5. Summary of literature

External shading devices are considered the first line of defense against direct solar radiation on glazed surfaces which are typically the weakest component in thermal insulation. Various design decisions are attributed to the functionality of shading devices. Effective shading device can protect the interior from overheating due to solar exposure, hence optimum functionality of these elements is crucial. Shading performance can be evaluated using various methods such as solar charts, software simulation, or Heliodons. Heliodons are thought to be effective instruments that can help designers and users comprehend the connections between the sun's course and its impacts on the architectural model. While operating Heliodons there are three main variables that need to be taken into consideration, i) geographical location (latitude) ii) solar azimuth and iii) solar altitudes. These variables are used to position the sun and the performance of respective shading performance can be derived by observing the shadows projected on the model.

2.6. Lessons drawn from the review and Research Gaps

External shading elements are one of the most effective strategies to provide shading. Various methods exist to analyze the performance of these devices. However, heliodon is identified as the most intuitive as it shows the apparent motion of the sun in a scaled model throughout the year. The reviews indicated that repeatability of the results is challenging to obtain in the case of Heliodons due to a lack of error analysis and a systematic calibration

procedure. In the case of computational tools, they have achieved greater market success than Heliadons, but the licensing fee and the learning curve can be a barrier. Moreover, local research regarding the investigation of existing shading devices to better understand the current application of these devices is lacking.

CHAPTER THREE

3. MATERIALS AND METHODS

The study's methods and procedures are discussed in this chapter. Particularly, the description of the study area, the data sources, the data collecting, and the data analysis techniques.

3.1. Description of the study area

Addis Ababa, the capital of Ethiopia was founded in the late nineteenth century and is a youthful capital city compared to other capital cities in the world. Addis Ababa has transformed from a modest agricultural community in the 1950s to a thriving urban metropolis today. Much of this urban transition began during Imperial Rule, but it has intensified since 1991.

The research is conducted in Addis Ababa, which is located in central Ethiopia with a coordinate of 9°1'48"N 38°44'24"E with an altitude of 2,355 m. High-rise buildings (i.e. buildings that have 13 or more stories) located in all districts of Addis Ababa will be included in this study (Figure 22 Map of Study area).

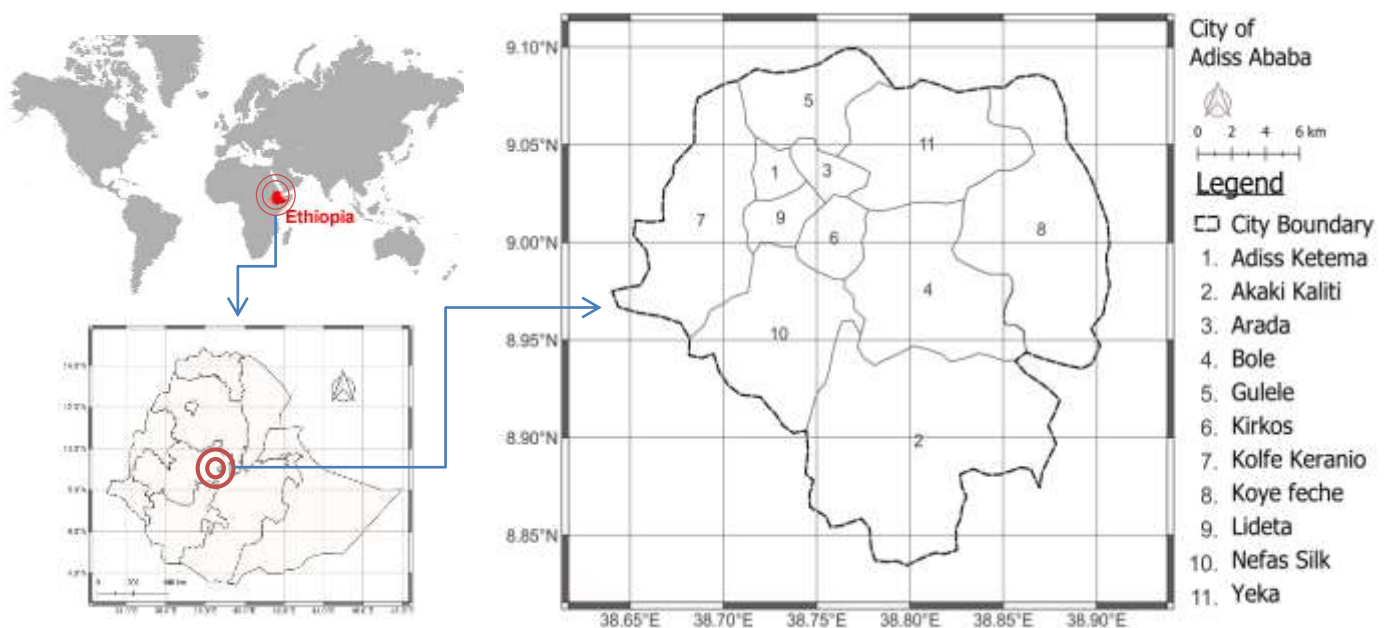


Figure 22 Map of Study area

Climate profile of the study area

According to the Köppen classification (2022), Ethiopia has a varied climate and landscape, that tends to range from the equatorial rainforest with high rainfall and humidity in the south and southwest to the Afro-Alpine. Afro-Alpine conditions can be found on the summits of the Simien and Bale Mountains, while the northeast, east, and southeast lowlands have desert-like conditions. Although Ethiopia is typically regarded as being arid, its precipitation shows a significant degree of fluctuation (The world bank group, 2020). There are three main climatic zones in Ethiopia:

- 1) The alpine vegetated cool zones (Dega), which are found above 2,600 meters above sea level and have temperatures ranging from below zero to 16 °C;
- 2) the temperate (Woina Dega) zones, which are found between 1,500 and 2,500 meters above sea level and have temperatures ranging from 16 °C to 30 °C; and
- 3) The hot (Qola) zone, which has temperatures between 30 °C and 40°C.

The designated study area which lies in central Ethiopia, with an elevation of 2,355 m above sea level and climatic conditions falls under a Temperate highland tropical climate with a dry winters climate (Classification: Cwb). Weather data from 2014 – 2021 shows that the average temperature lies between 25 °C during the hot season, and as low as 9 °C during the rainy season (Fazzini & et.al., 2015).

3.2. Research design

This particular research follows an inductive approach as it moves from specific observations of individual cases of shading devices to broader generalizations of the application of these devices in the study area. The research objectives required an empirical investigation of numerous buildings to assess the functionality of their shading devices using an instrument that can simulate the natural phenomenon. Hence, real-world data is examined in a simulated environment. The relationships between identified variables are studied intensively via a custom-made Heliodon using qualitative analytical methods to make a generalization that reflects the actual phenomenon. These procedures require a positivist viewpoint which attempts to observe and describe reality from an objective viewpoint (Kothari, 2004). Whereas, the research strategy employed the simulation method, which

according to Kothari (2004) involves the construction of an artificial environment within which relevant information and data can be generated by adjusting variables.

Based on simulations by heliodon within a predefined period, forecasts are made based on the perceived results and explained actualities and their inter-relationships. Therefore, to conduct this research an instrument is constructed to simulate shading effects using the stationary horizontal model Heliodon based on the model developed by Lechner (2015) which conceptually and physically reflects the apparent movement of the sun i.e. solar geometry.

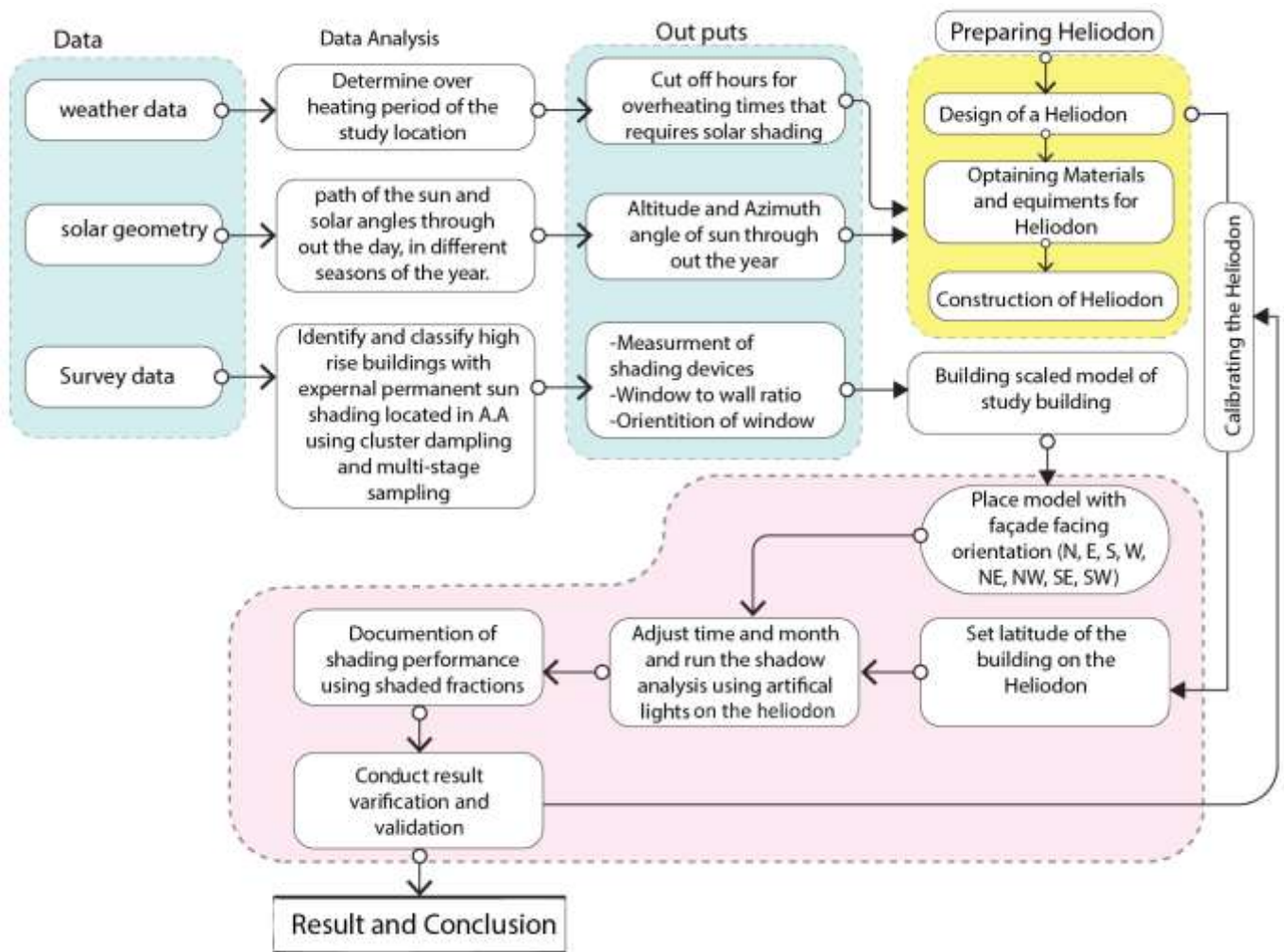


Figure 23 Workflow to investigate shading performance

Data gathered through measurements taken from the Heliodon is empirically examined to determine the effectiveness of respective shading elements of different buildings and different orientations. To assess the validity and reliability of results, a mean absolute error percentage is calculated using a computer simulation result as an accepted value to compare the results of this study against.

3.3. Data Source

Data is collected from various sources, exhaustive list of high-rise buildings in Addis Ababa that are currently completed or near completion is collected from an online database (<https://www.emporis.com>) and corroborated by site surveys. This allowed for the collection of detailed information on the building's geographic location, orientation, and shading types. The shading device dimensions are collected from site measurements when possible, and form document reviews are collected from designers and engineers.

Source of climate data

The weather data for the study area is derived from several public sources, TMYx files are typical meteorological year files derived from the Integrated Surface Database (ISD) that consists of global hourly and synoptic observations compiled from numerous sources with hourly data through 2021 using the TMY/ISO 15927-4:2005 methodologies. ISD individual year files are created using the general principles from the IWEC (International Weather for Energy Calculations) Typical Meteorological Years that was published in 2001. The resultant files have been peer-reviewed by interested parties. Detail of the data is listed below.

- Data station Location: Addis Ababa-Bole intl. AP, AA, ETH
- Latitude/Longitude: 8.98° North, 38.8° East
- Time zone from Greenwich: 3
- Data source: SWERA 634500 WMO Station Number
- Elevation: 2,355 m.

The climate data for this particular study used a SWERA data set collected from climate.onebuilding.org which is a set from the year 2007 – 2021. The TMY shows relevant data such as hourly, daily, and mean temperature which can be used to determine overheated times of the year (Figure 24).

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	487	504	493	466	465	428	372	388	450	507	526	497	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	562	509	390	323	316	260	165	182	283	437	589	595	Wh/sq.m
Diffuse Radiation (Avg Hourly)	135	163	215	224	238	233	243	244	236	200	146	135	Wh/sq.m
Global Horiz Radiation (Max Hourly)	1009	1118	1090	1095	1022	1000	984	1120	1092	1084	1015	975	Wh/sq.m
Direct Normal Radiation (Max Hourly)	1062	1057	1012	950	824	759	799	794	820	987	1030	1028	Wh/sq.m
Diffuse Radiation (Max Hourly)	516	676	662	692	531	630	620	666	608	640	450	597	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	5623	5899	5893	5698	5777	5365	4638	4775	5427	5983	6105	5716	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	5491	5944	4654	3942	3927	3261	2069	2240	3414	5150	6835	6832	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	1568	1915	2560	2735	2840	2926	3040	3005	2845	2364	1694	1551	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	52278	54381	53739	51172	51013	47301	41409	43223	49654	55026	56683	53527	lux
Direct Normal Illumination (Avg Hourly)	53857	48916	36978	30781	30007	24309	15448	17081	26529	41567	56338	56770	lux
Dry Bulb Temperature (Avg Monthly)	15	16	17	17	17	15	15	15	15	16	15	15	degrees C
Dew Point Temperature (Avg Monthly)	5	5	8	9	9	11	12	12	11	8	6	6	degrees C
Relative Humidity (Avg Monthly)	54	54	60	61	63	78	81	83	78	63	59	56	percent
Wind Direction (Monthly Mode)	90	150	120	120	0	0	300	0	0	120	120	120	degrees
Wind Speed (Avg Monthly)	3	4	4	4	4	3	3	2	2	4	4	4	m/s
Ground Temperature (Avg Monthly of 3 Depths)	15	15	15	15	15	15	16	16	16	16	16	16	degrees C

Figure 24 Summary of climate data (Climate consult)

3.4. Data collection

The necessary data to conduct this research is collected through primary and secondary sources. Site surveys, sketches, and photographs, direct measurements using measuring tape were primary sources and documents. On-site, measurements include window height and width, window to wall ratio, which is a major variable in determining the impact of climate factors, practically which cannot be covered by a roof. Another data collected is the façade orientation angle which refers to the azimuth of the particular surface facing north. This data is collected from the online google earth map services. Literature reviews from published and unpublished sources were secondary sources. Documentation reviews on selected buildings were used where primary data collection was not possible.

To study solar geometry, the polar equidistance coordinate sun path of the specified location was generated from the university of Oregon website and gaisma.com (Figure 25 Sun path diagram of Addis Ababa). And also typical meteorological year data is gathered from US department of energy weather databases to assess the temperature distribution of the study area from a weather station located near Bole International Airport.

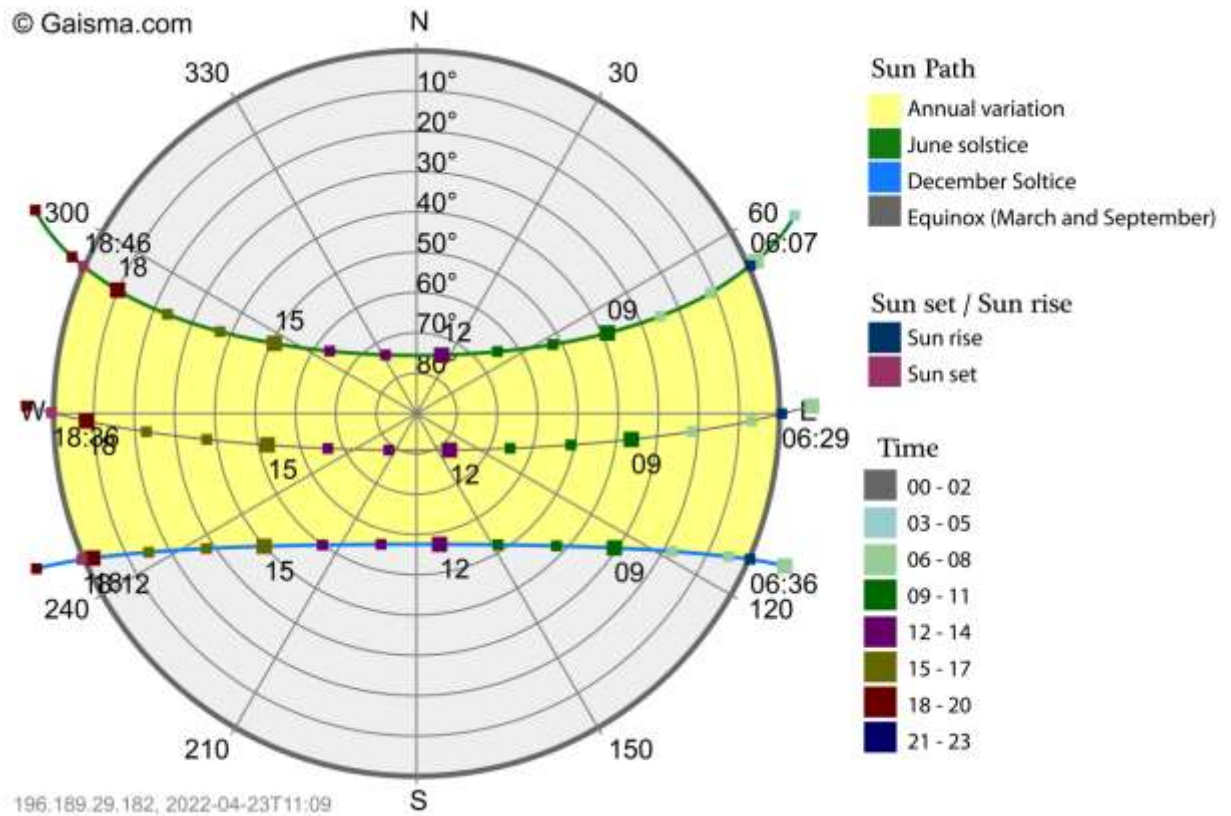


Figure 25 Sun path diagram of Addis Ababa

3.5. Sampling

The sampling frame of this research was high-rise buildings (i.e. buildings having 13 or more floors) within the region of Addis Ababa. As stated in the literature review, emphasis was given to high-rise structures because of their height and high façade fenestration area. This makes them extensively exposed to the impacts of atmospheric temperature and solar radiation from the sun. As a result, there is an inherent risk of overheating during the hot seasons. The inclusion criteria besides the height of the building are that buildings need to have distinguishable permanent external shading devices. In addition to having external shading, the buildings included in the total population are either completed or near completion where the solar shading elements are identifiable. The general sampling procedure is shown in Figure 26.

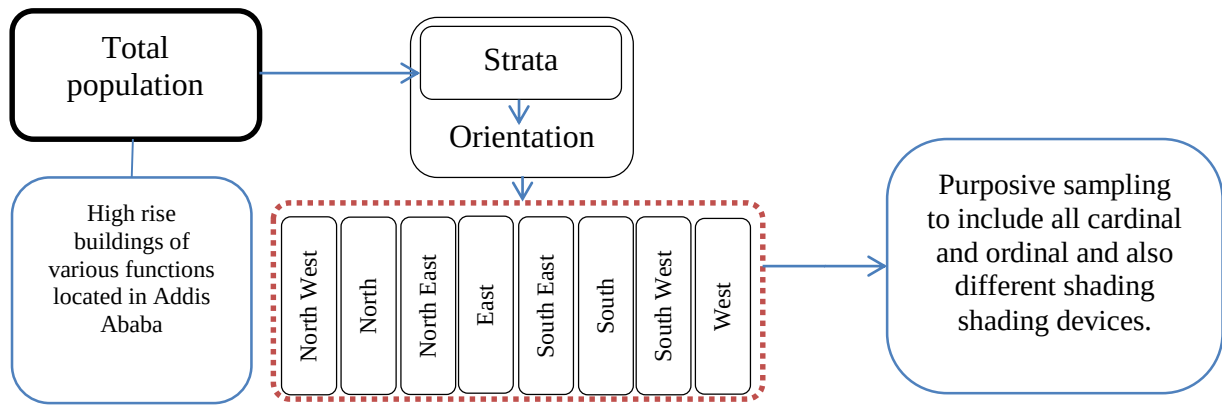


Figure 26 Sampling method

Using stratified sampling and purposive sampling, Buildings are categorized based on sampling frames of wall azimuth which refers to the building's façade hosting permanent external shading devices and is most commonly used to refer to solar orientation, which is how the building sits with reference to sun access. Building shading orientation is expressed in 4 cardinal directions and 4 ordinal directions (Figure 26). The sample buildings are selected on the above-mentioned criterion-based selection basis from each strata group. Parameters of interest for a shading device to be identified and measured are shading height, width, depth, and protrusion which can be shown in cross-section detail for clear understanding, and also the wall-to-window ratio of the shaded façade (See Appendix_1 for a complete list of high rise buildings).

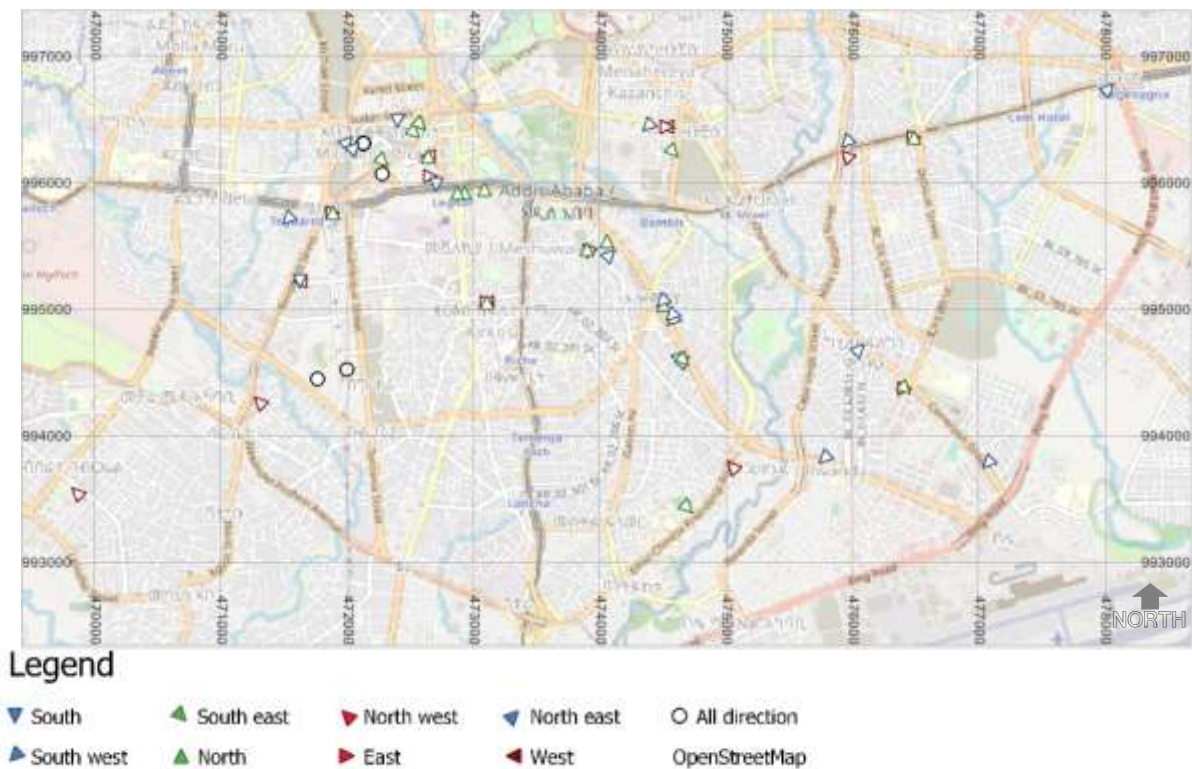


Figure 27 high rise buildings in Addis Ababa

A preliminary survey identified 46 high-rise buildings in Addis Ababa which are either completed or in the finishing phase and partially occupied with clearly distinguishable external shading elements. Among this list of buildings, 41% of buildings feature permanent external shading devices. The major axis of the buildings and their shading types is shown in the graph below in Figure 28.

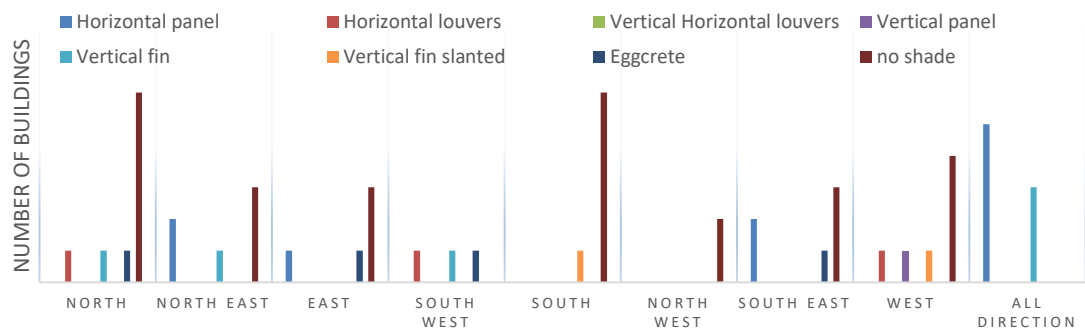
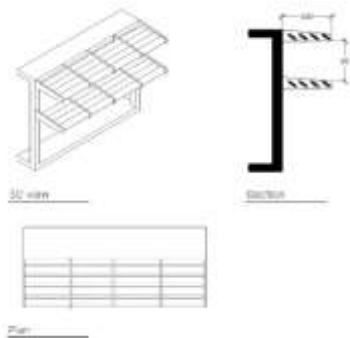
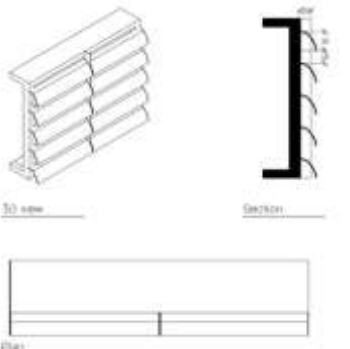
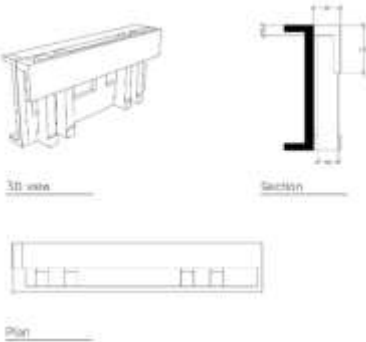
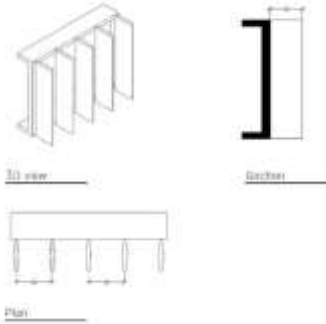
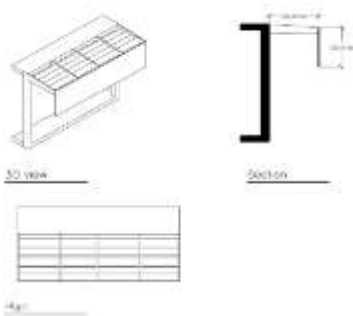
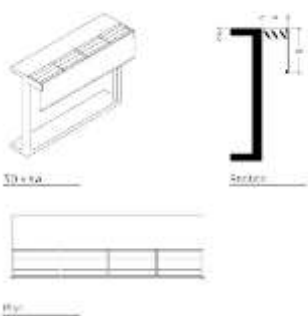


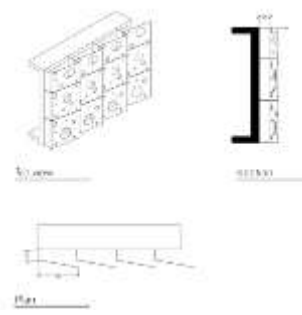
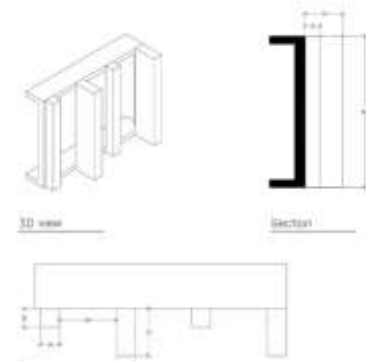
Figure 28 High-rise building and shading types

Based on the selection method a total of 8 buildings are selected. Buildings with their descriptions are provided in a tabulated format as shown below in Table 5.

Table 5 Selected Buildings

	Building name	Building information	Shading drawing	picture
1	Dashin Bank Hq.	Location - Mexico Function – Office Stories – 21 Shading Type – Horizontal louver Material - aluminum Orientation – South Window ratio – Full glazing		
2	Africa Insurance	Location - Bole road Function – Office Stories – 13 Shading Type – Horizontal Material - aluminum Shading Orientation – Southwest, Southeast Window ratio – Full glazing		

3	Giant Eagle Trading	Location - Mexico Function – Mixed use Stories – 17 Shading Type – Vertical fin Material - Concrete Shading Orientation – North, South, East, West Window ratio – 45%		
4	Wegagen bank Hq.	Location - Stadium Function – Office Stories – 23 Shading Type – vertical fin Material - aluminum Shading Orientation –East Window ratio – Full glazing		
5	MTSE Hq.	Location - Leghar Function – Mixed use Stories – 15 Shading Type – Horizontal louver Material - aluminum Shading Orientation – east, southeast Window ratio – Full glazing		
6	United Hq.	Location - Mexico Function – Office Stories – 35 Shading Type – vertical panel with horizontal louver Material - aluminum Shading Orientation – Southeast Window ratio – Full glazing		

7	Renaissance Building	Location - Megenagna		
		Function – Office		
8	Commercial bank of Ethiopia	Stories – 15		
		Shading Type – vertical slanted		
		Material - aluminum		
		Shading Orientation – Northeast		
		Window ratio – Full glazing		

3.6. Methods of Data analysis

The last decade has seen a significant improvement in building thermal and lighting performance thanks in large part to the increasing consideration of shade or natural light in architectural projects. This study is constituted of multiple analyses. The gathered quantitative data was investigated by a method of empirical analysis using percentage & comparative analysis.

The analysis method employed in this study consists of five main steps. The first is to identify overheated periods when shading is used to obstruct excess solar radiation, second, identify, sort, and select high-rise buildings within the study area that have exterior shading devices installed. Third, design and construct a custom sun emulation device (i.e. Heliodon) capable of demonstrating the sun path for the study location. Fourth, use the Heliodon to analyze to determine the effectiveness of shading devices on the sample buildings. And finally, conduct a validation analysis to determine the closeness of the results with other accepted methods. The method of data analysis for all the specific methods is described below.

Identifying the overheated periods

Identifying the overheated periods within which shading devices are required is a task that preceded the investigation of their functionality. According to (CIBSE, 2006) overheating period can be set as the operative temperature in the space exceeding an agreed threshold for more than a reasonable number of occupied hours per annum. As such a solar window which is that part of the sky dome through which the sun shines during the overheating season is determined by setting a threshold temperature acquired through literature reviews of various comfort standard documents.

For this particular study, a threshold of 20 °C base point and 23.9 °C upper limit temperature is applied. To limit the scope of the study to a manageable degree, the overheated threshold is set to be above 24 °C for a period of 2% or greater for a given month. To extrapolate the required data from weather data, climate consultant weather analysis software is used.

Determining shading times

The method employed to determine periods of the year when shading measures are needed is the use of shading masks. As defined by Lechner (2005), shading masks represent the sky as viewed from a reference point, indicating the portion of the sky that is visible and obstructed. The procedure to define shading masks, adopted from Olgyay, and developed at Princeton University is discussed as follows;

- I. The yearly temperature distribution is plotted on a time & temperature graph (Diurnal temperature exceeding the overheating threshold is identified (Figure 29)
- II. Overheated periods are indicated on an equidistance solar chart to generate shading masks.

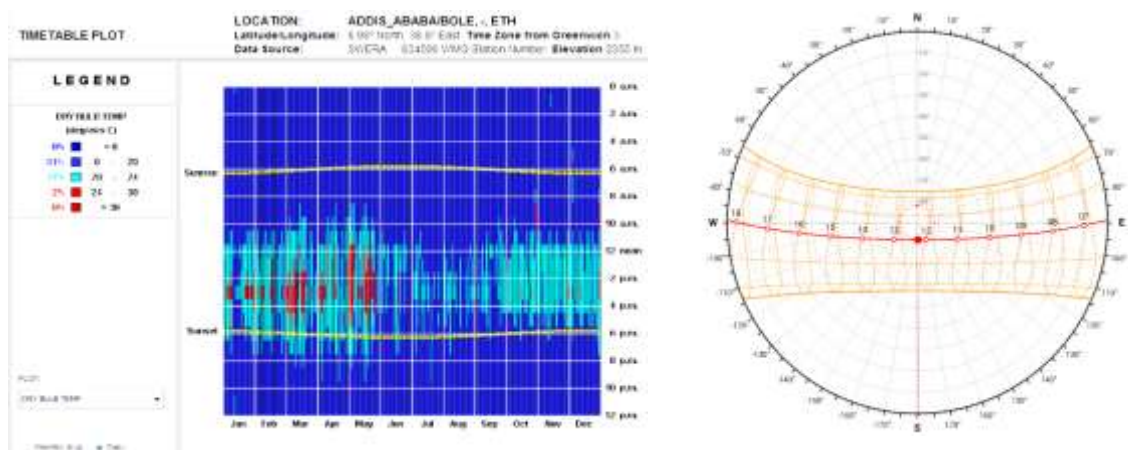


Figure 29 Time table plot (left), equidistant sky dome projection of a sun path diagram (right)

The combined diagrams precisely show the times of the year and the time of day when direct sunlight does or does not strike a point centered at the lower edge of the window.

Shading analysis

One of the limitations of using a Heliodon to investigate the performance of shading devices or to study shadows is that there is no definitive method put in place as standard procedure. Monitoring physical prototypes at reduced scales and comparing the results with full-scale buildings is one of the methods of analysis with the heliodon (Khorasgni, Proshasky, & et.al., 2014). A previous study conducted by (Cho et al.,2017) has identified methods of calculating shaded area (Figure 30). There are two approaches to calculating a shaded area created by an external shading device. The first is the cell method, in which an illuminated plane is divided into a grid of cells. The number of cells within a target region (i.e. the glazing) that do not receive sun rays is summed up. The second method is the point approach which involves projecting the coordinates of a shading element onto a target region to acquire the shadow's coordinates and then computing the area of the geometric form defined by the shadow's coordinates.

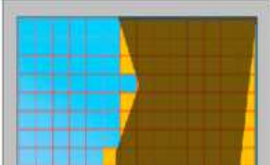
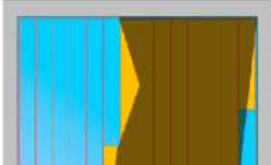
	Grid Method	Bar Method	Polygon Method
Type of calculation	Counting the number of cells (square)	Counting the number of cells (bar shaped)	Calculating the area of connected points
Level of difficulty	Very low	Low	Very high
Polygon shape	Rough	Slightly detailed	Detailed
Diagram			

Figure 30 Cell Method of determining a shaded area

This particular study used the polygon method of determining the shaded fraction of a façade with external shading devices. The scale model of the 1:40 scale with a window dimension of 3 m high and 4 m wide is divided into grids to map the shadow cast by the shading elements (See Figure 31 scaled model of selected shading devices). The shaded area is digitized and the area of the polygon created is determined as the shaded fraction which reflects the percentage of the shaded surface at the given time.

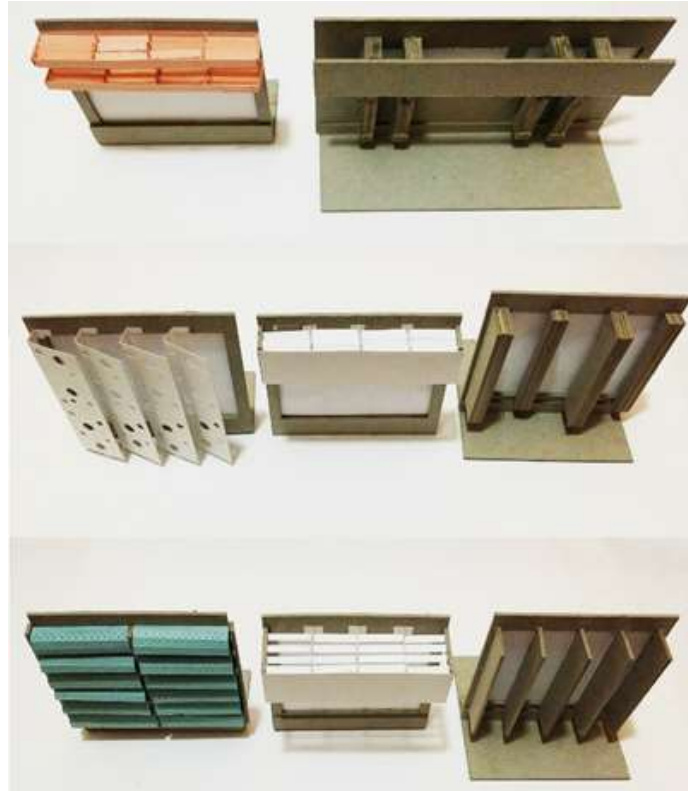


Figure 31 scaled model of selected shading devices

Development of Shading Analysis tool

As discussed in chapter 2, there are multiple analysis techniques to determine shading performance. This study uses a heliodon due to the ability of the device to physically represent the complex relationship between geometries, locations, and the variation of the sun's positions in time. As opposed to software simulations, Heliodons mimic the relationship between the sun and the study location by physically setting up the variables in real time. Also, the analysis method is intuitive making manual Helidon immediate to operate and easy to understand. This device can be used to study the shading property of a real fenestration system or scale model of a building or a part of the urban environment as a result of the movement of the sun on the celestial sky. To construct and use this device the following generalized procedures are followed;

- i. Identification of the independent variables
- ii. Design and constructing Heliodon with appropriate specifications so that it can simulate identified variables
- iii. Determining latitude, azimuth, and altitude of the sun for the study area

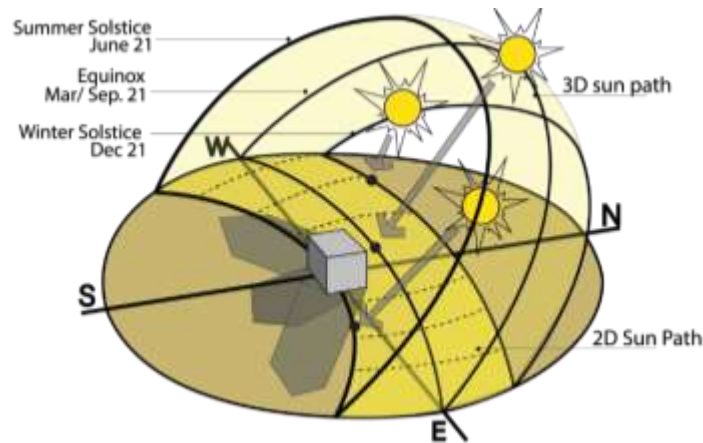


Figure 32 Projection of 2D sun path to 3D sun paths

To assess the functionality of external shading elements, an instrument known as Heliodon is reintroduced as an analysis method. Heliodon is constructed to mimic the three-dimensional sun path diagram of the selected study area as illustrated by Figure 32.

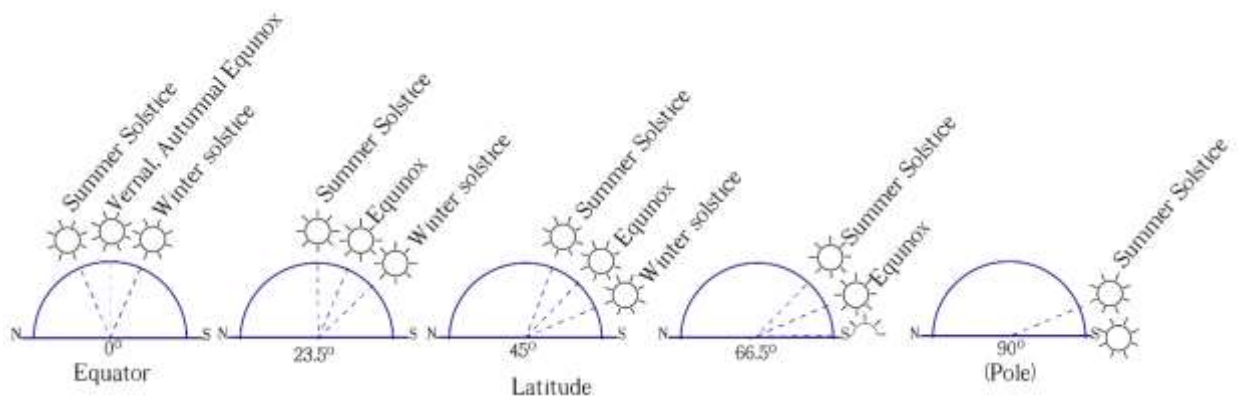


Figure 33 Solar declination of different latitudes

The Heliodon is expected to simulate the solar movement of any latitude, to accomplish this task, the arches that represent three-dimensional trajectories of the altitude and azimuth are expected to be movable. As shown above, in Figure 33, the sun's path shows variation in different latitudes and the center of rotation is the equinox path. From a practical perspective, the positioning mechanism and structure are adjusted by three solar geometry variables which are also determined to be the independent variables throughout this study:

- 1) The latitude, which determines the angle of the sun's position with reference to a location on Earth;
- 2) The day of the year, which defines the angle of the sun's declination; and
- 3) The time of day defines the azimuth or angle of the sun's position with reference to each hour of the day.

The sun emulator heliodon for this particular analysis is developed based on Lechner's (20015) model of conceptually clear heliodon where symmetrical months are represented on arches, depicting the path of the sun from West to East. Because of the annual symmetry of solar declination, all twelve months can be simulated with only seven paths, as can be seen on any sun-path diagram (Lechner, 2015). Among the seven trajectories, three are often used to demonstrate the movement of the sun throughout the year in a broadly generalized manner. These three prominent trajectories are the equinox, summer solstics, and winter solstices.

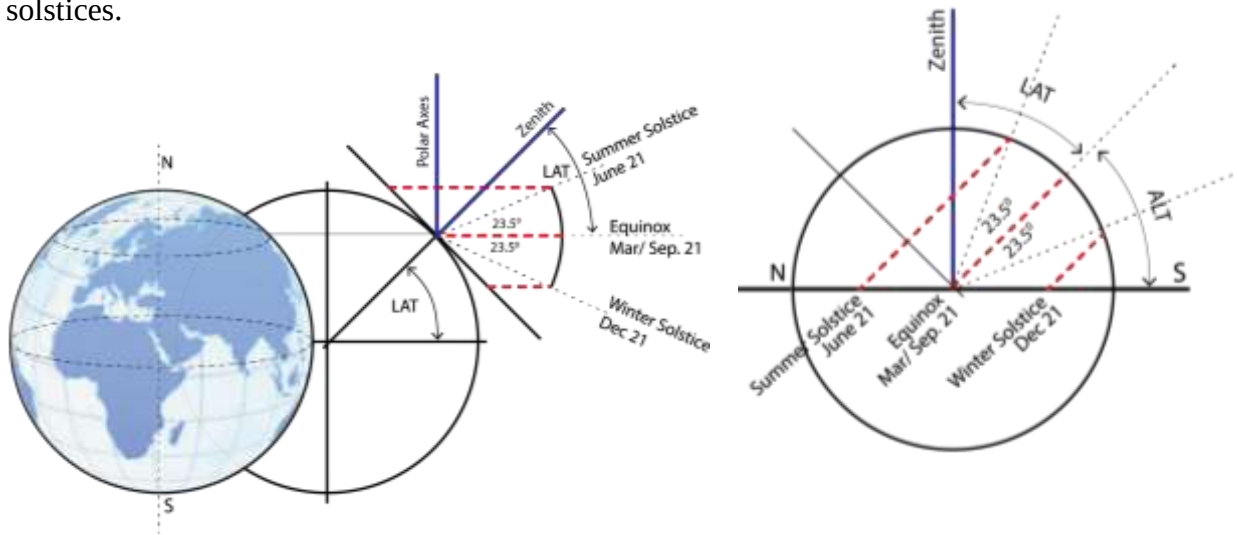


Figure 34 Solar curves Geo-centric view (left), Loco-centric view (Right)

As shown above, in Figure 34, the two solstices occur in June (20 or 21) and December (21 or 22). These are the days when the Sun's path in the sky is the farthest north or south from the Equator. A hemisphere's winter solstice is the shortest day of the year and its summer solstice is the year's longest. On the contrary, the equinox which occurs about (March 21 and September 23) represents the time when the sun is exactly above the equator making the day and night equal in length.

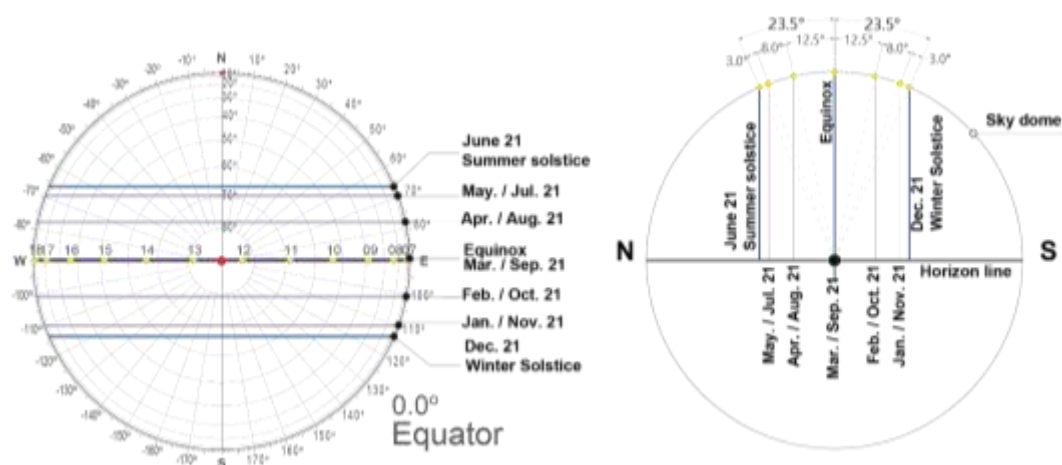


Figure 35 Tilt angle of each major paths

The angles of the summer and winter solstice each are determined to be 23.5° from the equinox trajectory. The trajectories between the equinox and solstice are calculated by projecting a polar equidistance solar path diagram to create a North-South elevation of the sun path trajectory as can be seen in Figure 35.

The design of the custom heliodon is required to rotate about the east-west axis to assume the actual sun path on a particular latitude. Also, the position of the sun in the sky dome should be represented. Thus, the custom heliodon is composed of parts that facilitate the movement of the sun on the sky dome. To enable this, the Heliodon features the following components;

- Stationary surface to place study model
- Arches that represent the movement of the sun in terms of azimuth and altitude.
- Movable Light sources fixed on arches emit lights as the representation of solar beams during different hours of the day.
- Rotating mechanism to lock the arches in place at a specific latitude

The Parts are designed to be cut and assembled (Figure 37 & 38) using an MDF board utilizing a CNC machine (See Appendix_2 for the cut list and detail parts). Equidistant sun path diagrams are used as a reference for the geometry of the heliodon construction. Variables adjusted while emulating the position of the sun in the celestial dome are the Latitude of the study area, time of the day which corresponds to the azimuth of the sun on a particular date, and solar elevation (altitude angle) of the sun which corresponds to the seasons of the year. This data is extracted from sun path diagrams projected vertically to find the positions of the sun in a 3-dimensional space. For instance Figure 36 shows the positions of the sun at solar noon every month.

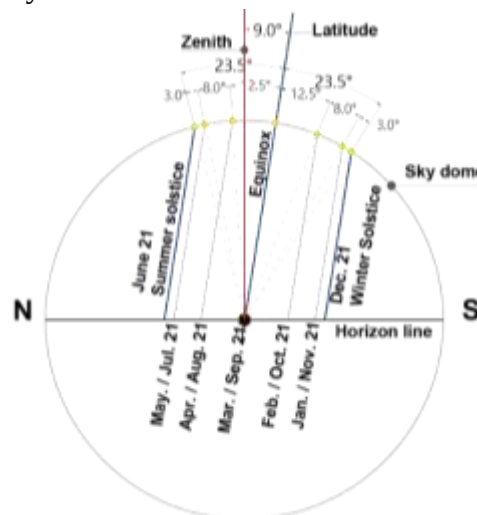


Figure 36 Solar declination at 9° N

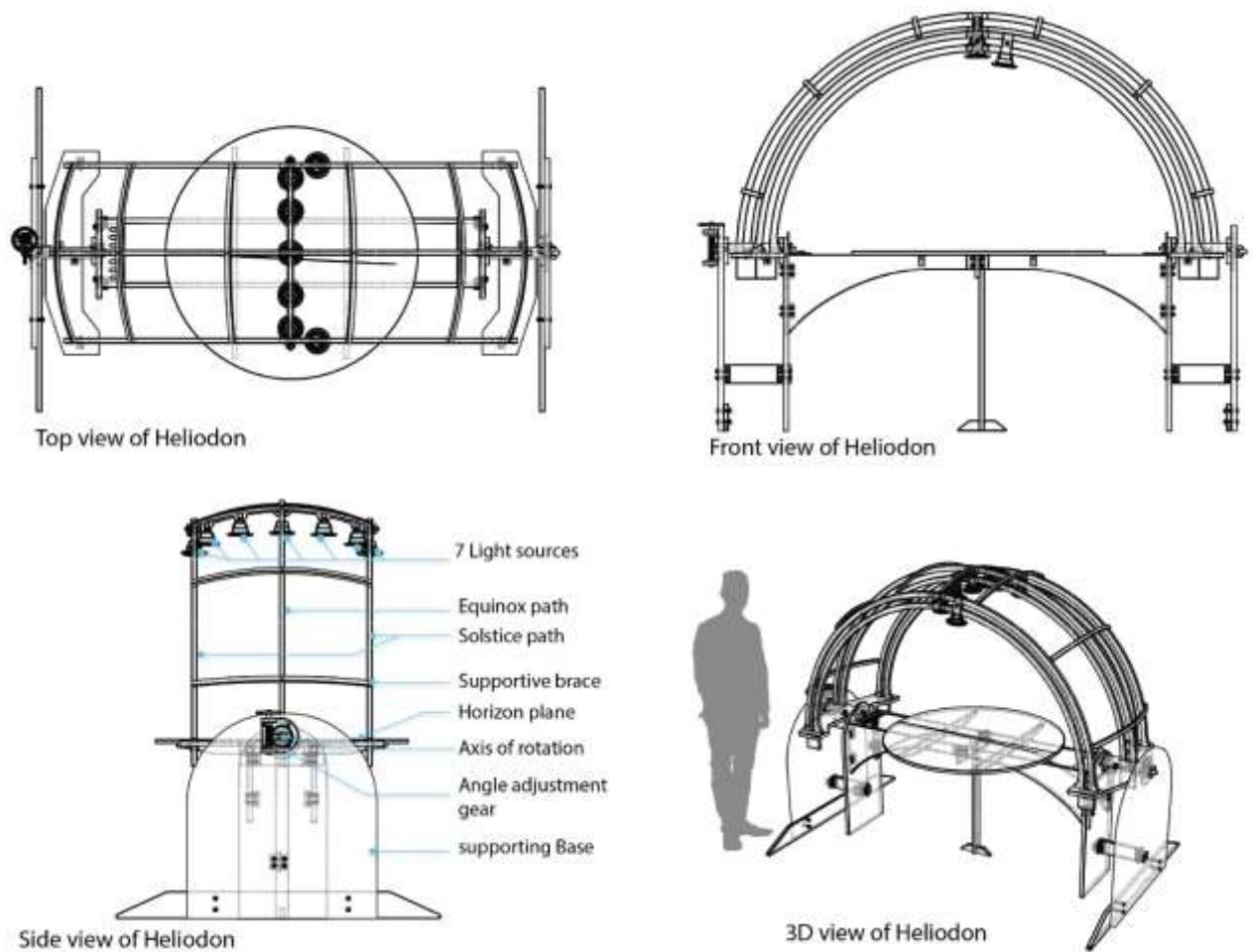


Figure 37 Heliodon design based on the conceptually clear model



Figure 38 Custom-made adjustable Heliodon

Measurement validation and verification

As discussed in the literature section, one of the limitations of using heliodon as an investigation tool is the lack of standardized procedures for calibration and verification, and as a solution to this drawback, different scholars suggest using computational tools for validation of the findings (Salgado-Conrado & et.al., 2022). Also to assess the operational validity of the device, (Sargent, 2011) outlines a method of comparison to other models to be applied which can be conducted as a subjective approach or objective approach. Since the model is an observable system, comparison using graphical displays can be used as a subjective approach, and comparison using Statistical tests as an objective approach.

To conduct a subjective approach to validating the results, computer simulation models are visually compared to that of the heliodon to draw an inference of similarity of results. This method does not quantify the degree of similarity between the results (Sargent, 2011).

As an objective approach, criterion validity is assessed. Numerous software programs enable simulations that are comparable to those that may be produced with a physical Heliodon (Salgado-Conrado & et.al., 2022). Regarding the accuracy of the findings, it can be said that the digital data produced by a computer simulation of a virtual heliodon is far more accurate and descriptive than the findings from analog models (Barrantes, 2021). Hence criterion validity can be conducted to assess the reliability of the results obtained by the Heliodon. Because a test's criterion validity measures how effectively it can forecast a specific result or how closely its results resemble those of other tests (Ralph, 2014). To validate the measurement, a random pair of results is used. The first measure which in this case is the result of the heliodon is the experimental value. The second measure which is the result of a computational simulation is the criterion variable and this measure is known to be a valid representation of the actual phenomenon. Ecotect 2014 software is used to generate shading effects which are used as a validated output to compare the measurements of the heliodon. To determine the degree of accuracy of individual results, the percent error is calculated using the following formula;

$$\text{Percent error} = \frac{| \text{Experimental value} - \text{Accepted value} |}{\text{Accepted value}} \times 100$$

Mean absolute percentage error is used to determine the average accuracy of the measurements taken. The formula to calculate MAPE is shown below.

$$M = \frac{1}{n} \sum_{t=1}^n \left| \frac{A_t - E_t}{A_t} \right|$$

Where: M = Mean absolute percentage error

n = fitted points

A_t = Accepted value (From Simulation)

E_t = Experimental value (From heliodon)

In this analysis, a smaller value in MAPE represents a higher degree of closeness to the accepted value while a higher percentage denotes an error of a higher degree.

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1. Determining overheating periods

To identify overheated periods a base point temperature of 15 °C is used. And according to Lechner, for an envelope-dominated building, the overheated period begins at 5 °C above the base point temperature. Therefore, for this particular study, the threshold temperature that would require the deployment of shading devices is 20 °C and 24 °C is the upper comfort level which constitutes the threshold temperature for overheating.

The city of Addis Ababa, experiences weather conditions mainly in the comfort zone, while the mean annual temperature falls within the range of 15 °C to 18 °C. The average high temperatures fall within the comfort ranges of 20 °C to 24 °C while the recorded maximum temperature can reach 27 °C (Figure 39). According to the weather data analysis 81% of the year experience temperature within the range of 0 °C to 20 °C, 17% of the year 20 °C to 24 °C and 2% above 24 °C. This data is summarized in Figure 40 as shown below.

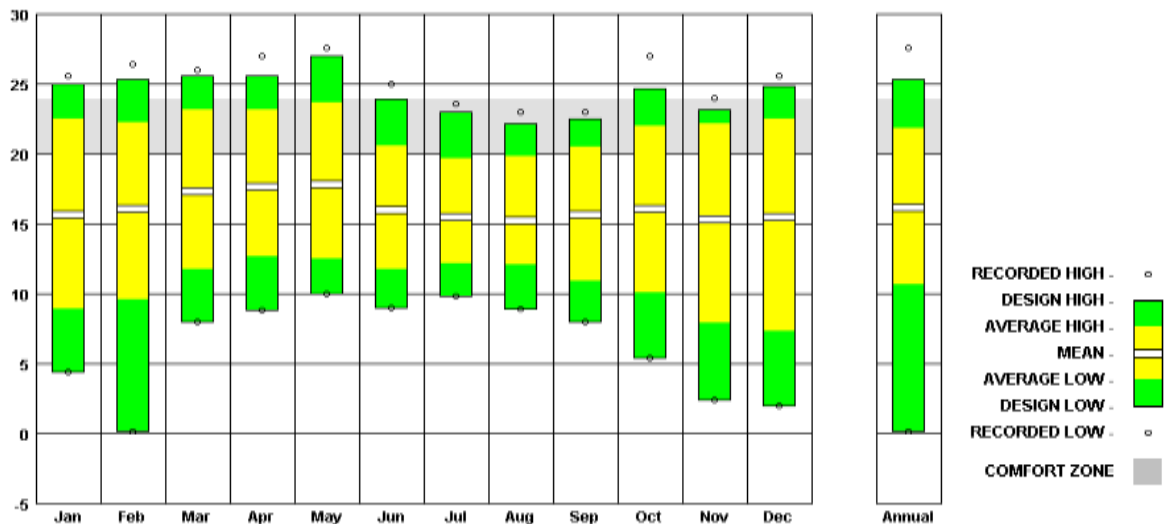


Figure 39 Temperature profile of Addis Ababa

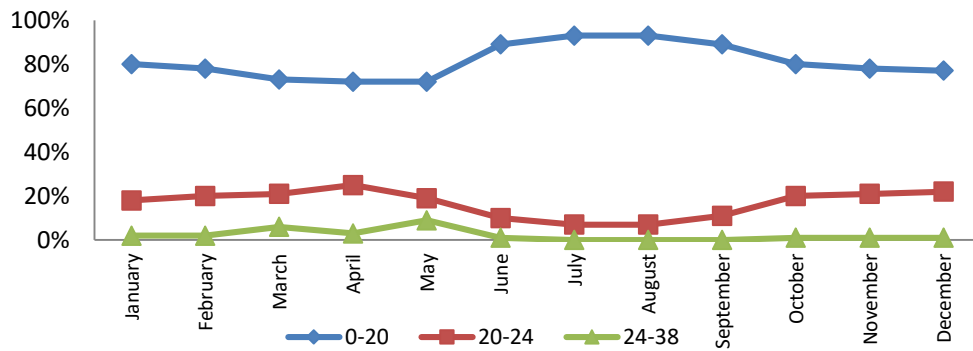


Figure 40 Temperature distribution in a year

Using weather data and climate consultant weather analysis software, Time table plot is produced which shows the diurnal and night-time temperature is extrapolated with the frequency of peach ranges of temperature throughout the day.

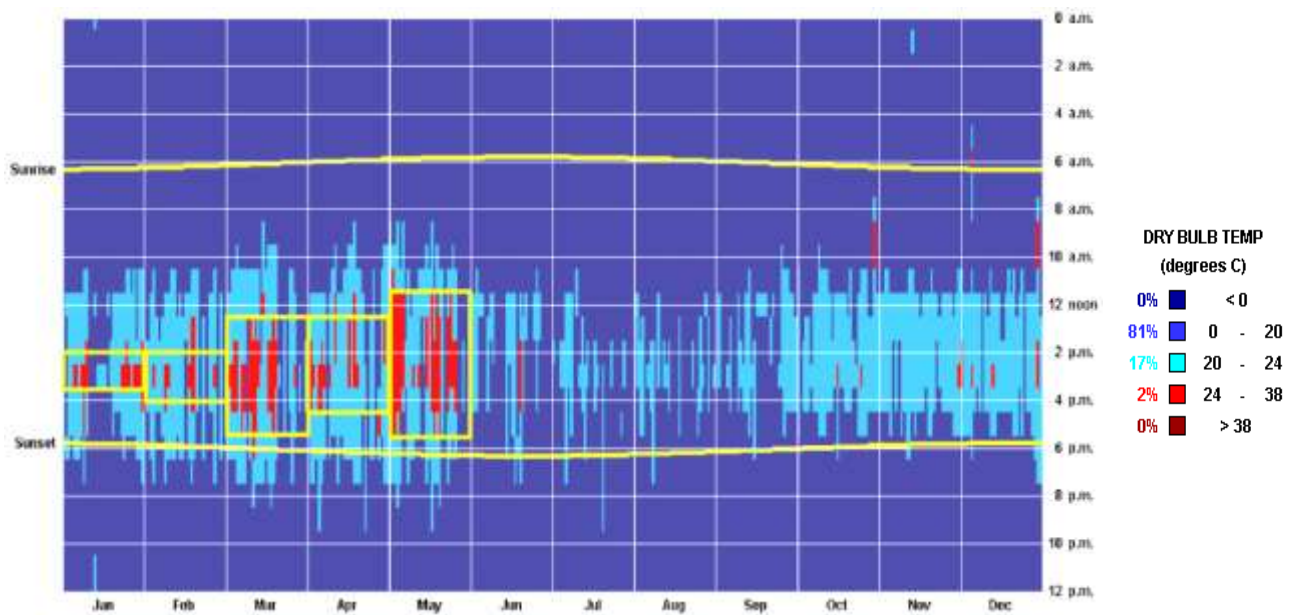


Figure 41 Time table plot

While most of the year experience 80% and above temperature below 20 °C, the chances of experiencing overheating are eminent in the typical sunny season (Figure 40). The timetable plot (Figure 41) analysis shows that the distribution of hot temperatures exceeding 24°C befalls between January and June. Among these months, May experience the highest level of overheating which accounts for about 9% of >24 °C temperature in the month. Furthermore, the timetable plot indicates that occurrences of overheating are concentrated in the time of the day between 10 am to 4:30 pm.

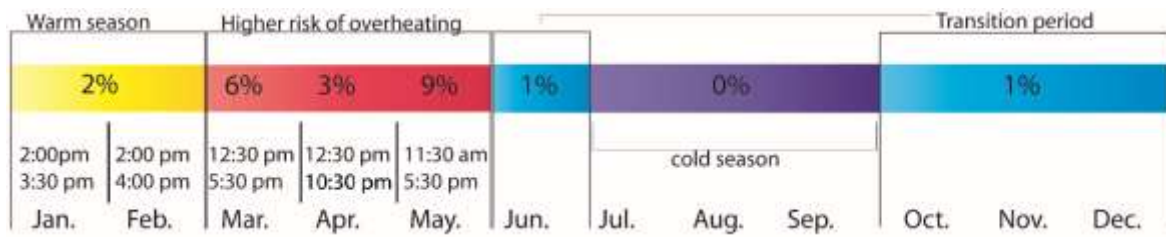


Figure 42 Percentage of overheating durations

A simplified version of the timetable plot represents the diurnal temperature variation for temperature threshold exceedance (Figure 42). As shown in Figure 42 the distribution of overheating days ranges from 1% to 9%. The occurrence of overheating is likely to happen from January to May.

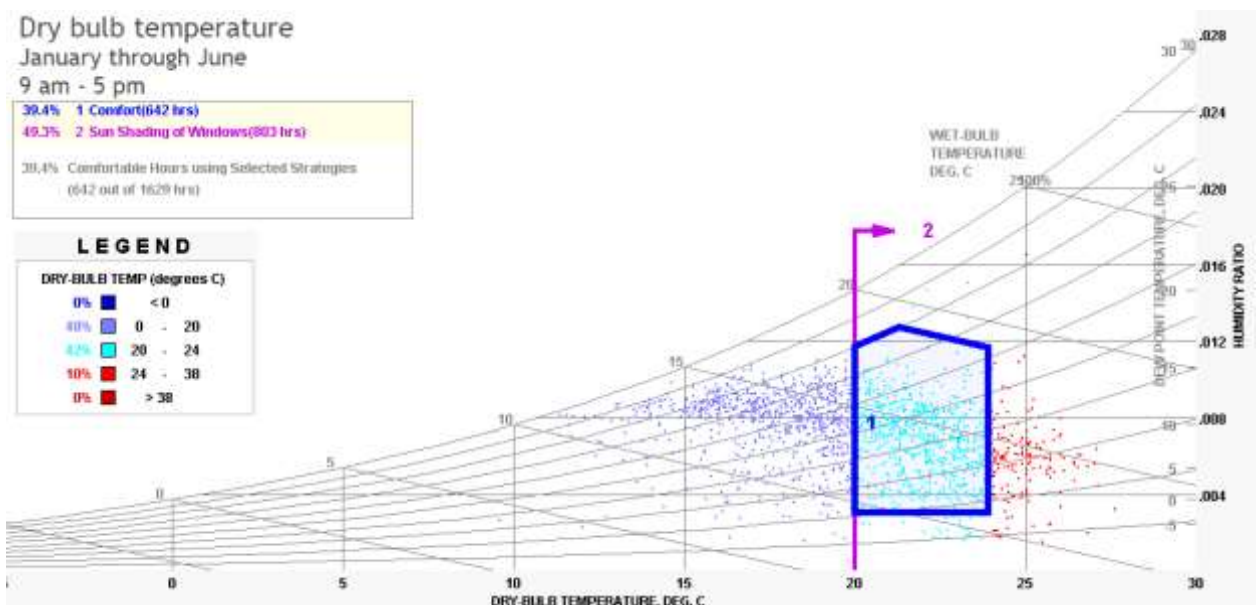


Figure 43 Psychrometric chart

The dry bulb temperature plotted on a psychrometric chart (Figure 43) for the months of January through June and during the intervals of 9 am and 5 pm which is typical working hours shows that 42% of the year experience temperature over 20 °C and 10% of the year having above 24 °C. By providing shading during this hot season 803 hours can be kept from overheating.

4.2. Shading mask for study area and orientations

By superimposing the weather data that identified the overheated period on the sun path diagram shading mask is prepared which represents the portion of the sky dome. The date and the time when shading should start and stop are marked on the sun path diagram: these points are joined and the enclosed area is shaded. The shaded area represents the position of

the sun in the sky when shading is needed. Figure 44 shows the shading mask of selected buildings.

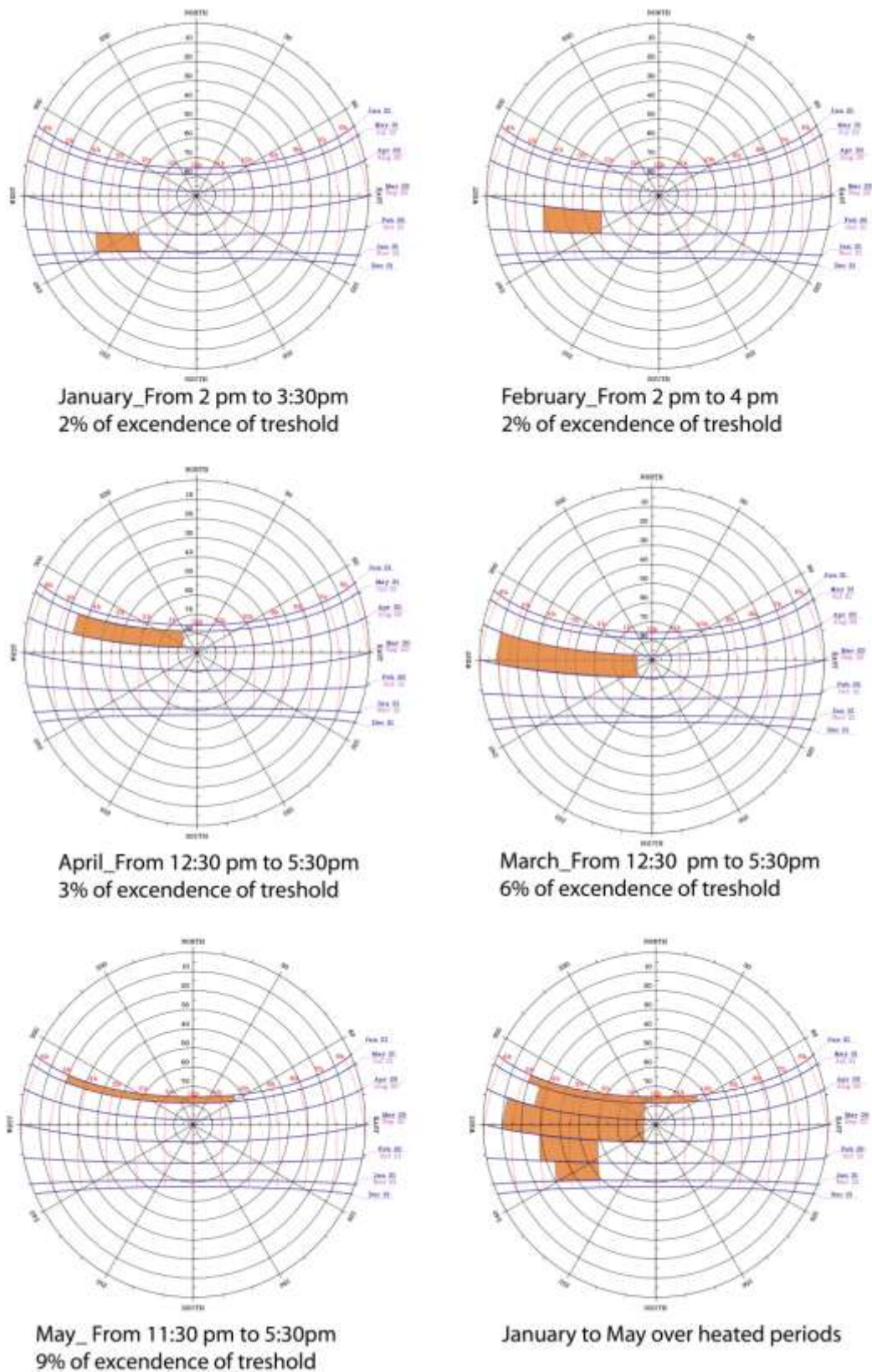


Figure 44 Shading mask

4.3. Analysis of the performance of shading devices

The shading performance of the shading devices is analyzed by using the shaded cell fraction method that uses scaled models of the external shading device in question. The scaled models placed on the heliodon are lit with LED lamps with corresponding sun location to the overheated period which is tabulated in Table 6. While operating the heliodon, latitude, and light source corresponding to the particular month, time of day and orientation of the model are adjusted. The custom-made heliodon can be tilted to the desired latitude as shown below in Figure 45. The percentage of shading in the given overheated period is derived by digitizing the shadow cast by the heliodon lights and the shading elements on the supposed window surface followed by determining the shadow polygon area.



Figure 45 Heliodon locked at 9 ° latitude for solar analysis

Procedures undertaken in this study are summarized in Appendix_2 along with design specifications for the custom-built heliodon. Shading performance results obtained in this analysis are shown in Appendix_3. The results are recorded with a camera phone and then digitized to a similar scale to determine the shaded fraction caused by the shading elements.

Table 6 selected sun shadings and orientation with overheating season exposure hours

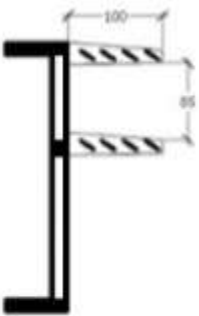
								Overheated seasons				
No.	Selected building	Building Orientation	Location	Shading type	Shading orientation	Shading Azimuth angle	Selected orientation	January	February	March	April	May
1	Giant Eagle Trading Building	South	9.00514 N, 38.742666 E	Vertical fins with overhang vertical panel	North + Waste	177.5° South, 90° East, 355.8° North	355.8°	-	-	12:30 AM - 5:30 PM	12:30 AM - 4:30 PM	10:00 AM - 5:00 PM
2	Renaissance Building	North east	9.018902 N, 38.800995 E	vertical slanted fins	North East	36.1° North east	36.1°	-	-	-	-	10:30 AM - 1:00 PM
3	United Bank Headquarters	South east	9.01368 N, 38.748713 E	Vetical panel with Horizontal Louvers	South West	230.8° South West, 286° North West, 163.3 South East	230.8 , 163.3°, 280°	2:00 PM - 3:30PM	2:00 PM - 4:00 PM	12:30 AM - 5:30 PM	12:30 PM - 10:30 Am	12:00 AM - 5:30 PM
4	Commercial Bank of Ethiopia	North east	9.012735 N, 38.748593 E	Vertical fins	All direction	23.1°, 46.8°, 106.8°, 179°, 1231°, 290°, 354.2°	46.8°, 179°, 290°, 354.2°	2:00 PM - 3:30PM	2:00 PM - 4:00 PM	12:30 AM - 5:30 PM	12:30 AM - 4:30 PM	10:00 AM - 5:00 PM
5	Dashen Bank Headquarters	North	9.016534 N, 38.749732 S	Horizontal louver	South	180° south	180°	2:00 PM - 3:30PM	2:00 PM - 4:00 PM	12:30 AM - 5:30 PM	-	-
6	Africa Insurance	South	8.99243 N, 38.780435 S	Horizontal curved louver	South East west	98.3° South East, 188.3° south west, 280° Nort West	190°	2:00 PM - 3:30PM	2:00 PM - 4:00 PM	12:30 AM - 5:30 PM	-	-
7	MTSE Building	West	9.012581 N, 38.75209 S	Horizontal louver with vertical panel	East	1.8° North, 87.1° East, 179.6° South	87.1°	-	-	-	-	10:30 AM - 12:00 PM
8	Wegagen Bank	North		Vertical fins	waste	92.7° Ease 87.3° West	272.7°	2:00 PM - 3:30PM	2:00 PM - 4:00 PM	12:30 AM - 5:30 PM	12:30 PM - 10:30 Am	12:00 AM - 5:30 PM

4.3.1. Dashen Bank HQ Building shading analysis

The Dashen bank building features an overhanging slanted louver in a horizontal plane commonly known as Brise-soleil, which is a mode of shading that uses a series of horizontal blades to control the amount of sunlight and solar heat that reaches the building façade. This shading extends in the southern façade of the building in a shelf configuration

The southern façade of the building is fitted with double permanent shading (see Table 7). Analysis was conducted using a scaled model and Heliodon. The façade is aligned with the correct azimuth and each overheated period exposed to direct sun rays is investigated.

Table 7 Dashen Bank HQ Shading description

Shading device							
							
Plan		3D view		Section			
	Location	Function	Stories	Shading Type	Material	Azimuth	WWR
Dashen Bank	Mexico 9.016534 N, 38.749732 S	Office	21	Horizontal louver	Aluminum	180°	Full glazing

Using a solar path diagram with a shading mask overlay, the overheated period that affects the selected shaded façade is determined to be January, February, and March with varying degrees of exposure (Figure 46).

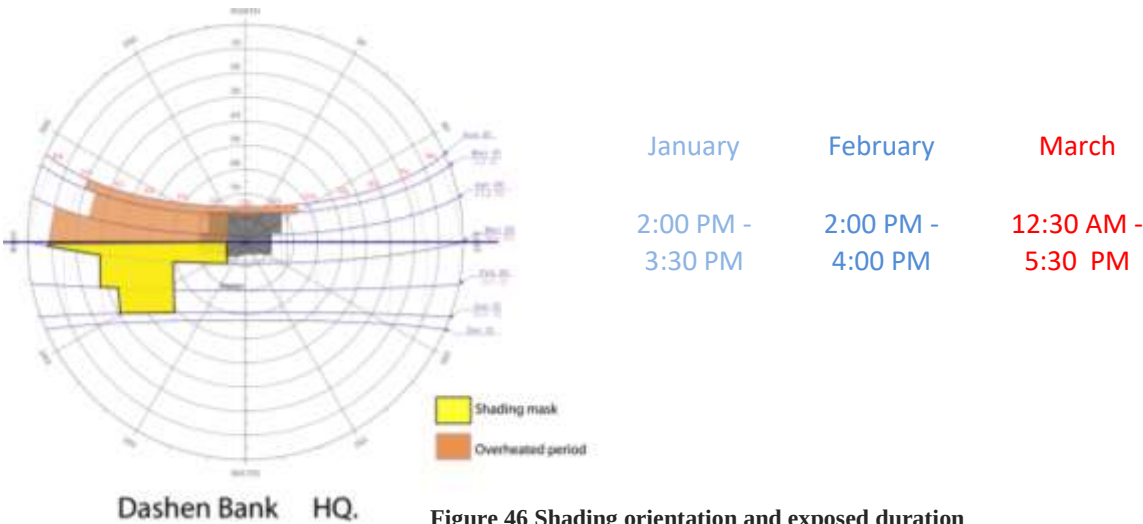


Figure 46 Shading orientation and exposed duration

The analysis indicated that throughout the overheated season the functionality of the external shading devices exhibited a varying degree of shading performance. The above table shows the hourly shading in respective months.

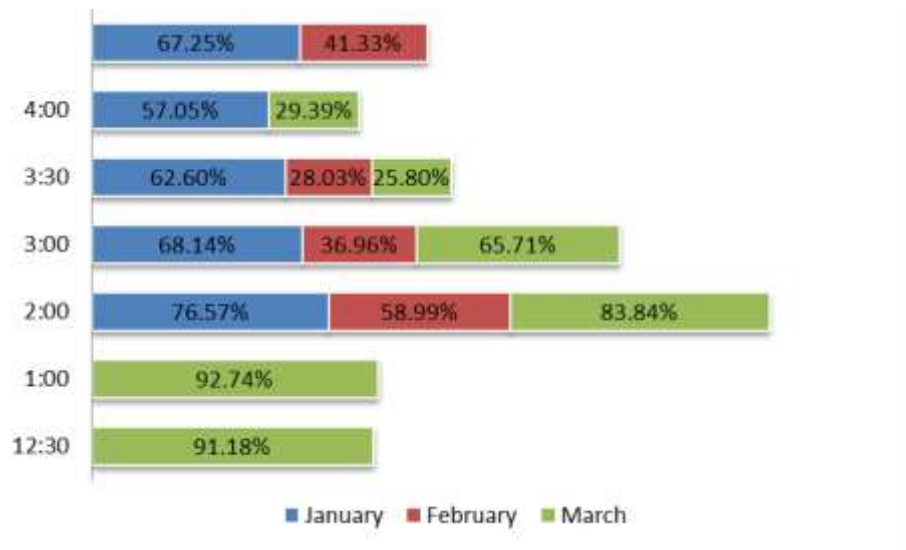


Figure 47 Hourly Shaded fraction

As shown in Figure 47 above, during the overheated period shading devices on the building provide shading within the range of 25% and 91%. Maximum shaded façade is recorded during the month of March which is above 90%.

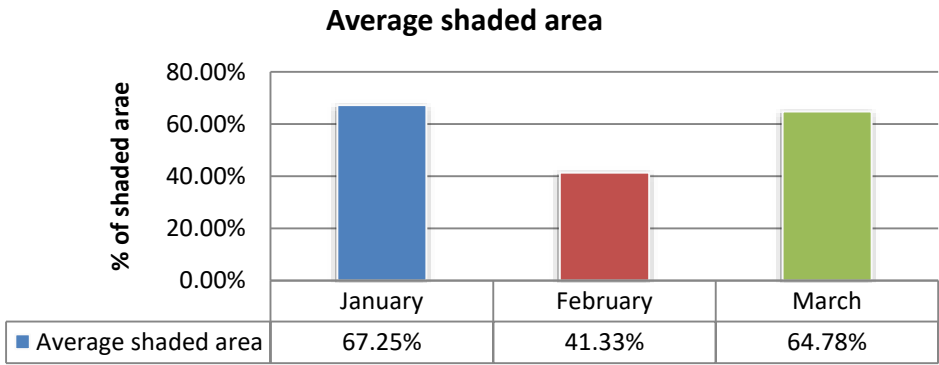


Figure 48 Average monthly shaded fraction

Furthermore as shown in Figure 48, at March 5:00 and 5:30 the light beams show diffused patterns on the window surface hence creating a completely shaded surface. This is due to the altitude of the sun having no significant amount of direct rays landing on the surface under study. In general, the external shading device facing south is functional in January to a higher degree. While February has below 50% shaded fraction.

4.3.2. Africa insurance building shading analysis

Africa insurance building is an office building that has a distinctive shading system. As shown in Table 8, the external shading device is a curved horizontal louver with small perforations. The shading devices cover the entire glazed surfaces of the building protecting against solar radiation throughout the year.

Table 8 Africa insurance shading description

 3d  Plan  section							
	Location	Function	Stories	Shading Type	Material	Azimuth	WWR
Africa Insurance bldg.	Bole 8.99243 N, 38.780435 S	Office	13	Horizontal perforated louver	Aluminum	280°	Full glazing

Using a solar path diagram with a shading mask overlay, the overheated period that affects the selected shaded façade is determined to be the month of May for this particular façade azimuth (Figure 49).

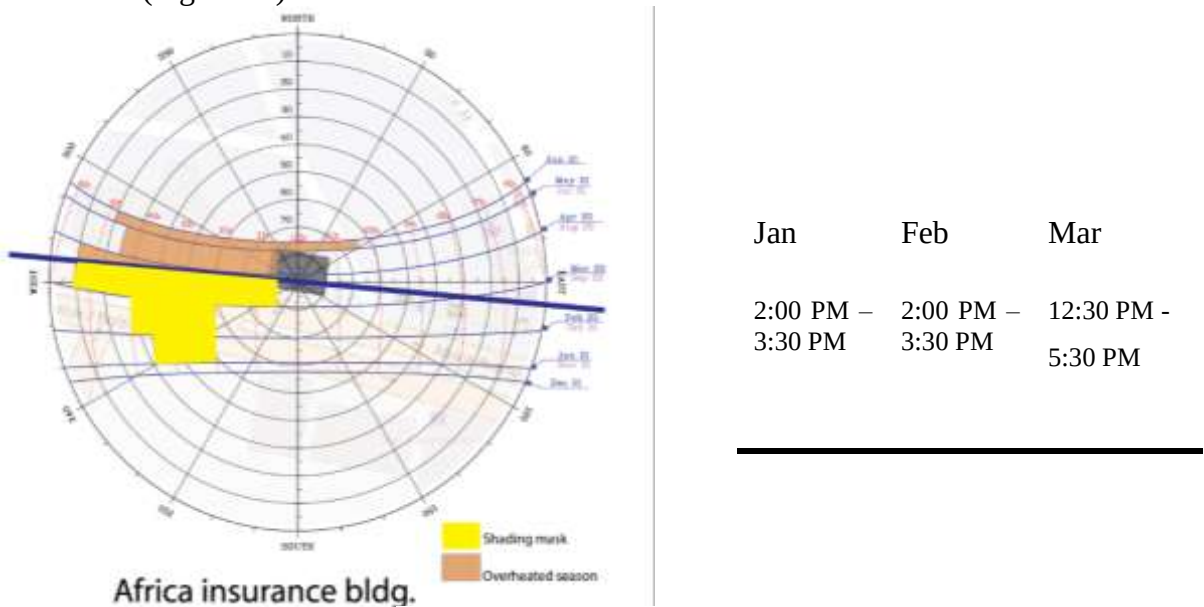


Figure 49 Shading orientation and exposed duration

The selected orientation exposes the facade due south and the façade is exposed to about 10 hours of solar exposure during the overheated season. The performance of the shading device is easily predictable due to the opaque design of the shading element. As is evident by the analysis conducted by Heliodon, the shading element blocks a significant amount of incident solar rays from entering the building (Figure 50).

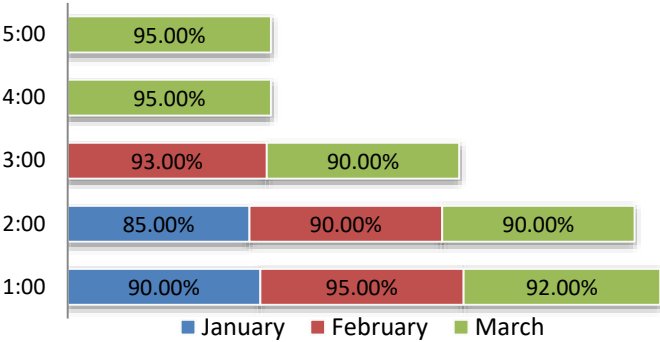


Figure 50 Average shaded fraction

Monthly average shading performance is above 87% as shown in Figure 51. Observing the performance of the shading in the selected orientation, other directions are expected to experience a similar level of insolation. Contrary to the shading performance the emulation has indicated the inverse relation between shading and restriction of access to natural light.

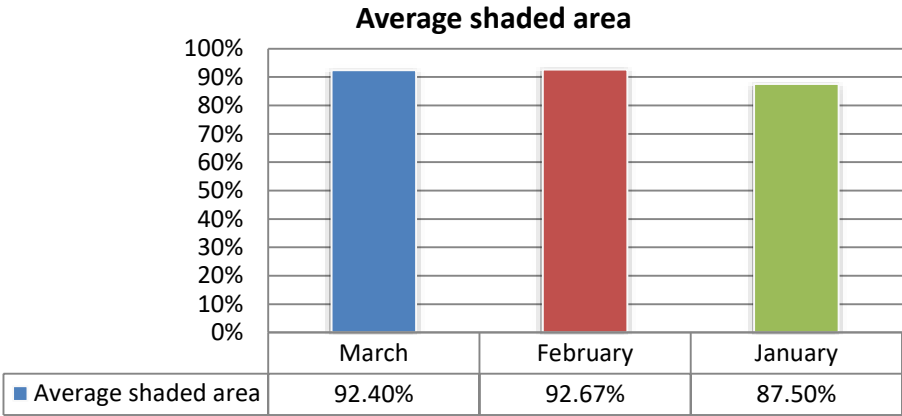


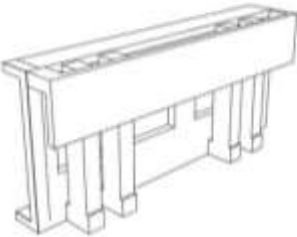
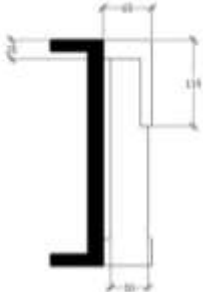
Figure 51 Average monthly shaded fraction

4.3.3. Giant Eagle Building shading analysis

The giant eagle trading building is a recent development near the commercial and business district of Addis Ababa. The major axis of the building extending east-west exposes the front façade to a southern orientation. An external shading system integrated with the building’s structure with similar construction material. Even though the shading elements are placed in

all directions of the building façade, only Northern shading elements are examined in this study.

Table 9 Giant eagle building shading description

 3d  Plan  section							
	Location	Function	Stories	Shading Type	Material	Azimuth	WWR
Giant Eagle Trading Bldg.	Mexico 8.99243 N, 38.780435 S	Mixed-use	17	Vertical fins with vertical panel	Concrete	280°	partial glazing

The solar chart with an overlay of the overheated period is used to determine the time of exposure. Accordingly, the majority of May and April experience a higher duration of exposure and to some extent, the month of March (Figure 52).

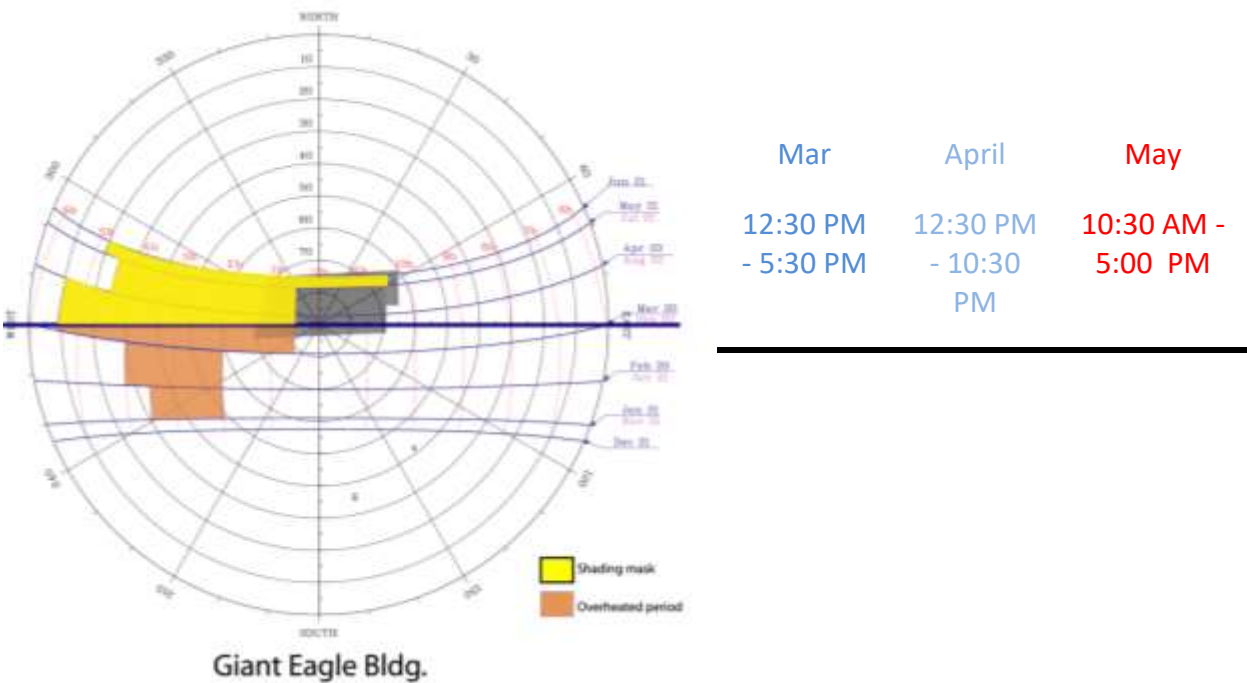


Figure 52 Shading orientation and exposed duration

The analysis showed that the time 4:00 am to 1:00 pm experiences the highest level of shading. Due to the high chance of exposure to solar radiation from the northern side during May, shading elements are required in this direction. Evidently, the shading provides relatively high performance during May accounting for 68% of the overheated period of the month (See Figure 53).

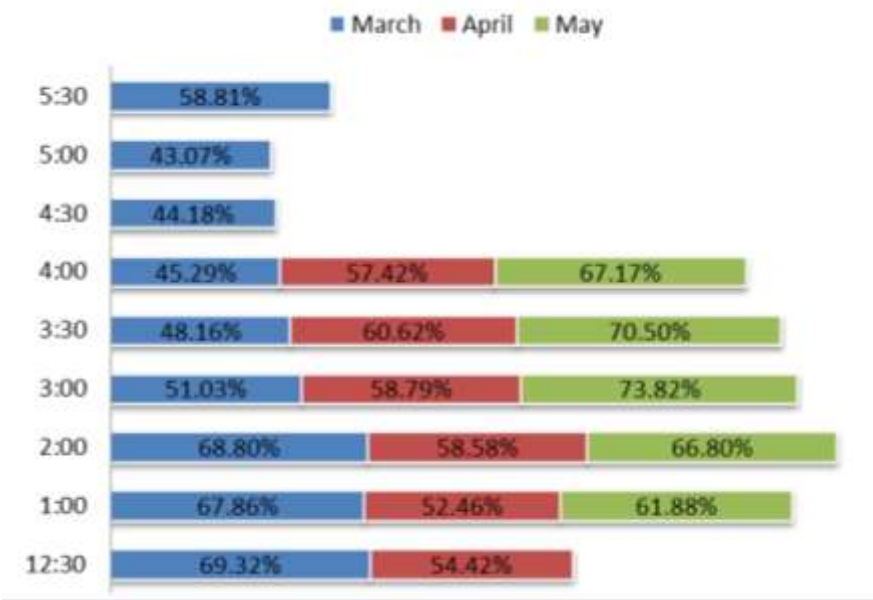


Figure 53 Hourly shading fraction

For the majority of the overheated season, the hours between 1:00 PM to 4:00 PM are shaded with the shading element. Similar to other north-facing elevations the solar radiation is intensified during May. As shown in Figure 54 the shading performs better during May which is when the highest percentage of overheating is recorded. May, April, and March show shading performance from high to low respectively.

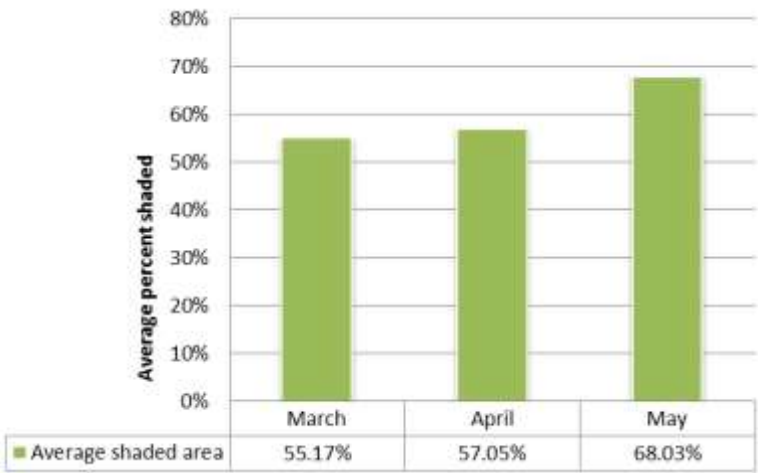
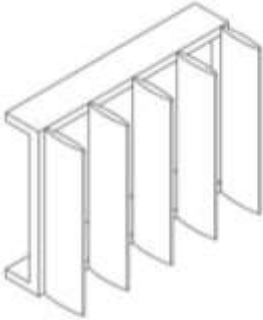
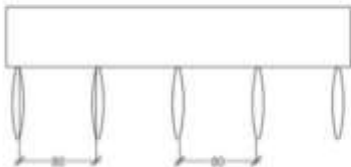


Figure 54 Average monthly shaded fraction

4.3.4. Wegagen bank HQ building shading analysis

One of the high-rise buildings with integrated vertical fins is Wegagen bank HQ. located in Addis Ababa. The oval vertical fines are integrated parts of the cladding facing east and west (Table 10).

Table 10 Wegagen bank shading description

  							
	3d	Plan	section				
	Location	Function	Stories	Shading Type	Material	Azimuth	WWR
Wegagen Bank	Stadium 9.011719 N, 38.756211 E	Office	23	Vertical fin	Aluminum	179°	Full glazing

The building is oriented with its long axis in the north-south direction, exposing the majority of the facades of the buildings to east and west solar radiation. The side analyzed in this particular study is the west-facing elevation which experiences a high amount of exposure

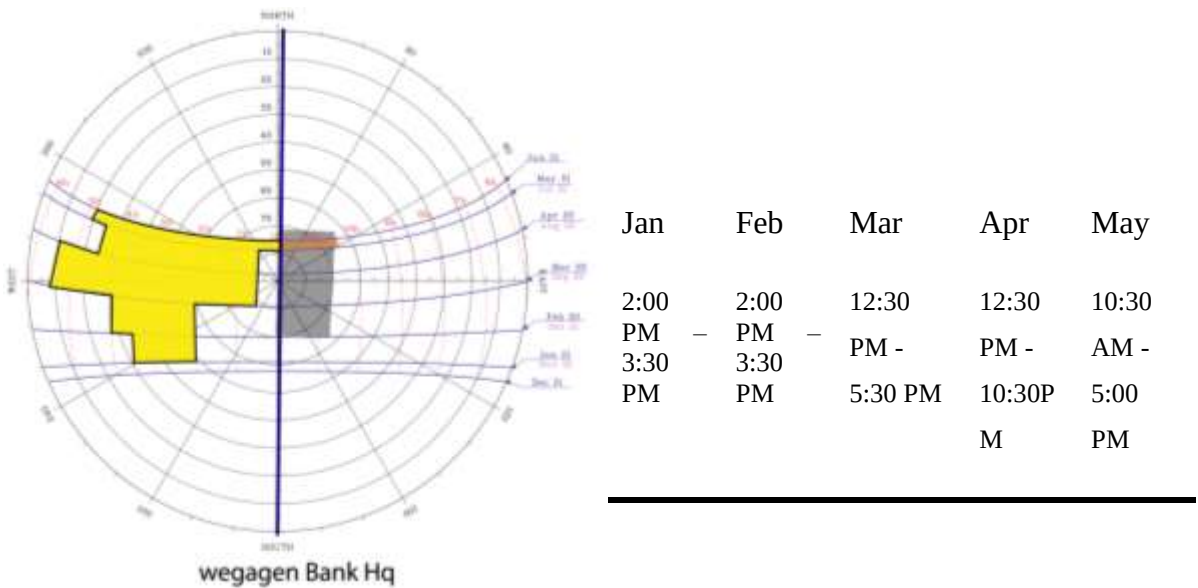


Figure 55 Shading orientation and exposed duration

during the afternoon. Through the out overheated period, the western façade is exposed to the majority of direct solar radiation (Figure 55). Hence the application of solar shading devices integrated into the façade is a practical solution besides adding visual interest to the building.

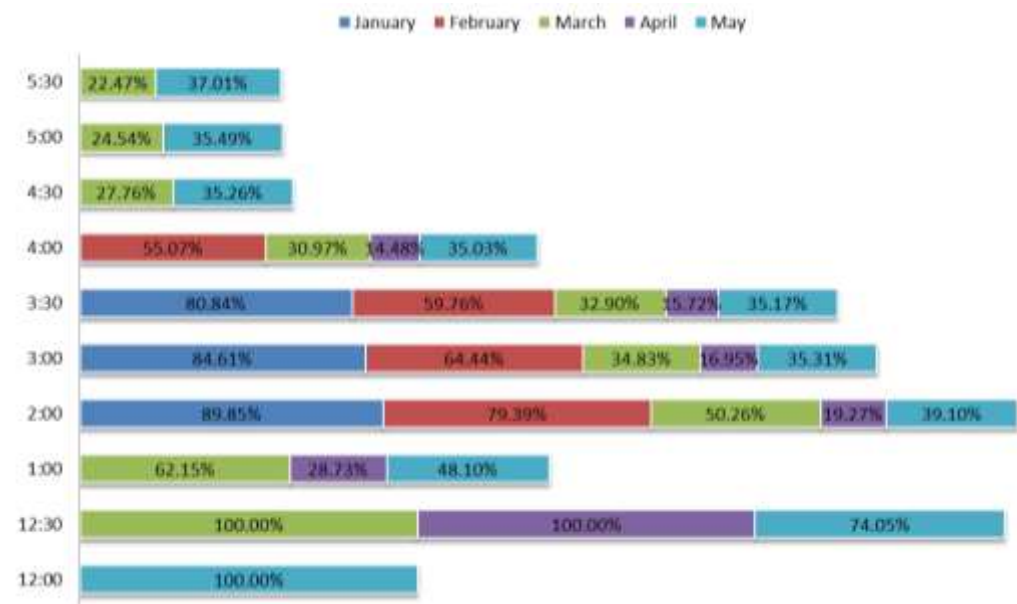


Figure 56 Hourly Shaded fraction

The analysis shows that the daytime from 12:00 PM to 4:00 PM is the time of day throughout the overheated period when the shading devices are highly functional (Figure 56).

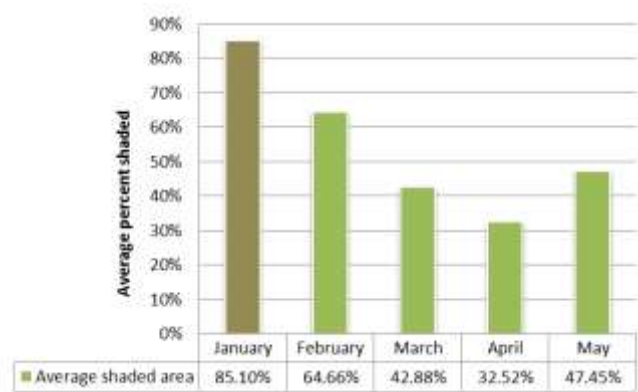


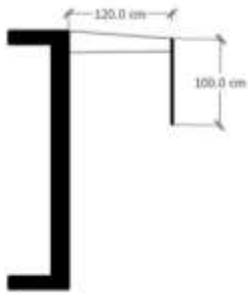
Figure 57 Monthly shaded fraction average

The performance of the shading elements is reduced during March and April (Figure 57) due to the azimuth of the sun which results in parallel solar rays with the shading elements. On the contrary, the vertical fins perform on a higher level during January and May as the sun's rays are intercepted at an angle.

4.3.5. MTSE building shading analysis

The newly constructed MTSE around Lagar is one of the imposing buildings with externally fitted sun breaks. The shading system employs a combination of vertical panels and horizontally fixed (Table 11) slanted louvers to provide shading in all directions except for the northern side.

Table 11 MTSE building shading description

   3d Plan section							
	Location	Function	Stories	Shading Type	Material	Azimuth	WWR
MTSE Building	9.012581 N, 38.75209 S	Office	15	Horizontal perforated louver	Aluminum	87.1°	Full glazing

Despite having shading elements in 3 orientations, for this particular study, the selected orientation is eastern shading elements. As shown in Figure 58, By overlaying the solar chart with the overheated season the resulting shading mask reveals that the eastern bound elevation is exposed to direct solar gain during May for about 2 hours.

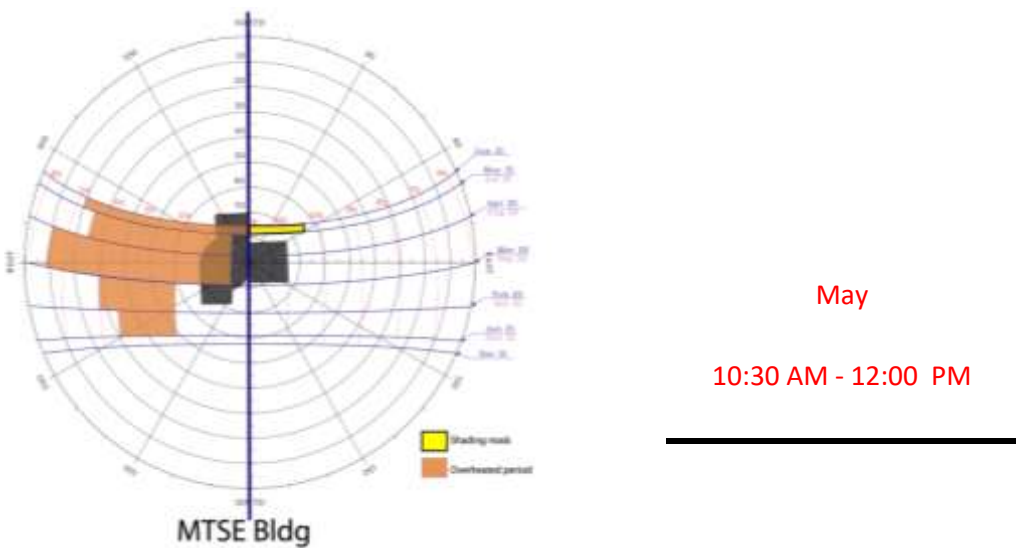


Figure 58 Shading orientation and exposed duration

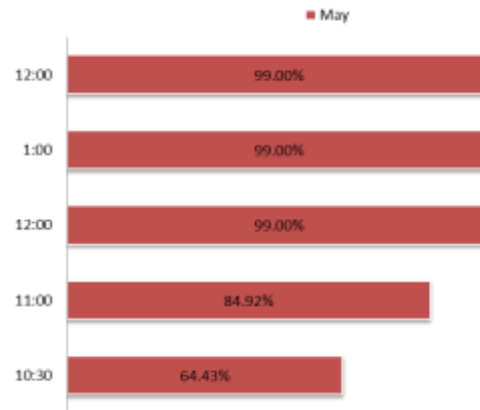


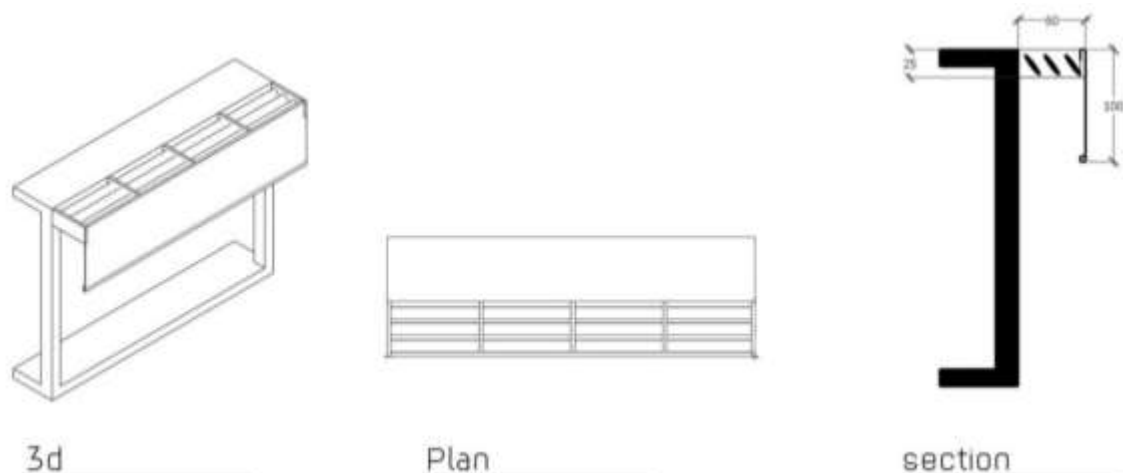
Figure 59 Hourly shaded fraction

The solar emulation revealed that the shading performs well when the sun angle is high (**Error! Reference source not found.**). This is due to the extended overhang of 120 cm created by slanted louver panes on the horizontal plane. On the time of the day when the sun is lower the vertical panel blocks the solar rays from reaching the façade, this configuration of shading has demonstrated a shading performance of 65% to 99% resulting in a nearly uniform shadow distribution on the window surface.

4.3.6. United Bank HQ Building shading analysis

United HQ is one of the tallest buildings in the city featuring externally fitted shading elements. The shading system is similar to MTSE shading configuration but the span is reduced by half and the vertical panels are perforated. The aluminum building cladding façade with the curved wall employs a combination of vertical panels and slanted louvers on a horizontal plain (Table 12).

Table 12 United bank HQ shading description



	Location	Function	Stories	Shading Type	Material	Azimuth	WWR
United Bank HQ	9.01368 N, 38.748713 E	Office	35	Vertical panel with Horizontal Louvers	Aluminum	230.8 °, 163.3°, 286°	partial glazing

By overlaying the overheated season onto the sun path diagram it is shown that the building façade with external shading is exposed to direct solar radiation for the majority of the overheated period which spans from January through May. The curved façade of the building

created a higher level of exposure as shown in **Error! Reference source not found..**

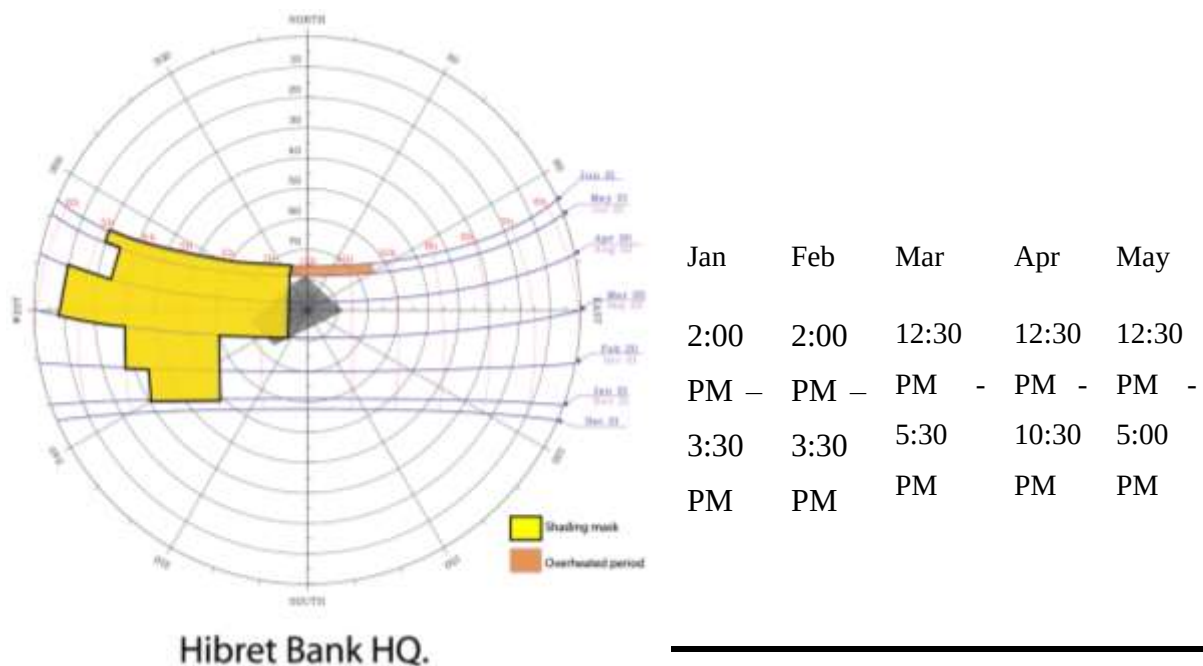


Figure 60 Shading orientation and exposed duration

For this study wall azimuths of 230.8 °, 163.3° 286° are studied which correspond to South West, South East, North, and West respectively. The performance of the shading elements is investigated in each selected wall azimuth and the result is compared to reveal the correlation of this particular shading system with the wall azimuth.

Wall azimuth of 163°

This particular orientation is exposed to the morning time of 2:00 AM to 4:00 AM. The shading device performs relatively better during February due to the higher altitude of the sun. shading performance is shown in Figure 62**Error! Reference source not found.** and monthly average shadin is shown in **Error! Reference source not found..**



Figure 61 Hourly shaded fraction

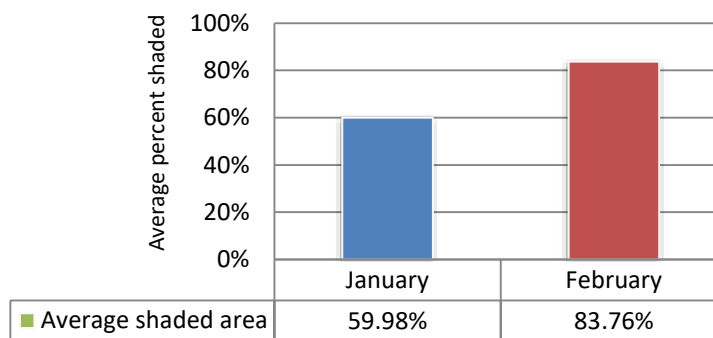


Figure 62 Monthly average shading

Wall azimuth of 230°

Wall azimuth of 230° is exposed to afternoon solar exposure with the highest performance observed during 2:00 PM and the lowest performance observed when the sun is low in the late afternoon (Figure 63).

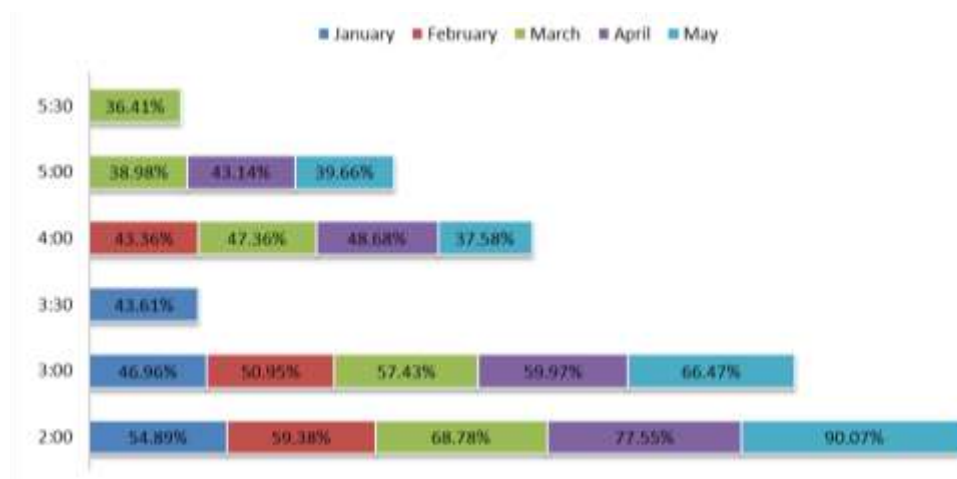


Figure 63 Hourly shaded fraction

Overall the performance of shading elements is lower compared to the rest of the orientations.

Wall azimuth of 280°

The north-western orientation of shading is exposed to a significant amount of solar gain during the afternoon throughout the overheated period. Throughout the overheated times, 1:00 PM to 4:00 PM is found to be shaded frequently. The shading performance is shown below in Figure 64 and 65.

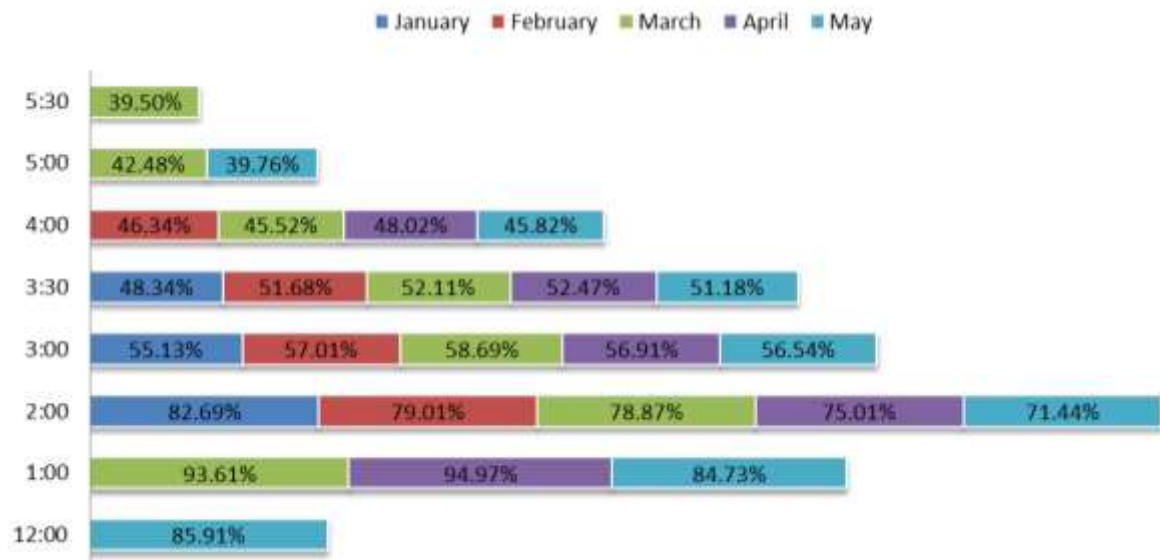


Figure 64 Hourly shaded fraction

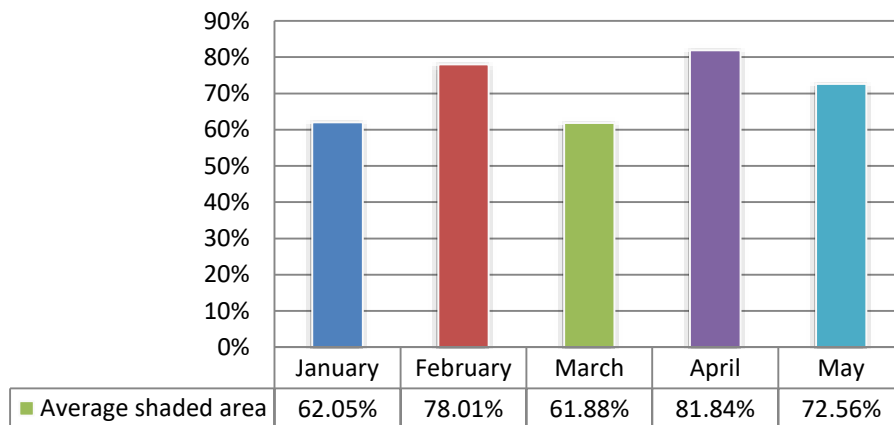


Figure 65 Monthly average shaded fraction

Figure 66 shows, Overall the external shading system integrated into the United Bank HQ showed a varying degree of functionality. The northwestern orientations demonstrated the highest level of shading throughout the overheated season.

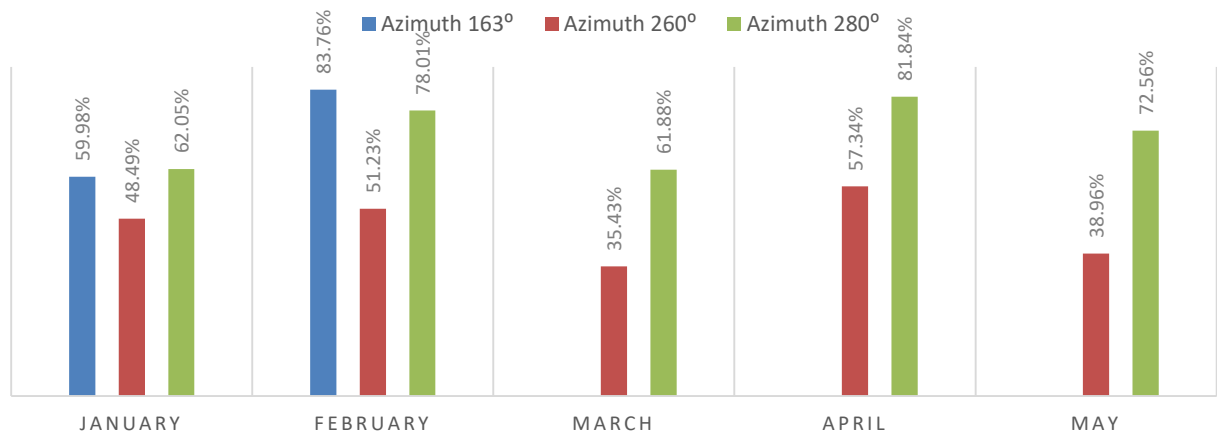
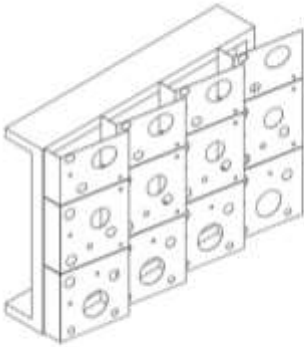
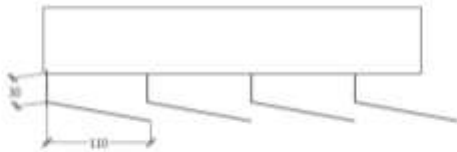
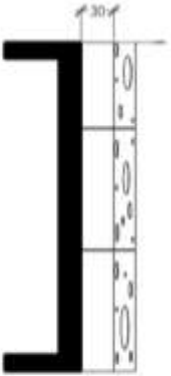


Figure 66 Comparison of performance in 3 different orientations

4.3.7. Renaissance Building shading analysis

The distinctive shading installed in the exterior façade of the Renaissance building features vertical slanted fins with circular perforated patterns. The shading system also greatly attributes to the visual character of the building as it features a contiguous appearance in the vertical and horizontal planes (Table 13).

Table 13 Renaissance Building shading description

  							
	3d	Plan	section				
	Location	Function	Stories	Shading Type	Material	Azimuth	WWR
Renaissance Bldg.	Megenagna	Office	15	Vertical slanted fins	Aluminum	36.1°	Full glazing

Overlaying the overheated period with the solar chart it is shown that the northeastern elevation is exposed to overheating during May. In this orientation mid-day exposure is the major threat during the overheated time (Figure 67).

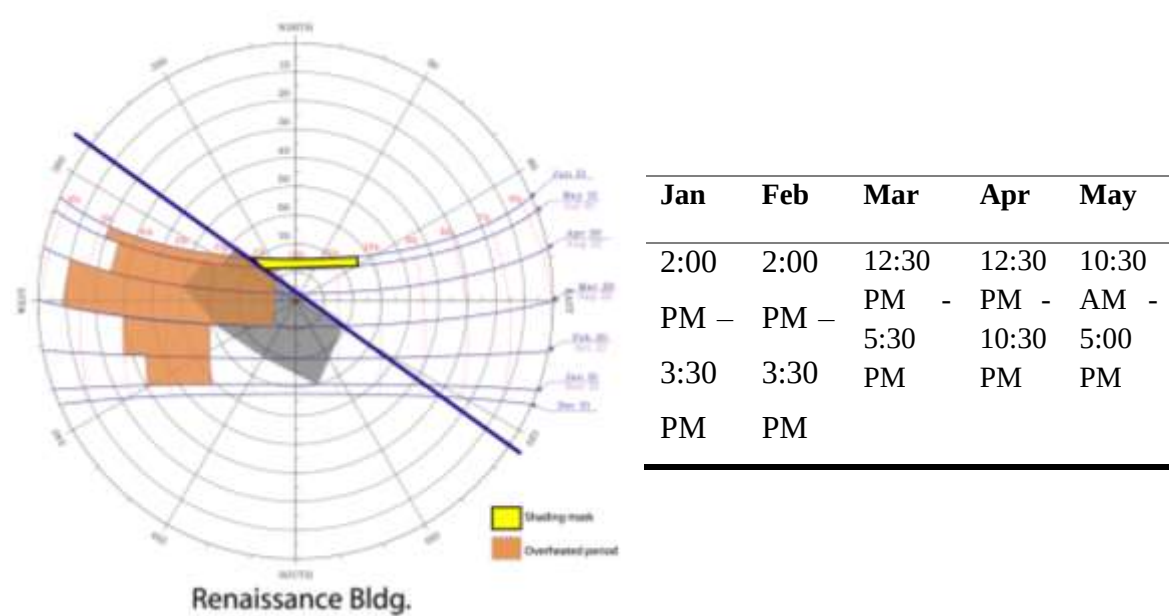


Figure 67 shading orientation and exposed durations

The orientation of the façade with the external shading device faces north eastern hence being exposed to the overheated radiation during May. The analysis shows that the shading system is most effective during 11:00 PM while shading than 25% of the glazed surface before 10:30 AM (Figure 68).

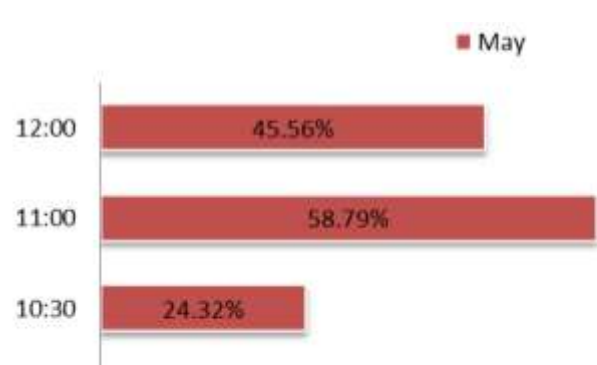


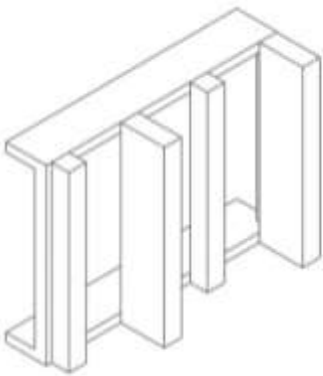
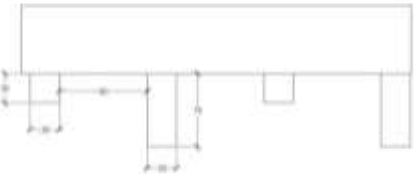
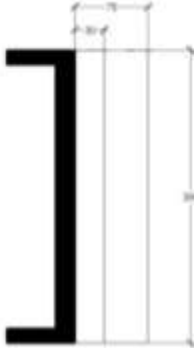
Figure 68 hourly shaded fraction

4.3.8. CBE HQ Building shading analysis

The newly constructed iconic building in the capital integrates vertical fins in the façade. The shading elements play a significant role in the visual aspect of the building. The vertical fins with an extrusion of 75 cm and 30 cm are placed in an alternating manner in all façade

directions. Even though the walls are slightly slanted, for this study, walls are considered vertical (Table 14).

Table 14 CBE HQ building shading description

							
3d			Plan			section	
	Location	Function	Stories	Shading Type	Material	Azimuth	WWR
CBE HQ	9.012735 N, 38.748593 E	Office	46	Vertical fins	Aluminum	354°, 46°, 179°,280°	Full glazing

Since the facades of the building are fully glazed facing all directions, the overheated season affects all orientations of the building. For this study elevations with a wall azimuth of 354°, 46°, 179°, and 280° are selected and evaluated (Figure 69).

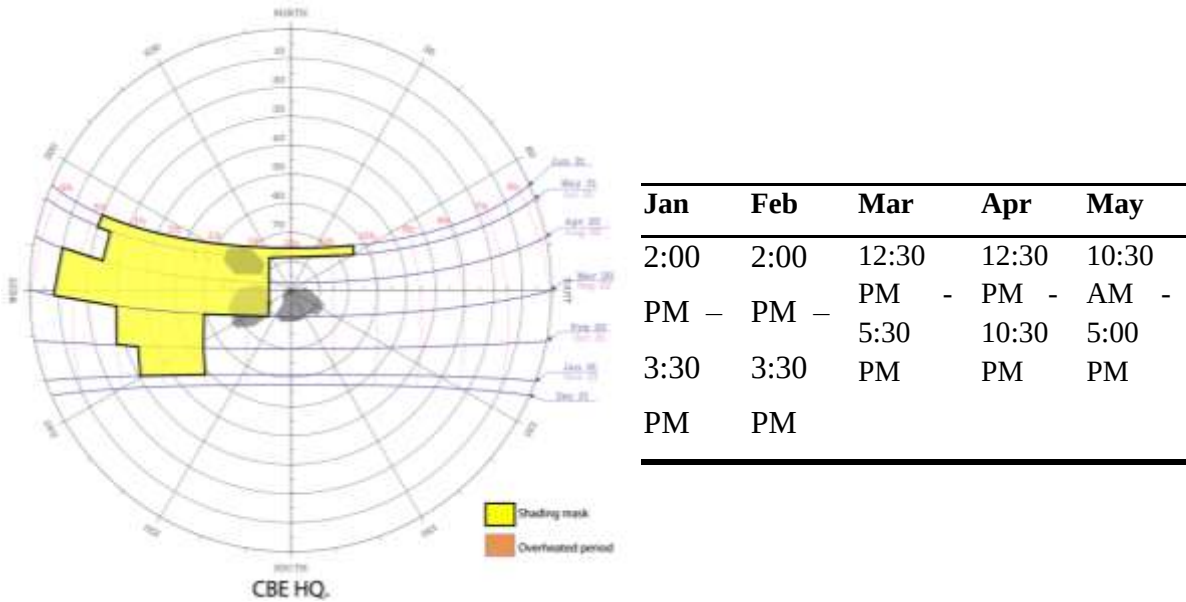


Figure 69 Shading orientation and exposed durations

Wall azimuth of 46.8°

The northeastern elevation is exposed to 2 hours of solar gain during May and the shading systems show 45.28 % of the shaded surface due to the shading elements in place. The shading performance reduces as the sun approaches midday due to the elevated altitude of the sun (Figure 70).

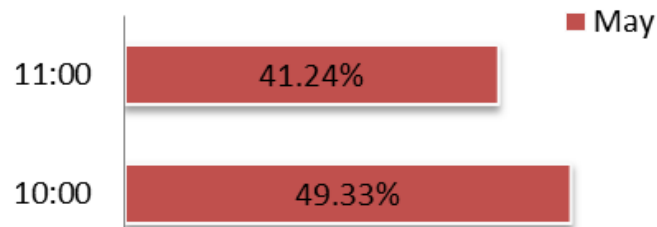


Figure 70 Average shaded surface during overheated period

Wall azimuth of 179°

The southern façade receives radiation during January, February, and March. The duration of overheating in this direction is relatively lower during January and February while March presents a challenge due to its higher duration of overheated times and perpendicular sun rays for the wall surface (Figure 71).

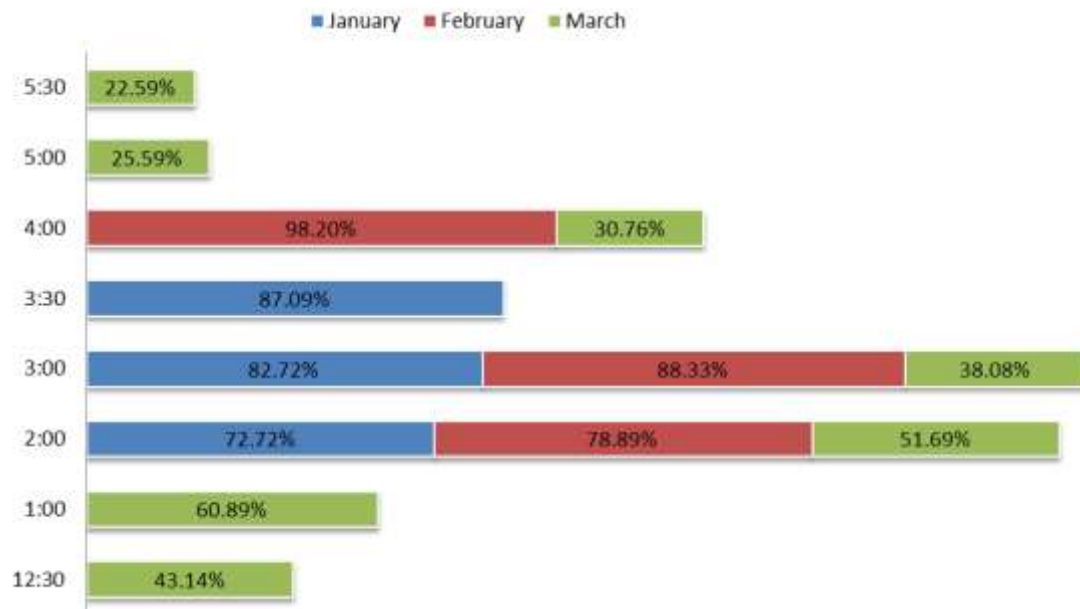


Figure 71 Hourly average shaded fraction

During January and February shading performance picks to 80% and 88% respectively. This is due to the overheated segment of the day occurring in the afternoon between 8:00 PM and 10:00 PM which results in angled sun ray incidents intercepted by the shading systems. Comparably the shading elements perform below 40% during March (Figure 72).



Figure 72 Comparison of monthly shaded fraction

Wall azimuth of 280°

The north-western façade of the building intercepts solar radiation from January to May. Among the months January is the most shaded during the overheated period. And during the daytime, 1:00 pm to 4:00 pm experiences a high amount of shading and the performance reduces by half during May (Figure 73).

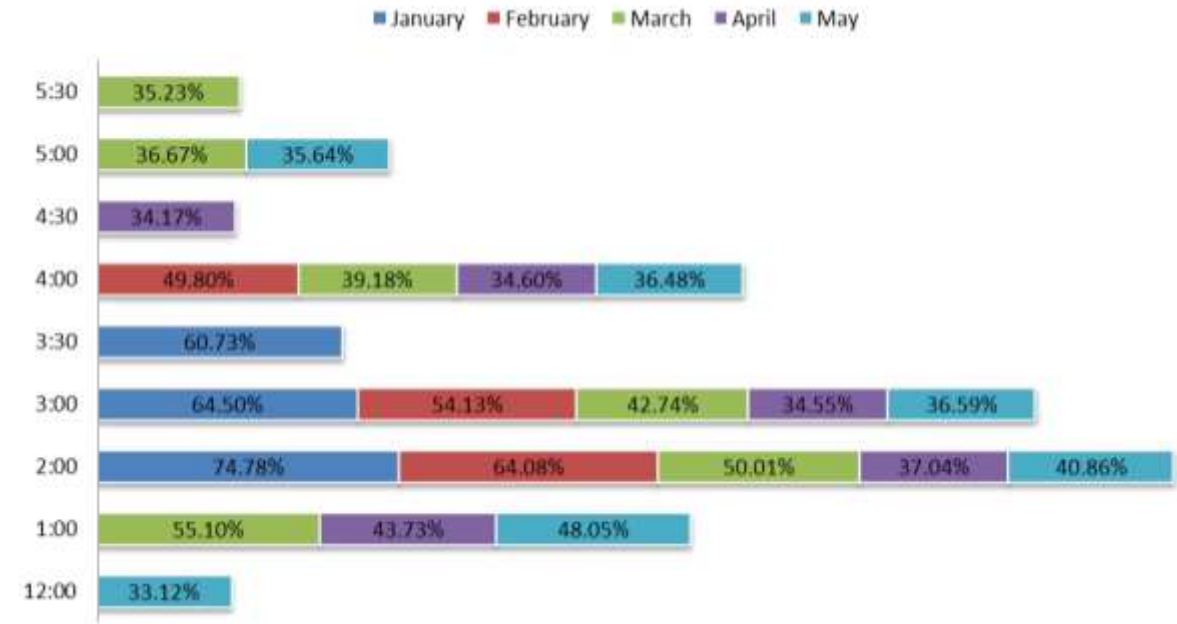


Figure 73 Hourly average shaded fraction

As shown in Figure 74 Shading performance showed high shading during January and shows reduced affectivity as it reaches the month of May. This can be attributed to the drawback of vertical fins in their capacity to shade parallel sun rays to the extrusion of the fins.

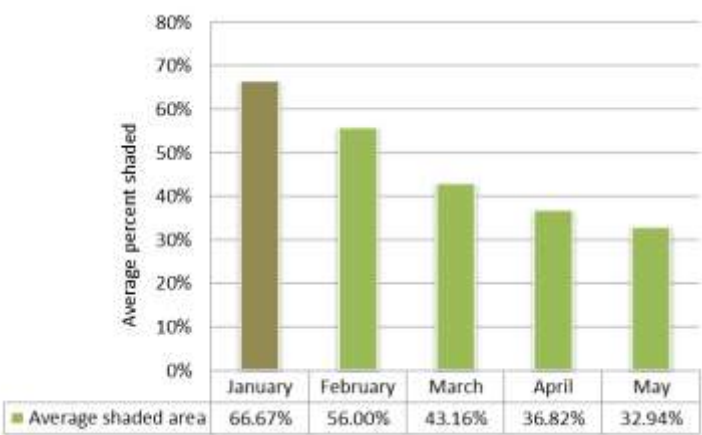


Figure 74 Monthly average shaded fraction

Wall azimuth of 354°

In the northern orientation, the most concerning exposure occur in May, and the vertical shading devices installed provided shading for 53% of the overheated period during May. The effectiveness of the shading system increases during the late afternoon while showing below 33% near mid-day (Figure 75).

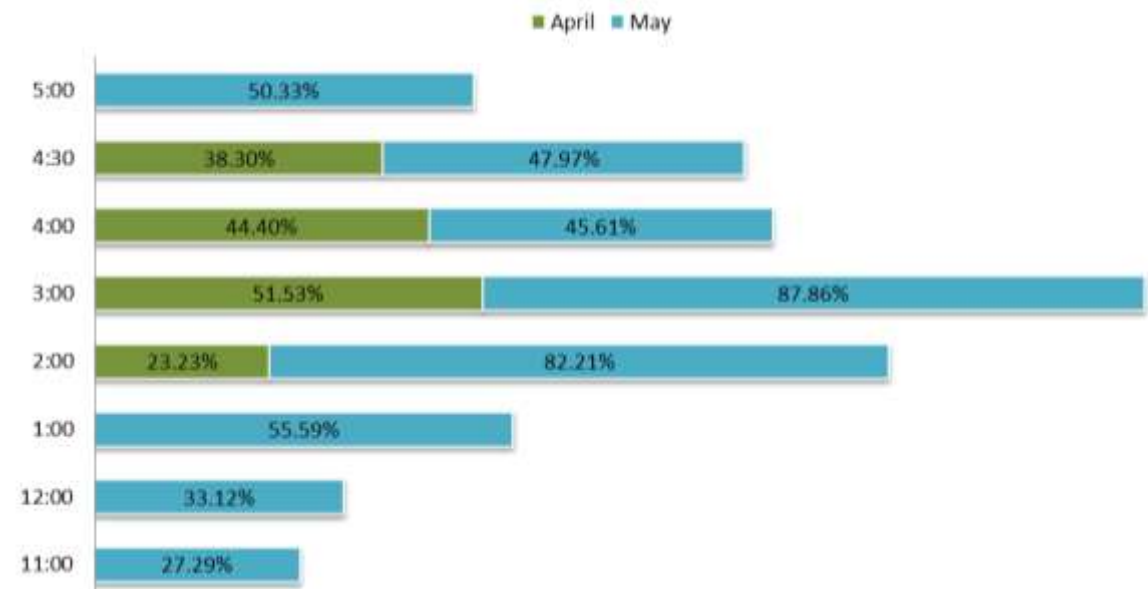


Figure 75 Hourly shaded fraction

The analysis in this orientation shows a low performance of less than 40% average shading during April and relatively higher performance during May(Figure 76).

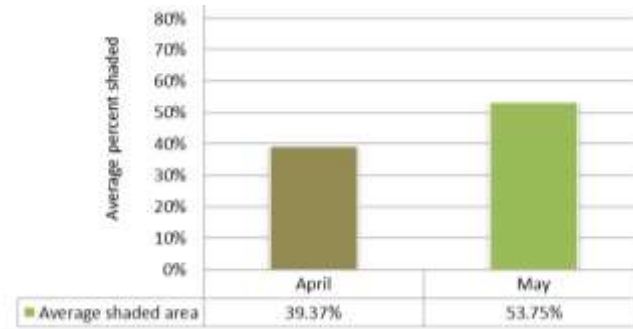


Figure 76 Monthly average shaded fraction

Comparison of shading performance in 4 orientation

In general, CBE building is fitted with vertical fin shading with a similar but alternating profile. For this study, the façade's vertical inclination is not taken into account. The performance of these elements during the overheating season varies with the respective orientations. The shading elements show high performance in the southern and northern facades, conversely, the shading performs relatively poorly in eastern and western orientations (Figure 77).

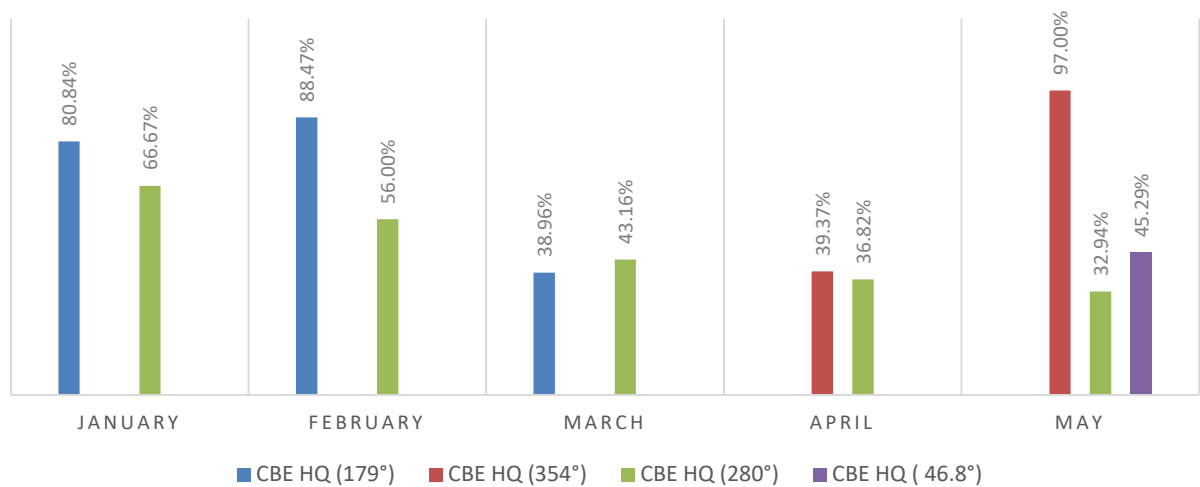


Figure 77 Comparison of shading performance in 4 different orientations

4.4. Result verification

The result verification is carried out by comparing the results obtained through measurements taken by the custom-made heliodon against a computer-simulated shading performance. In this particular case, the ECOTECT solar analysis tool is used to generate a shadow profile as a result of different shading elements (Figure 78).

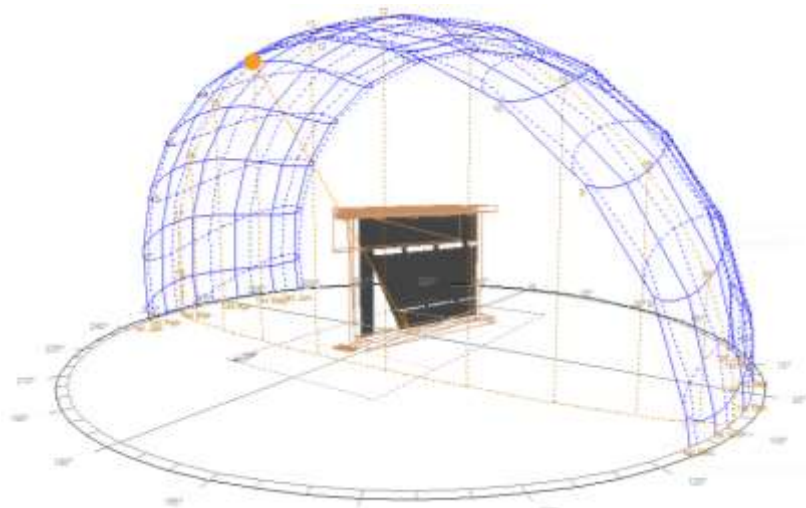


Figure 78 Ecotect shadow analysis viewport

The procedure applied to determine the shaded fraction of the window area in Ecotect is similar to that of the custom-made heliodon. The results show similarity however the computer simulation shows greater detail of shadows on the window plane which is created as a result of shading elements. A few example pairs of shadows created by both methods are shown below in Table 15.

Table 15 Result comparison between computer simulation and heliodon results

	Computer simulation result		Heliodon results	
Wegagen bank bldg. shading at an Azimuth of 36.1° during May				
United bank bldg. shading at an azimuth of 163° during January				

Dashin bank bldg. at an
azimuth of 180°
During February



As shown below in Figure 79, the results obtained by the computer simulation showed a relatively higher performance as compared to the results obtained by the custom-made heliodon. In general, the results by the heliodon showed underperformance and the mean absolute percent error is calculated to be 13.2%.

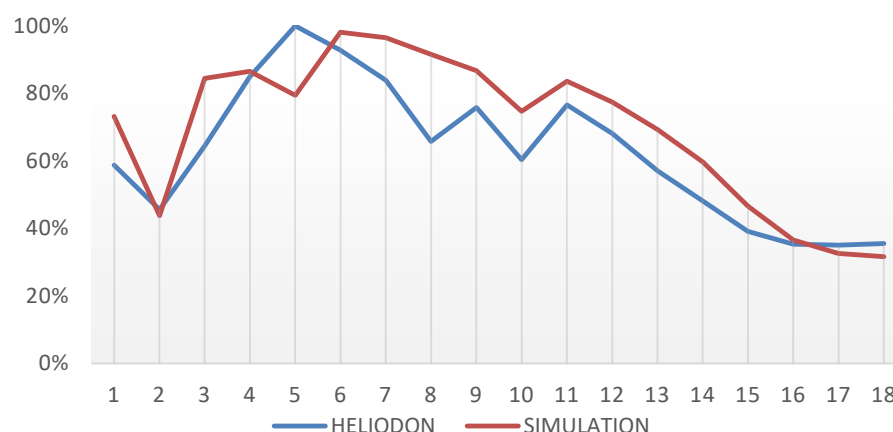


Figure 79 Result Comparison

4.5. Result and Discussion

Prior studies such as those by (Shahdan & Ahmad, 2018) have shown the effectiveness of external shading devices in providing shading for windows. As mentioned in the literature review various shading devices are used worldwide to protect building glazing from excessive solar exposure. And different attributing factors are considered during their designs. By simulating the variables attributing (i.e. solar altitude and azimuth) to the effectiveness of the shading devices the measure of effectiveness is determined.

The initial objective of the study was to assess the effectiveness of external permanent shading devices installed in high-rise buildings of Addis Ababa. As such, the analysis is conducted using a custom-built heliodon. The result of this study indicated that different shading elements perform with a high-performance variation. Comparing eight different shading devices in different orientations results are presented and discussed below.

4.5.1. Overview of the general performance of shading devices

Overall the study included eight different buildings with 6 different types of external shading devices (Table 16). The shadings can be simplified as vertical, overhang, and a combination of both. Each shading element is examined with its respective orientation during the overheated period.

Table 16 Types of shading devices in the study

			
Overhang horizontal louvers in a horizontal plane and overhang vertical panel	Vertical fin slanted	Overhang horizontal louvers in a horizontal plane and overhang vertical panel	Vertical fin
			
Horizontal curved perforated louver in a vertical plane	Vertical fin	Double Overhang horizontal louvers in horizontal plane	Overhang vertical panel with vertical fins

In comparison of shading devices (Figure 80), the highest shading performance is installed on the Africa insurance building, facing south. This external shading device is perforated aluminum retrofitted on a preexisting full-glazed façade. The higher performance of this shading is a product of the shading type. Despite being oriented toward the south, the shading device achieved around 90% of shading. The installed shading is mostly opaque with small perforations which do not allow the penetration of direct solar radiation.

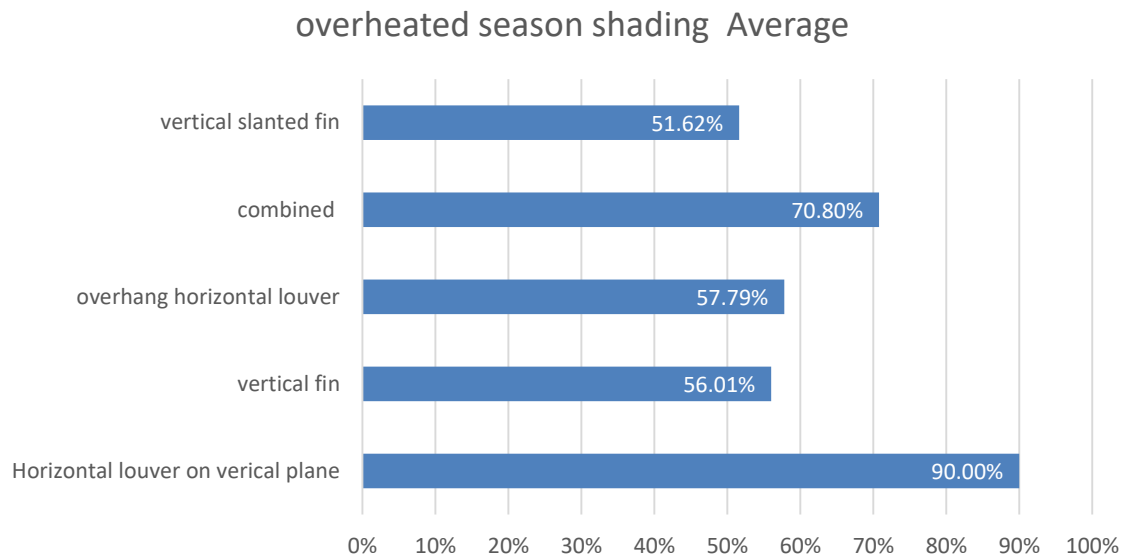


Figure 80 overheated season shaded average

While comparing the types of shading with their respective shading performance during the overheated period, horizontal louver shadings perform more than 28% above the rest of the shading systems. Following is the combination of horizontal and vertical panel shading configuration which showed an average performance of 70%. On the other hand, vertical fins demonstrated lesser performance but still maintained above 50% shading during the overheated period.

In terms of building orientation (shown in Figure 81) the building that showed the highest shaded wall surface is observed as the Africa Insurance building followed by the MTSE HQ. Even though MTSE and United Bank Building have similar shading devices the overhang dimension plays a crucial role in shading performance. Similarly, the highest performance is obtained with the combination of vertical and horizontal shading elements such as the one installed on MTSE HQ and the United HQ building. It can be noted that the results are in line with the principles of effective shading, (Asfour, 2018) horizontal shading devices are usually used in the southern façade, while vertical shading devices are recommended in the eastern and western façade. This is justified by the fact that horizontal shading devices are effective against the high midday sun, while vertical ones are effective against the low sun (Mandalaki & Tsoutsos, 2020).

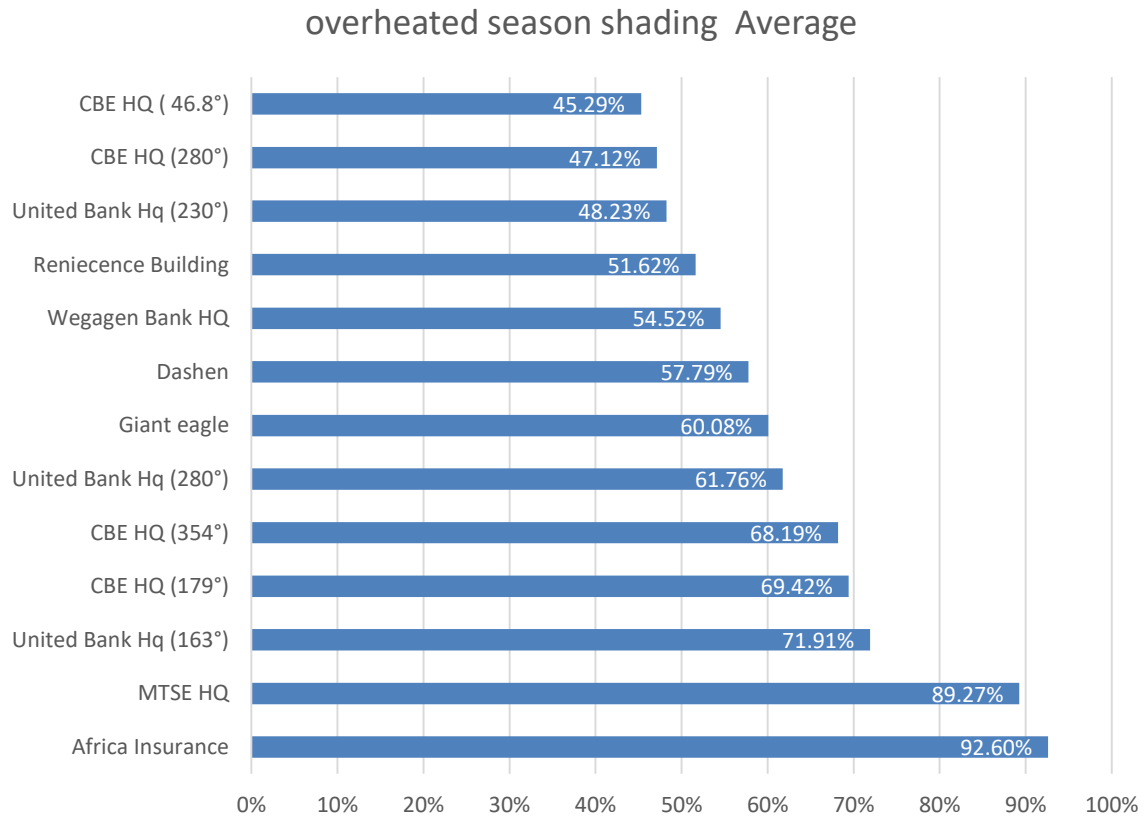


Figure 81 Average shaded surface during overheated period

Result verification revealed that the heliodon results have a Mean absolute error percentage of 13.2% which indicates a moderate closeness to the computer simulation model. A higher degree of close results is obtained from the analysis of vertical fin shading elements.

Further study on the comparison of the selected solar shading devices in a similar orientation (Figure 82), resulted in a similar result where horizontal louvers on a vertical plane outperformed those of vertical shading. Southern orientation is the least desirable orientation for a tropical zone (Shahdan & Ahmad, 2018) and in this specific orientation, the months from January to March is exposed to overheating. The analysis shows that during this time the glazing requires full coverage as that provided by horizontal louvers on a vertical plane. Recommendations by (Asfour, 2018), state that horizontal shading elements are most effective for glazing facing south.

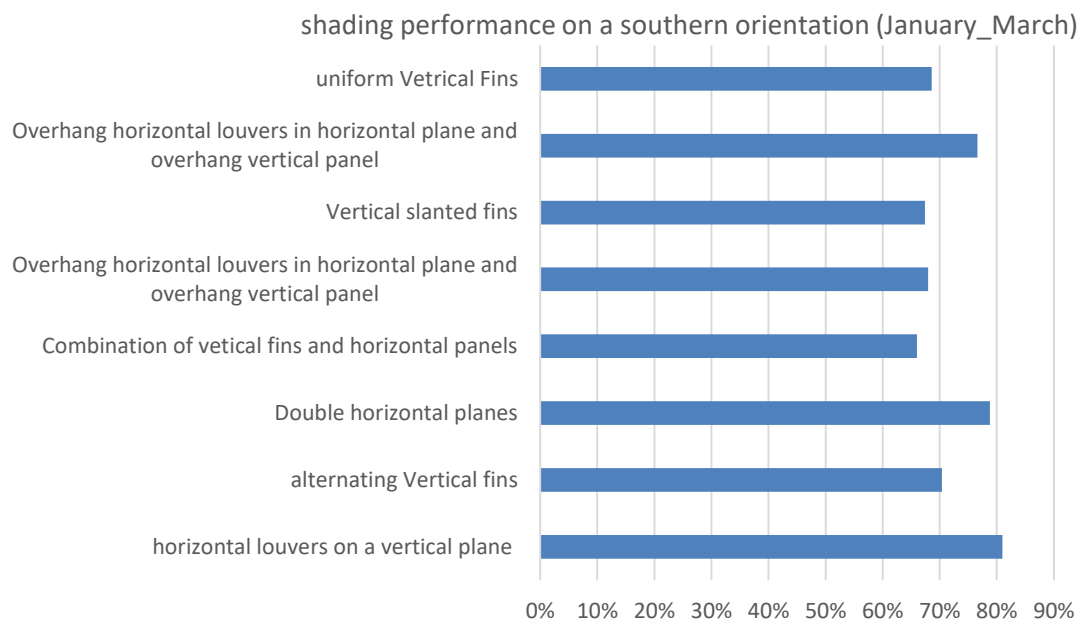


Figure 82 Shading performance in southern orientation

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study was designed to determine the effectiveness of shading elements installed as external permanent shading devices on high-rise buildings in Addis Ababa. To accomplish this aim the study undertook the development and construction of the analysis tool called Heliodon.

One of the more significant findings to emerge from this study is that of the performance of selected shading devices for the duration of the overheated season. The investigation of the shading devices for their respective orientation has revealed that the average shading performance is above 50% in all external permanent shading devices. With the highest shading performance recorded at 93%. The highest shading performance is achieved by horizontal louvers on a vertical plane that covers the entire elevation of the glazing. On the other hand, the lowest performance is achieved by vertical fins used in the eastern and western elevations. The second major finding was that, the application of custom-built Heliodon for solar studies. The accuracy of the results collected from analysis conducted using the custom-built heliodon is determined to have 13.2% of percentage accuracy which indicates moderate accuracy as compared to the conventional computer simulation.

Although this current study is based on a small sample of buildings in an ever-expanding construction boom in the city, the findings of this study suggest that shading devices of the high-rise buildings of Addis Ababa do not fully shield against direct solar radiation during the overheated season. In general, the implication of these findings is, therefore, the questionable design decisions of shading elements on high-rise buildings. Another implication of this is the possibility that Heliodons can be used as an integral part of the solar design process as a demonstration and also to some extent as an analysis tool.

The empirical findings in this study provide a better understanding of the general functionality of shading devices in the city. The study has demonstrated the use of Heliodon as an analysis tool in solar architectural studies. The methods used to assess the performance of shading elements may be applied to locations beyond the study site. Taken together the findings can enhance our understanding of solar geometry, shading performance, and solar design approaches in general which is one of the central aspects of sustainable architecture. This is the first study to employ a custom-built heliodon to assess shading performance in

Addis Ababa hence this research will serve as a base for future studies and broadens our understanding of solar analysis tools.

The current study has only examined the effectiveness of shading performance during overheated periods. And also the research was not specifically designed to evaluate the incidence intensity of solar radiation on glazed surfaces. Finally, some important limitations need to be considered, one being the apparent errors that can accumulate while using scaled models and taking measurements. The most important limitation lies in the fact that there is no established and standardized method to design, construct, calibrate and conduct such analysis on Heliadons.

5.2. Recommendation

The implication of this study is multidimensional regarding the findings and the methodology adopted. This research has revealed the gap in adopting shading devices as a way of protecting glazed surfaces against excessive solar gains. Hence it is recommended that a better understanding be established while implementing such design decisions. More research is required to precisely determine the efficiency of shading performance either using a high-precision Heliodon or computational simulations further studies need to examine more closely the links between shading types and preference and performance of shading devices.

Regarding the method of analysis, it is recommended that further research be undertaken to adopt various Heliodon types and designs as an analysis tool with higher accuracy and precision as these devices can be invaluable instruments for a greater grasp of solar geometry and its implication of shading performance.

A better understanding of solar geometry through physical models and Heliodons would help us establish a greater degree of accuracy in the design of shading elements. Hence, a natural progression of this work is to design effective shading elements for each building orientation, creating a catalog of shading devices for both new constructions and retrofitting existing buildings in the city. Furthermore, Although it is typically advised to employ vertical shading devices at the eastern and western facades and horizontal shading devices on the southern facades, the designer may utilize the same type on all three faces to meet particular architectural requirements.

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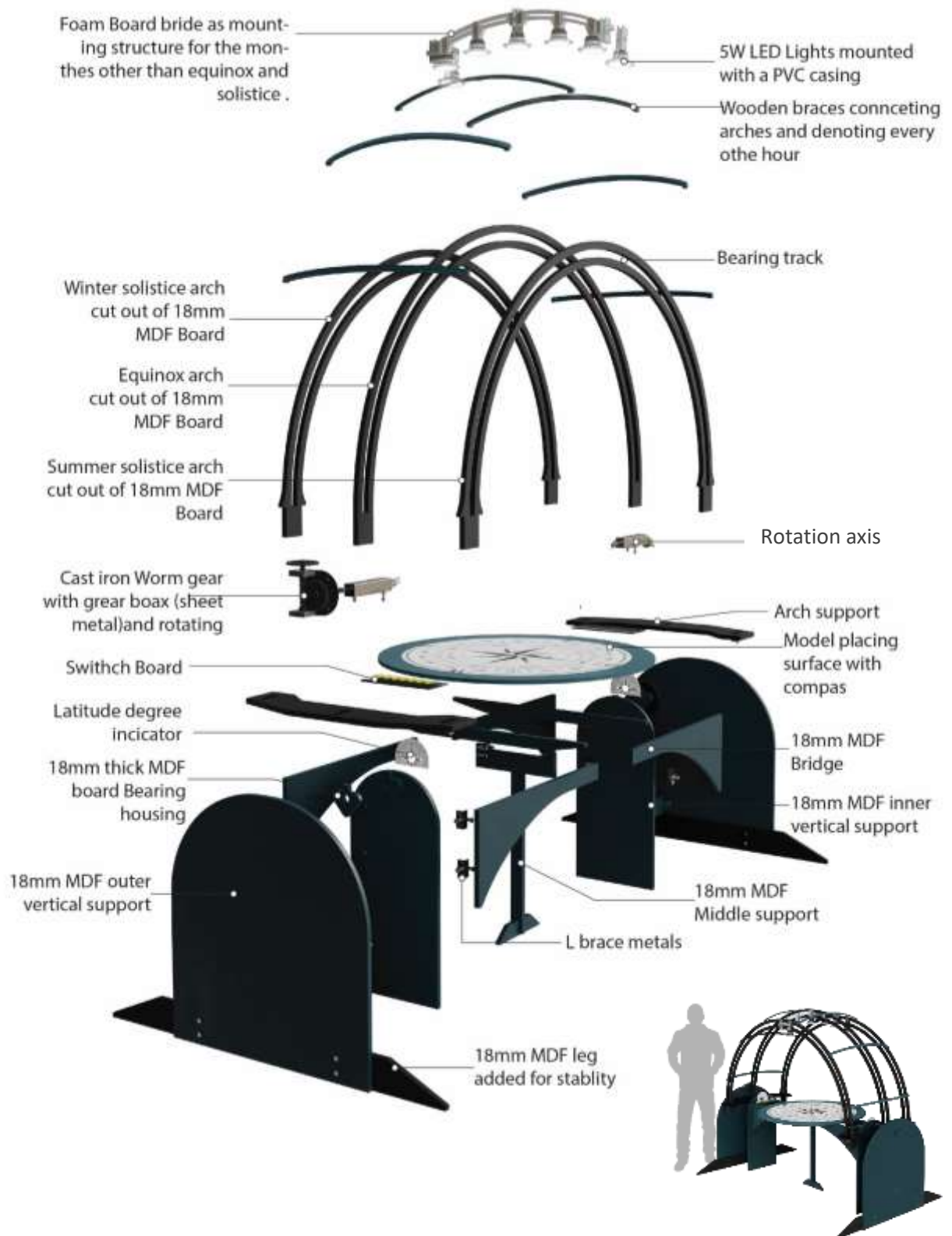
Appendix_1

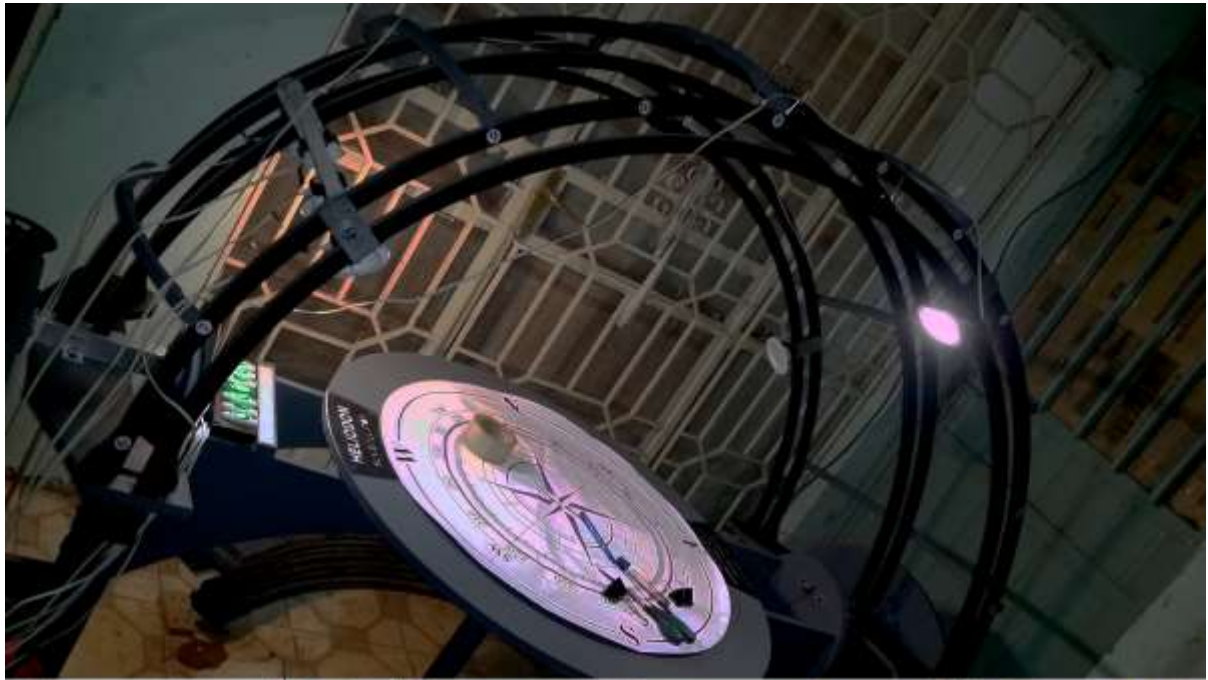
Table 17 List of high rise building in Addis Ababa

List of High rise buildings								
No	Building	Height	Floors	Subcity	latitude	longtitude	Shading type	Orientation
1	Noah Real Estate Tower	≈135 m	36	kirkos	9.01147	38.754576	no shade	North
2	ORDA Headquarters	≈101 m	27	kirkos	9.01139	38.754052	eggcrate	North
3	Wegagen Bank Headquarters	≈90 m	23	kirkos	9.011653	38.756041	vertical fin	North
4	Leghar Hotel	≈70 m	18	kirkos	9.014054	38.751901	overhang horizontal louver	North and west
5	Awash Bank Tower	≈70 m	18	kirkos	9.022361	38.75198	noshade	North and south
6	Athlete Derartu Tulu Building	≈63 m	16	Bole	9.018552	38.799667	no shade	North west & North
7	Bloom Tower	≈56 m	15	kirkos	9.016112	38.768546	no shade	North & North east
8	Arada Building	≈59 m	15	Arada	9.032663	38.752488	no shade	North & South
9	Noah Plaza	≈55 m	14	Bole	8.994675	38.790419	no shade	North
10	Dashen Bank Headquarters	≈82 m	21	Lideta	9.016534	38.749732	overhang horizontal pannel	South
11	Giant Eagle Trading Building	≈64 m	17	Kirkos	9.00514	38.742666	vertical fin	South & west
12	Snap Plaza	≈55 m	14	Bole	8.989801	38.78763	no shade	South & East
13	Ethiopian Insurance Corporation Headquarters	≈51 m	13	Kirkos	9.012017	38.752502	overhang horizontal pannel	South
14	Intercontinental Hotel	≈66 m	17	kirkos	9.016132	38.769102	eggcrate	West & east
15	MTSE Building	≈59 m	15	kirkos	9.012581	38.75209	overhang horizontal pannel	East & South east
16	Kassa Grand Mall	≈55 m	14	kirkos	9.003127	38.746657	no shade	East
17	Ethiopian Television	≈55 m	14	kirkos	9.018332	38.75174	no shade	East
18	Intercontinental Hotel	≈66 m	17	kirkos	9.016132	38.769102	eggcrate	West & east
19	Noah Diplomat Apartments	≈56 m	15	Kirkos	9.02	38.4647	no shade	North east
20	Renaissance Building	≈59 m	15	Bole	9.018902	38.800995	vertical slanted fin	North east
21	Sur Tower	≈59 m	15	Kirkos	8.999798	38.77011	no shade	North east & North west
22	Yobek Commercial Center	≈55 m	14	Lideta	9.013699	38.74768	no shade	North east
23	Mado Hotel	≈55 m	14	Kirkos	9.000317	38.783007	no shade	North East
24	Azzeman Hotel	≈51 m	13	bole	9.005401	38.763611	no shade	North east
25	NIB Bank Headquarters	≈137 m	35	Lideta	9.014866	38.75045	no shade	soth east
26	Zemen Bank Headquarters	≈112 m	30	Lideta	9.014377	38.749877	no shade	south east
27	Legacy Real Estate Tower	≈86 m	22	Kirkos	9.016287	38.751344	overhang	south east
28	Eilei Building	≈82 m	21	Kirkos	9.014366	38.769611	eggcrate	South east
29	Information Network Security Agency	≈64 m	17	Kirkos	8.988937	38.770671	overhang	South east
30	United Bank Headquarters	≈131 m	35	Lideta	9.01368	38.748713	overhang vertical pannel	South east
31	K-Kare center	≈86m	22	Kirkos	9.008386	38.746668	no shade	South east
32	Addis Ababa City Government Building	≈59 m	15	Arada	9.00955	38.741769	vertical slanted fin	South west
33	Lex Plaza	≈59 m	15	Bole	9.014919	38.78213	no shade or overhang	South west
34	Getu Commercial Center	≈55 m	14	Kirkos	9.002313	38.769544	overhang or no shade	South west
35	Lebenz Tower	≈49 m	13	Kirkos	9.000743	38.767305	no shade	south west
36	Oromia International Bank Bulding	≈49 m	13	Kirkos	9.002627	38.769408	no shade or overhang	South west
37	Africa Insurance Building	≈51 m	13	Bole	8.99243	38.7804352	horizontal louver	South west
38	Athelete Derartu Tulu Building	≈63m	16	Bole	9.018552	38.799667	no shade	northwest & north
39	Africa Union	≈78 m	20	Kirkos	8.998785	38.746085	vertical fin	all direction
40	African Union Grand Hotel	≈55 m	14	Kirkos	8.99812	38.743954	vertical fin	all direction
41	Commercial Bank of Ethiopia	≈215 m	48	Kirkos	9.012735	38.748593	vertical fin	all direction
42	Sengatera 40/60 Condominiums I	≈49 m	13	Lideta	9.014974	38.747284	overhang balconi	all direction
43	Sengatera 40/60 Condominiums II	≈49 m	13	Lideta	9.014974	38.747284	overhang balconi	all direction
44	Sengatera 40/60 Condominiums III	≈49 m	13	Lideta	9.014974	38.747284	overhang balconi	all direction
45	Sengatera 40/60 Condominiums IV	≈49 m	13	Lideta	9.014974	38.747284	overhang balconi	all direction
46	Sengatera 40/60 Condominiums V	≈49 m	13	Lideta	9.014974	38.747284	overhang balconi	all direction

Appendix_2

Parts of custom-built heliodon





Angle adjusting worm gear



Switches and latitude angle indicator



LED light



Bridge connecting months between solstices and equinox

Figure 85 Custom-built heliometer



Prepare the Heliodon surface



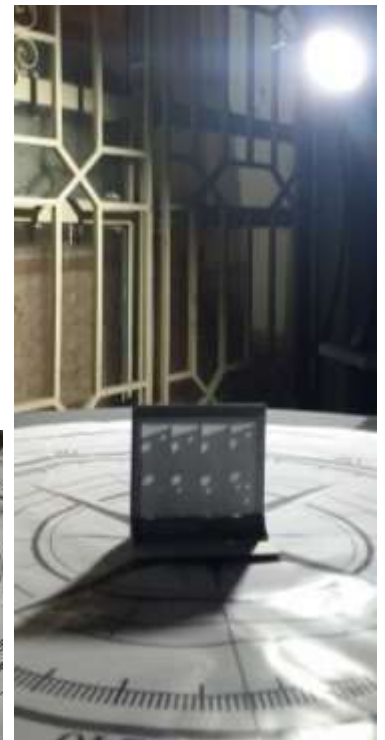
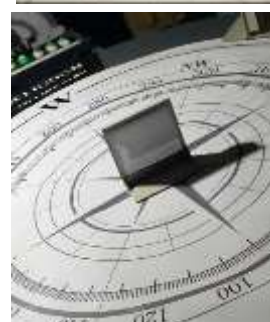
Set latitude of the study location



Set study models according to their respective wall azimuth



Turn on lights for specific months and hours when overheated is determined to



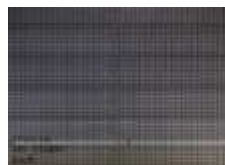
Collect the shadow cast by shading elements form the supposed glazed surface (pictures were

Figure 86 Overall procedures followed in the study

Appendix_3

Africa insurance façade shaded fraction_ Azimuth 188⁰

January

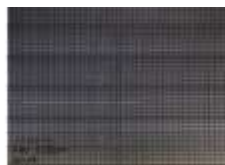


2:00pm



3:00pm

February



2:00pm



3:00pm



4:00pm

March



1:00pm



2:00pm



3:00pm



4:00pm



5:00pm

MTSE façade shaded fraction_ Azimuth 87.1⁰

May



10:30 pm



11:00 pm



12:00 pm

Renaissance façade shaded fraction _Azimuth 36.1⁰

May



10:00 pm



10:30 pm



11:00 pm



12:00 pm



1:00 pm

CBE façade shaded fraction_ Azimuth 280⁰

January



2:00 pm



3:00 pm



3:30 pm

February



2:00 pm

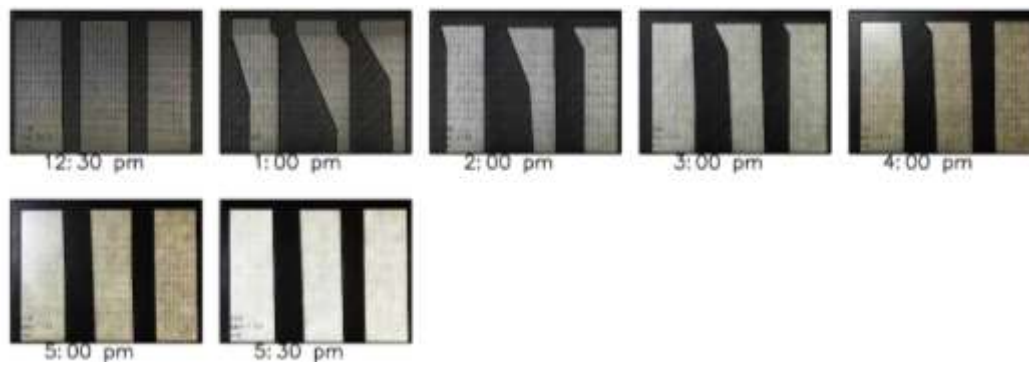


3:00 pm

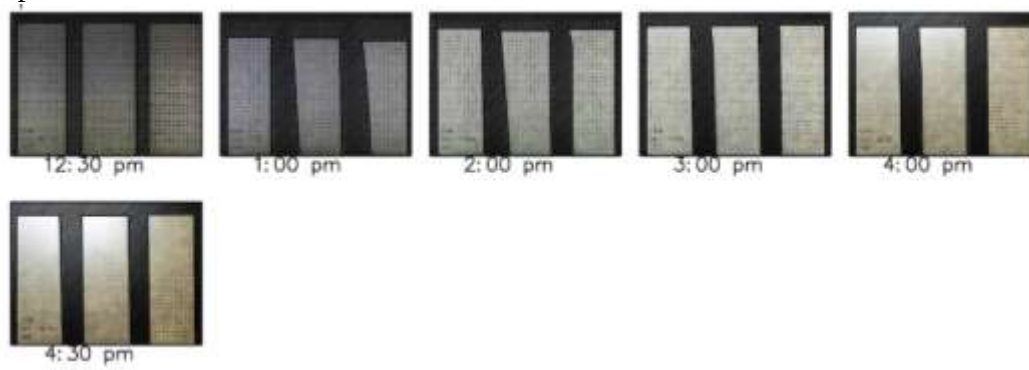


4:00 pm

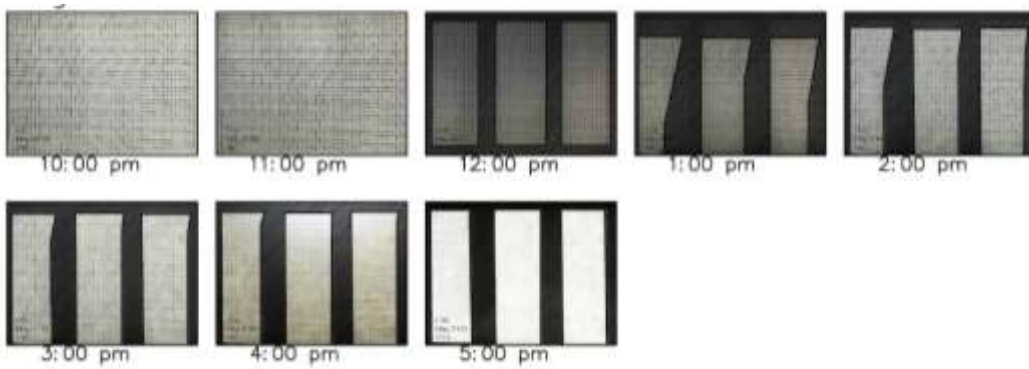
March



April

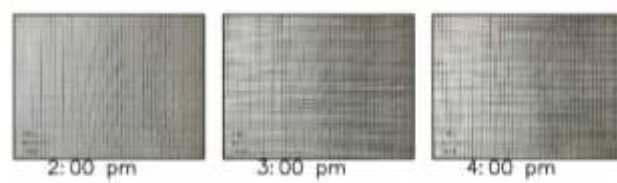


May

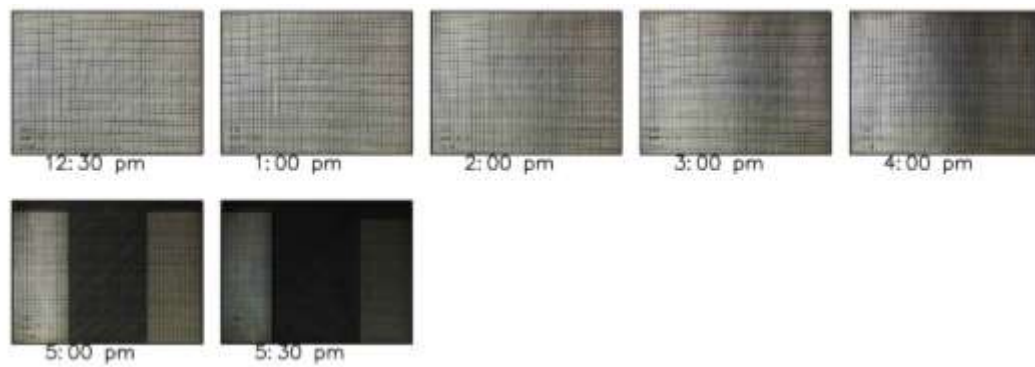


CBE façade shaded fraction_Azimuth 354⁰

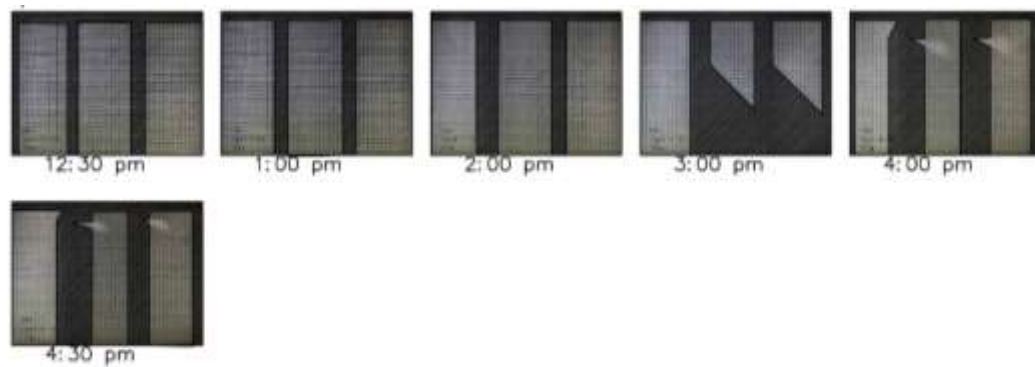
February



March



April

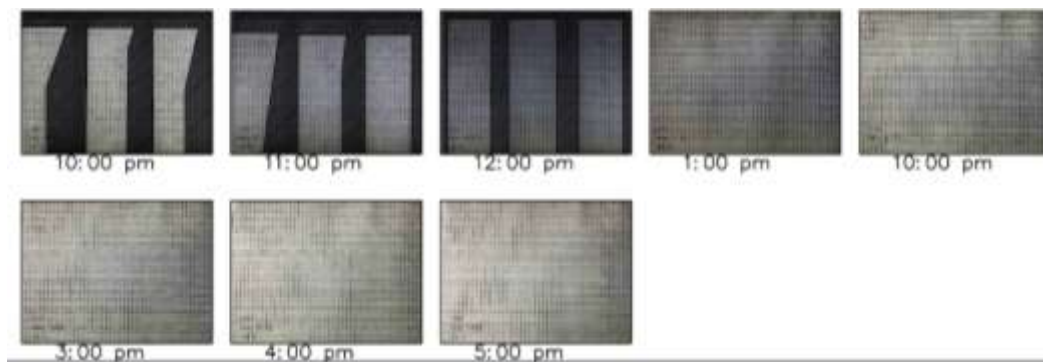


May



CBE façade shaded fraction_ Azimuth 46.8°

May



CBE façade shaded fraction_ Azimuth 179°

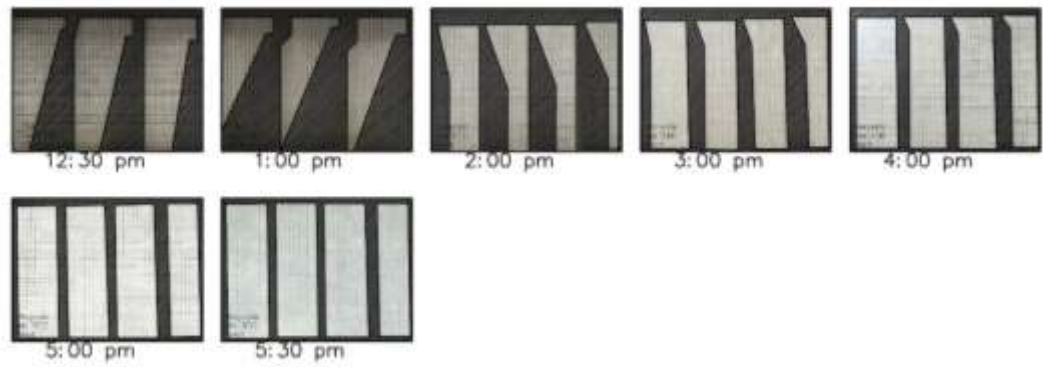
January



February



March



Dashin façade shaded fraction_ Azimuth 180°

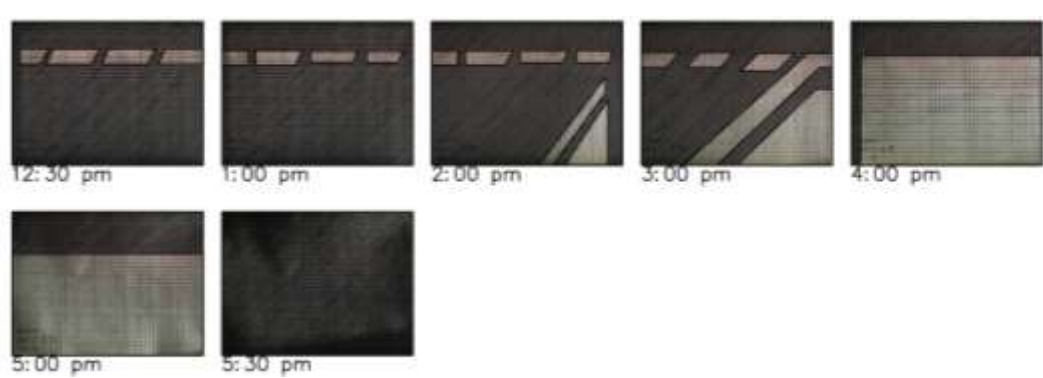
January



February

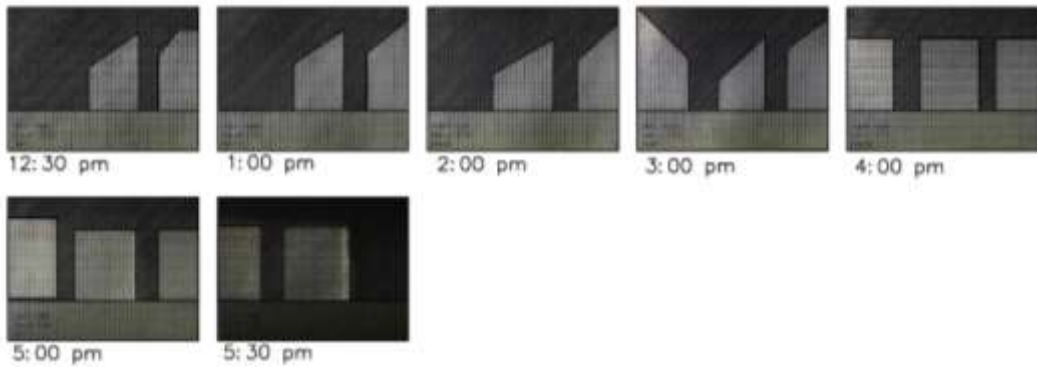


March

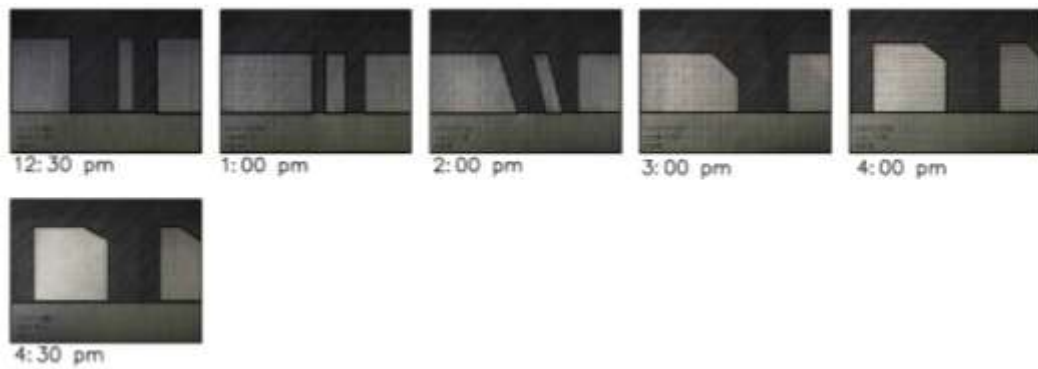


Giant eagle façade shaded fraction_ Azimuth 355.8°

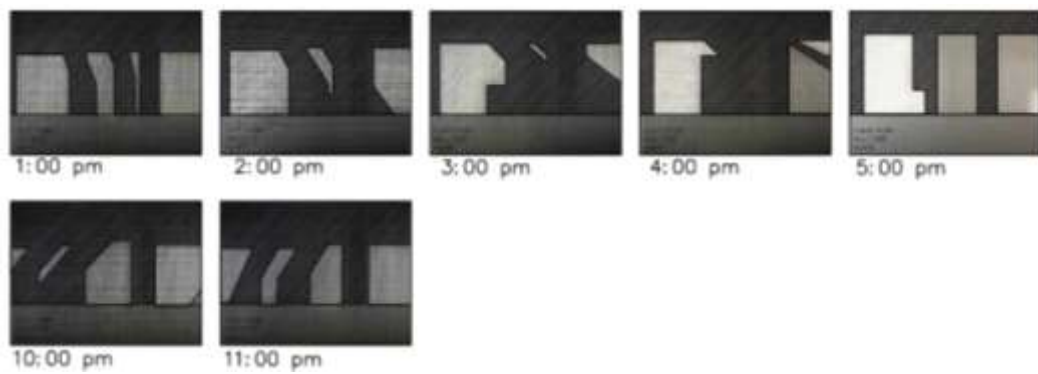
March



April



May

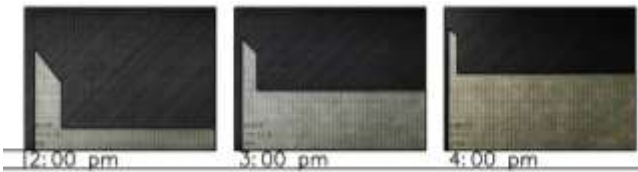


United façade shaded fraction_ Azimuth 280°

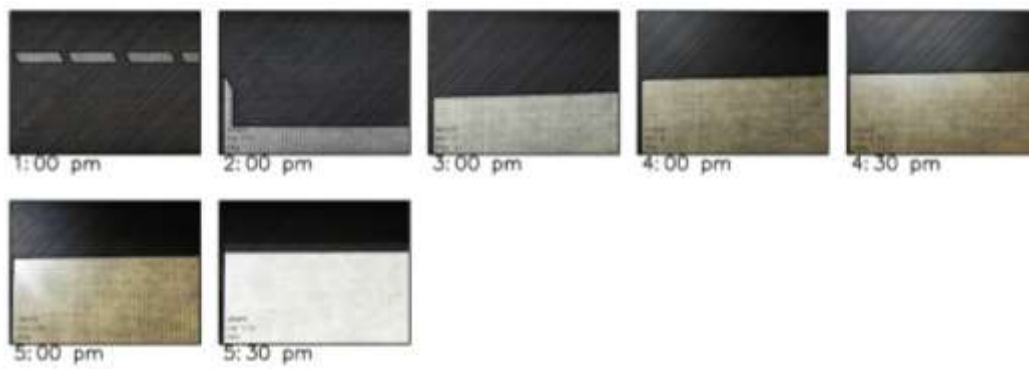
January



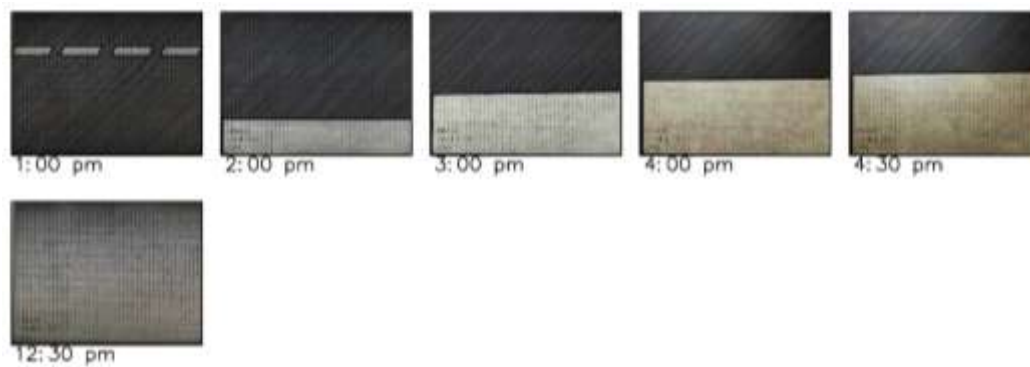
February



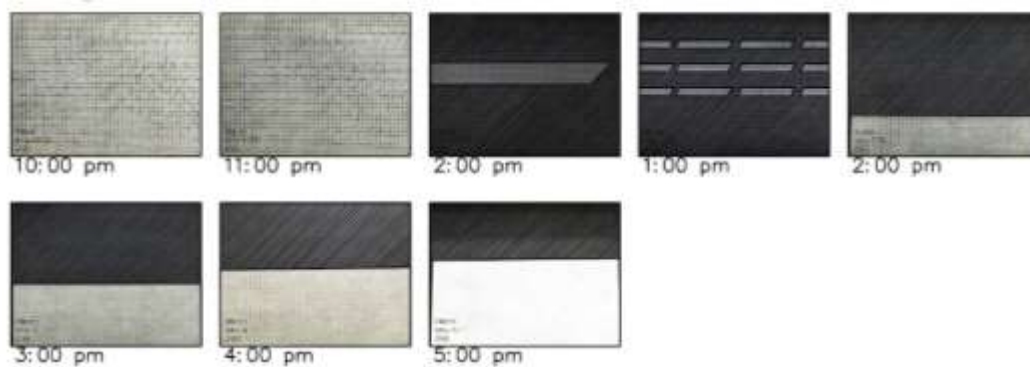
March



April

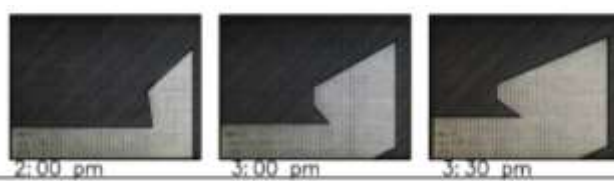


May

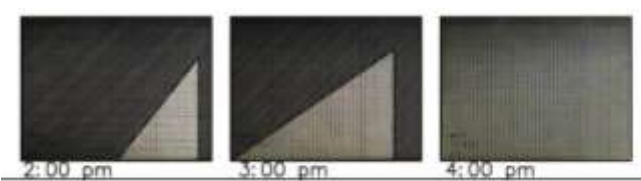


United façade shaded fraction_ Azimuth 163°

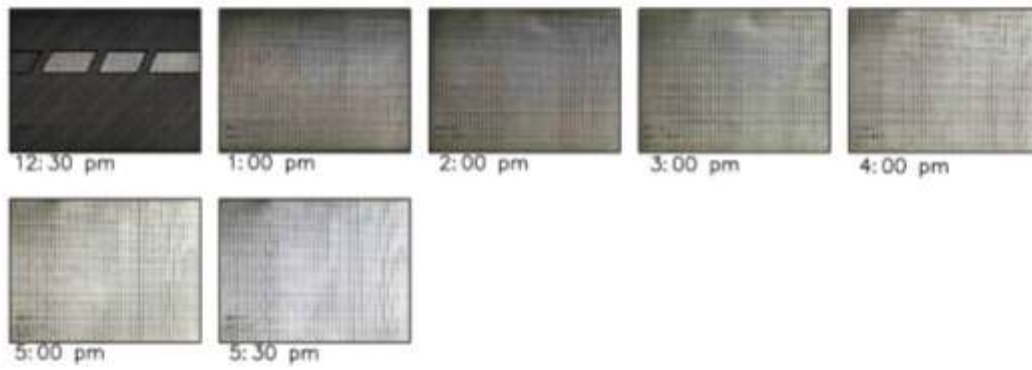
January



February

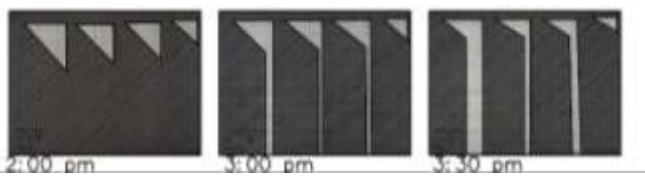


March

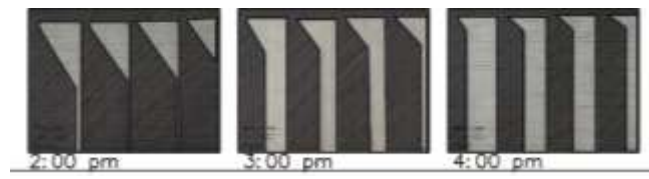


Wegagen façade shaded fraction_ Azimuth 272.7°

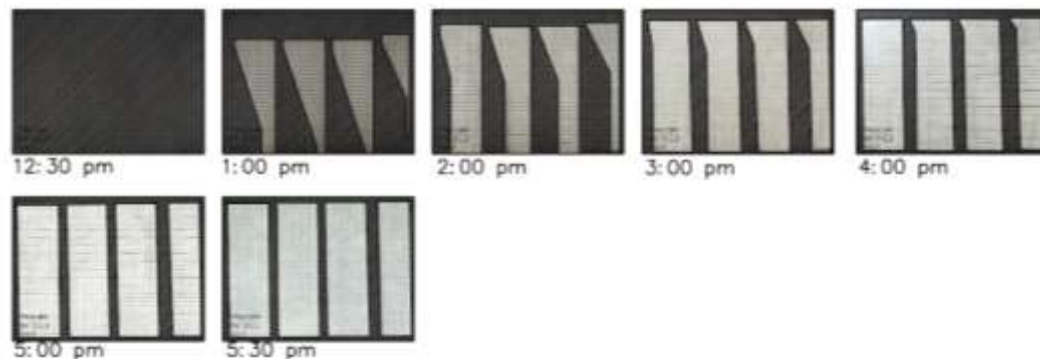
January



February



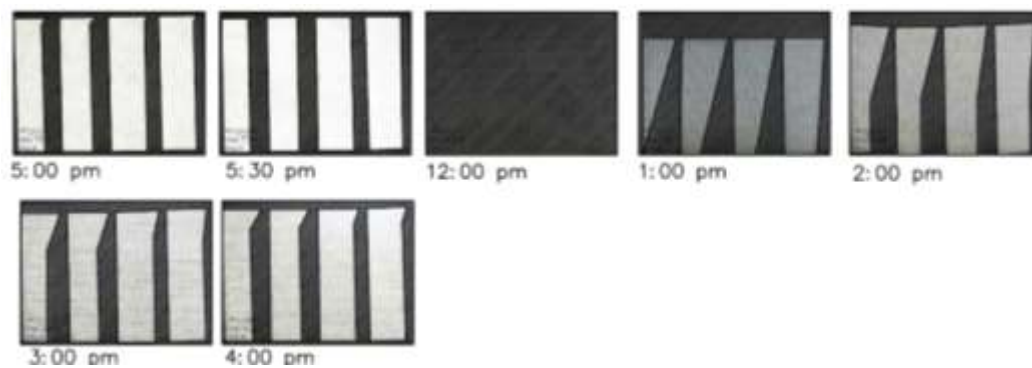
March



April



May



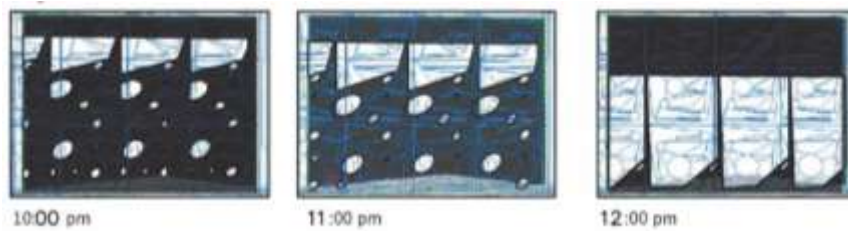
Appendex_4

Software simulation

Randomly selected external shading device analysis using Ecotect 2014

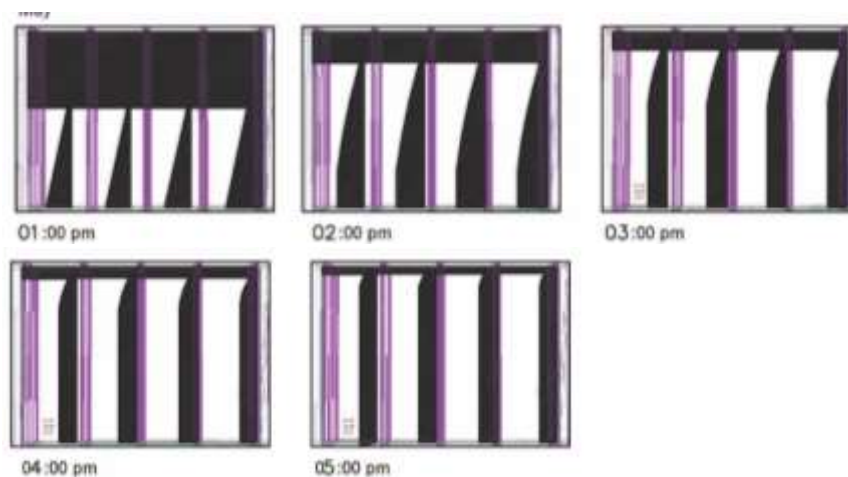
Renaissance façade shaded fraction_ Azimuth 36.10

May



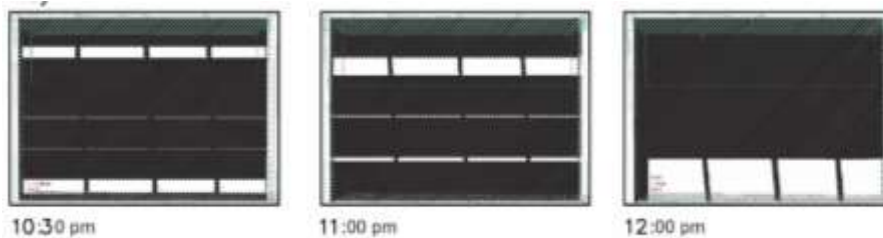
Wegagen façade shaded fraction_ Azimuth 272.70

May



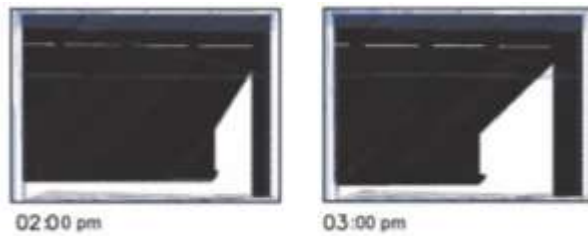
MTSE façade shaded fraction_ Azimuth 87.10

May



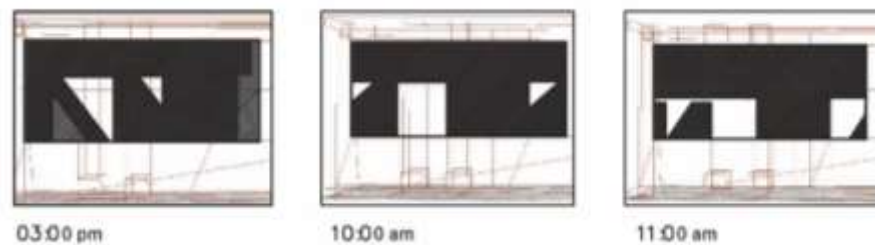
United façade shaded fraction_ Azimuth 87.10

January



Giant eagle façade shaded fraction_ Azimuth 355.80

May



Dashin façade shaded fraction_ Azimuth 1800

February



March

