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THE IMPACT OF GLASS FACADE ON USERS COMFORT

The case of radiation vulnerable offices in Addis Ababa

By

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A THESIS

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Abstract

The aim of this thesis was to assess the impact of glass facades on human thermal and visual comfort. The study focused on indoor environment, nearby open spaces and drivers in the emerging central business district (CBD) area of Addis Ababa. The research ranged from mapping radiation vulnerable streets of the city to selecting and analyzing the thermal and visual performance of individual buildings. The assessment was conducted using methodologies such as subjective evaluation, experiment and computer simulation. The result showed that, the ranking of indoor thermal environmental conditions slightly differed between female and male, and between perimeter and interior zone. Out of 120 participants, 78.33% dissatisfied with the thermal environment, 13.33% were comfortable, and 8.33% did not notice the thermal environment. During outdoor environment analysis, out of 50 drivers, 84% valued the risk of glare, 10% complained about the risk of accident and the rest 6% did not notice visual impact of glass facades. On the other hand, the computer simulation output of selected offices showed that March, April and May are the hottest months of the year while critical time of the day was between 2:30pm and 4:00pm. Both the survey and the simulation results showed that, with fully glazed facades, the indoor temperature gradually rises up and affects occupant's comfort and productivity.

These results finally discussed and interpreted into guidelines which offers basic considerations during overall urban setup strategies as well as particular building facade component production in the city. Afterwards, the guideline was tested through innovative methodology of using light simulation and critical solar angle analysis which led to solar responsive geometric configuration. This component basically responds to particular thermal discomfort period of the day, which in this study called 'critical time' while for the rest of the day, it could be opened and closed. To sum up, the study generally concerned with the role of building skins in relation to natural light and the importance of adaptive solar shading as this plays an extensive role in tropical climates, like Addis Ababa where the facade has a direct impact on the thermal and visual comfort.

Keywords: Day-lighting, Solar gain, Air temperature, Thermal mass, Thermal comfort, Visual comfort, Glass facade, Effective shading, Computer simulation

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INTRODUCTION

1.1 INTRODUCTION

The construction industry in Addis Ababa is one of the prime investment sectors which is booming with office blocks, housing, hotels and others. This phenomena has created a platform for architects and engineers to explore emerging glass materials and facade construction technologies. However, current trend of glass facade and construction trends in Addis Ababa need to critically question its performance and users thermal and visual satisfaction.

Contemporary understanding of the building skin has changed the way in which architects approach facade design. There is a fundamental change in emphasis from **form** to **performance.** Technological advancement has made possible, modern buildings, to use glass facades widely with different transparency and treatment. Glass is chosen by many designers and manufactures because of its unique visual effect and enormous performance. However, large glazed areas allow direct solar radiation which may affect indoor and outdoor visual comfort as well as thermal comfort due to high thermal conductivity. (Wurm, J., 2007).

In tropical mega cities, it’s highly recommended to analyze radiation angles and other climatic conditions before facade decisions. (Jackson &Hudman., 1990). In applying climate-responsive architecture principles, it is useful to understand the basics of climate itself and its characteristics. Previous studies showed that, early People's discovery of the temperature moderating benefits of caves grew from an understanding of climate that comes only from a direct and constant experience of the elements. Through urbanization, industrialization, geographic mobility and a reliance on mechanically produced comfort, we in the 20th century have largely lost that first-hand experience of climate. As a result, we no longer understand how buildings respond to particular climates. (G.Z. Brown, Barbara-Jo Novitski, 1981).

This thesis was primarily concerned on the impact of glass facades on human visual and thermal comfort. It evaluated emerging office buildings’ facade performance and effect through different tools and methods. A list of radiation vulnerable buildings, in the evolving central business district (CBD) area, were mapped and evaluated. Finally the result was discussed and lesson was learnt for further interpretation of the results into guideline and design outputs.

1.2 BACKGROUND OF THE STUDY

Throughout history, brick and stone had been the principal means of construction. Its load bearing nature limited the width of glass openings. However, by structural inventions such as frame structures, designers have achieved larger window openings and eventually transformed into glass walls in order to allow natural light in to the indoor environment. In the 19th century, there was a magnificent transformation from post and lintel load bearing facade to liberated glass walls. Skeletal framing was promoted by the development, first of cast iron, then of wrought iron, and later of steel and reinforced concrete. (Wurm, J., 2007).

In the modern architectural movement, where natural light, transparency, health and social wellbeing are priority, glass is used to provide and also symbolize these ideas.

"*In the traditions of the modern architecture, glass is of the party of order and hygiene. It stands for the replacement of the slums of the huddled poor by clean crystal towers. It stands for the illumination of the dark places of vernacular superstition by the pure light of rationality. Worldwide, it has become the symbolic material of clarity, literal and phenomenal."* (Reyner Banham, 1981).

Nowadays, building structures became lighter and permeable to heat transfer, producing variable internal environment especially in equatorial and Polar Regions. This leads to the development in air conditioning. Frank Lioyd wright's Larkin building, buffalo, USA, as Banham (1969) claimed, became the first masterpiece of its mechanical services.

Architects began to take these new technology into their designs and implemented in many buildings. However, with the energy crisis of the 1970s and need for reduction in CO2 emissions, there was a shift into green concepts of natural lighting and ventilation. This concept also has a lot to do with visual and thermal performance of building envelopes. The facade has become a selective filter of solar energy and with emerging technologies of low emissivity coatings, a key element in passive solar energy design in energy efficient buildings.

1.3 STATEMENT OF THE PROBLEM

Global Climate change in combination with rapid urban development in Addis Ababa, which has radically reduced the green footprint, are expected to change surface temperature of the city. This phenomena of temperature rise probably questions the sustainability and performance of existing and upcoming glass facades. The trend of using glass facade is promoted because of technological advancement which has made possible the use of liberated envelopes on modern buildings. In addition to this, Office buildings in Addis majorly use glass facade to promote daylight entry and visual contact. However, glazed curtain walls and large windows on building facade increases the risks of **overheating** and **visual discomfort**. (C.Gallo,et. al.1998)

Overheating is happening due to the glass property of high thermal conductivity while **glare**, negative aspect of light, happens due to high contrast either directly or by reflection and it creates both **discomfort** and **disability**. (Derek Phillips, 2004). According to the random observation, most of the offices in Addis Ababa use either manually adjustable indoor shading devices (mostly plastic louvers) or fixed external shading devices. Unfortunately, the internal shadings cannot protect the heat gain because of heat transmission through the glass facade into the indoor environment before it reaches the shading device. The static nature of external shading devices has also reduced the buildings ability to respond to the dynamic nature of radiation angle. In addition to this, negative impact of glass facade on outdoor public spaces, nearby buildings and drivers is also expected.

1.4 OBJECTIVES OF THE STUDY

General objectives

The general objective of the thesis was first to study the effect of existing offices' glass facades on occupants visual and thermal comfort, then to propose a suitable methodology for the selection of appropriate glass material as well as effective shading systems, which responds to the incident solar radiation.

Specific objectives

1. Mapping radiation vulnerable streets of the city in the emerging central business district and identifying radiation vulnerable office blocks.
2. Assessing and measuring occupants' visual and thermal satisfaction in different office buildings and floors.

What are the possible methods to measure thermal and visual performance of current glass facades in the emerging business districts of Addis?

3. Studying the visual effect of glass facades on drivers, nearby streets and buildings.

What are the critical hours where glare from glass facades interfere outdoor activities?

4. Studying recent glass materials, technologies and performance.

What are appropriate glass materials and technologies for Addis Ababa which allows daylight entry and transparency while avoids glare and overheating into the indoor environment?

5 . Proposing a guideline and testing its effectiveness through a prototype facade.

Are there any possibilities of proposing a general facade design guideline for local buildings, which gives an overall clue about appropriate glass material selection, design and use of effective shading system?

Hypothesis

"If the current glass facade material selection and use in Addis Ababa has increased the risk of **overheating** and **visual discomfort**, then, controlling radiation through the use of appropriate glass materials and effective shading systems may increase users' thermal and visual comfort.

1.5 SIGNIFICANCE OF THE STUDY

The current practice of architecture in Addis Ababa in terms of glass facade usage and performance was studied in order to understand its effect on indoor and outdoor environment. A scientific method of study known as computer simulation was applied in this thesis to study natural light behavior and its effect on human visual and thermal comfort. This was done, first by mapping radiation vulnerable streets in the emerging central business district and then identifying daily and monthly discomfort period of the area. Afterwards, a general design guideline was set for appropriate glass material selection and usage as well as effective shading system design. This was showed through innovative facade prototype which develops **radiation responsive geometrical configuration** according to critical discomfort hours of the day and months of the year.

1.6 SCOPE AND LIMITATION OF THE STUDY

The study covered building science technology and applicability to the local context. It overviewed the performance of glass facade design and construction in specific place in Addis Ababa and its effect on thermal and visual comfort of its users. In addition to this, the study also explored **emerging high performance glass material types** and **effective shading system design strategies** in the global context.

Concerning the limitations of this research, the time frame constrains comes at the first place. More variable parameters and cases could have been assessed if the time limit was more spacious. Due to this, qualitative data was taken for specific times. It was also challenging to gather reliable data from glass material importers and suppliers about the performance of imported glass materials. On the other hand, Lack of prior research and studies on related topics in the local conditions was also a challenge for the researcher to put point of reference.

1.7 LOCATION OF THE STUDY AREA

The emerging central business district (CBD area) with in 2 kilo meter radius from Mexico Square was the focus of the study. This area was selected due to the current government interest for renewal which is primarily showed up with evolving glazed office constructions (mainly banks and insurances). These offices are vulnerable to radiation due to street orientation, low glass material performance, and absence of external shading systems.

Target group - Planners, Architects, glass suppliers, building owners and users were the main concern of the study.

Figure 1.1: Emerging CBD area (from Lideta up to stadium) – Google earth map- date: 3/11/2016

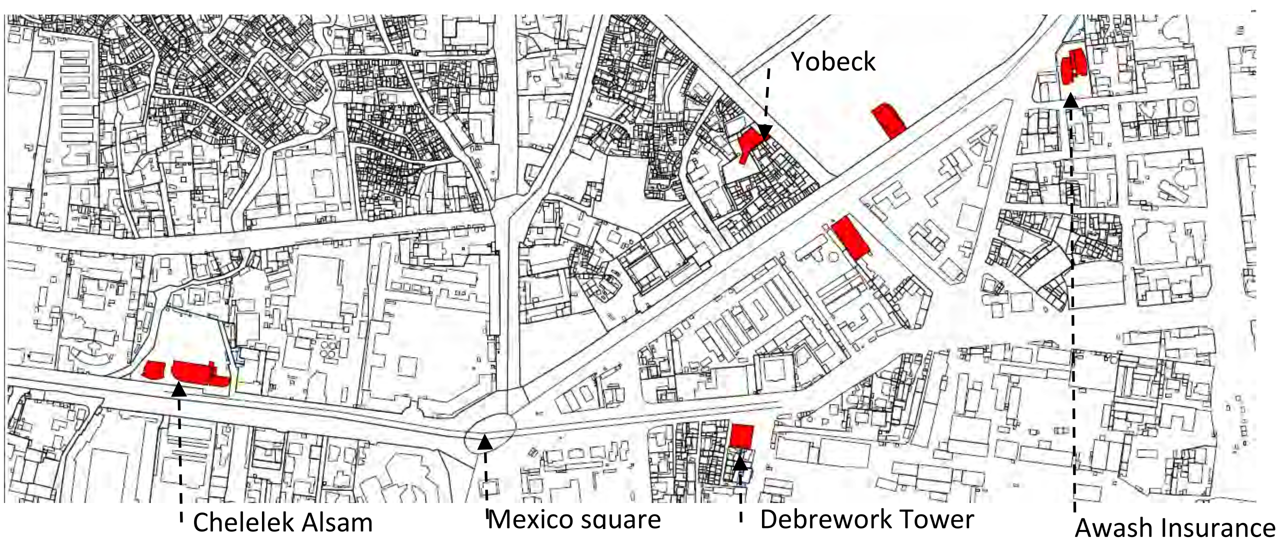


Figure 1.2: selected radiation vulnerable office buildings – Nortec map of Addis - 2011

1.8 RESEARCH OUTLINE

This thesis is composed of five chapters according to the hierarchy of the study. Chapter one contains background of the study, statement of the problem, research objectives and questions, scope and limitation of the study, location of the study area and research outline. Chapter two deals about comprehensive review of literatures. Chapter three discusses research methodology which is the foundation of the entire paper. Chapter four focuses on case studies and prior studies. Chapter five analyze and interpret data and finally reveal findings and results which could be used as an input for the guideline. Chapter six tests the guideline developed through innovative envelope prototype. Finally, chapter seven presents recommendations and future research ideas.

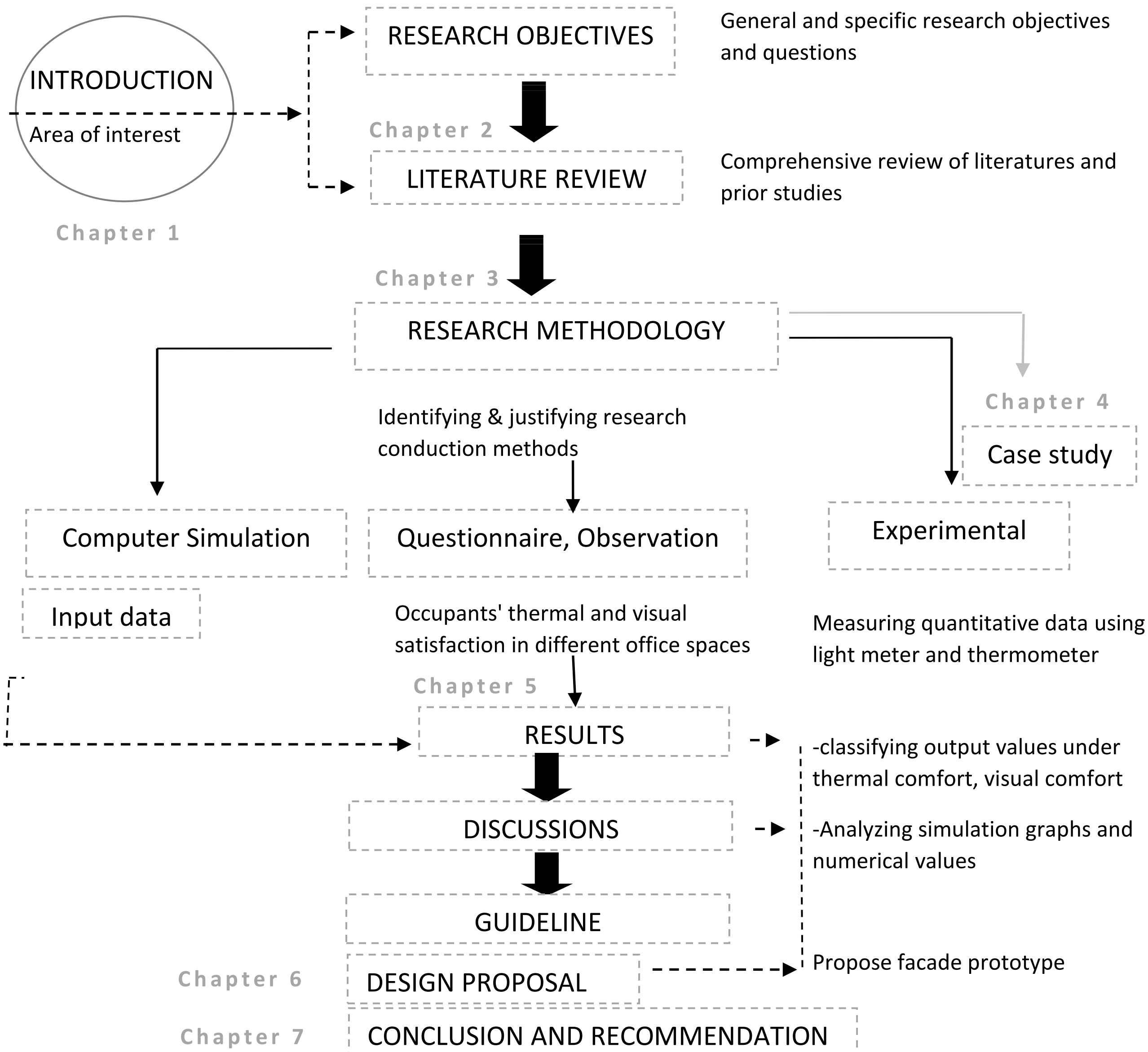


Figure 1.3: Research outline and hierarchy of study

Chapter

2

LITERATURE REVIEW

2.1 INTRODUCTION

A comprehensive literature review has been carried out by means of searching online scientific journals and databases such as "ELSEVIER", "ISSUU" which provides paramount scientific journals, articles and books. Related topics on various books has also been studied. The literatures were searched and filtered based on some keywords such as day-lighting, thermal comfort, visual comfort, Adaptive shading, and simulation.

2.2 SOLAR RADIATION

Solar radiation that reaches the earth surface consists of two components. These are direct and diffuse solar radiation. The earth is surrounded by an atmosphere which contains various gaseous constituents, suspended dust and other solid and liquid particles. Due to this solar radiation is altered through absorption, reflection, refraction or diffraction. According to Steven Szokolay(2008),Solar radiation that reaches the surface of the earth can be measured in two ways; Irradiance, in W/m^2 i.e. the instantaneous flux or energy flow density, and Irradiation, in J/m^2 or Wh/m^2, an energy quantity integrated over a specified period of time.

The movement of the sun is illustrated through sun path diagram or solar chart. Several methods are in use for the construction of solar charts. The orthographic, or parallel projection method is the simplest, but it gives very compressed altitude circles near the horizon. The equidistant method is used occasionally, but this is not a true geometrical projection. The most widely used sun path diagram is the stereographic chart (developed by Phillips, 1948).

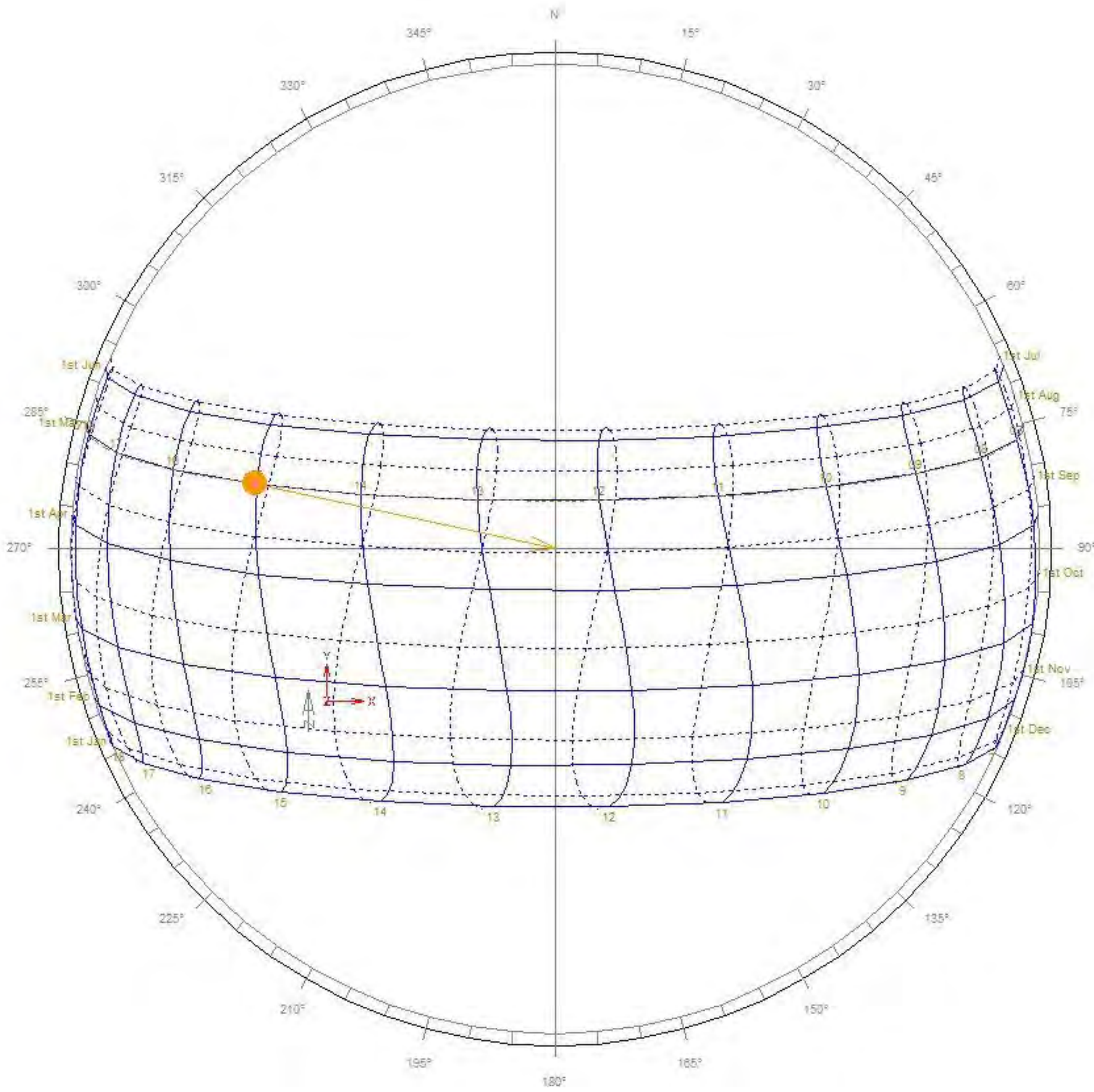


Figure 2.1: A stereographic sun-path diagram for latitude 9^0 N, Addis Ababa [Ecotect software]

2.2.1 PHYSICAL PROPERTIES OF NATURAL LIGHT/DAYLIGHT

Modern physics recognizes two properties in electromagnetic radiation: **waves** and **particles**. The wave property of light is characterized by its duration T, its frequency ν, and its wavelength λ. The particle property of light is distinguished by its photons whose energy ΔE = h.v in which h is the Planck constant and is expressed in electron volts (as in quantum theory).Natural light, or white light – the only kind that enables the eye to distinguish colors precisely consists of visible electromagnetic radiation of various wavelengths ranging from 380 – 780 nm of wavelength.

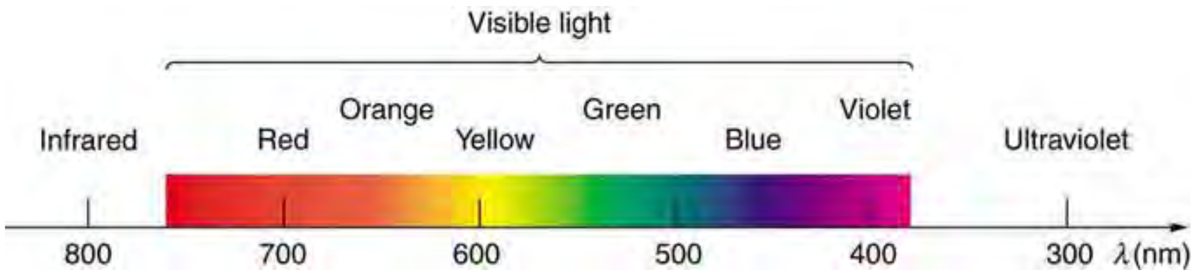


Figure 2.2: Visible light spectrum [https://en.wikipedia.org/wiki/Visible_spectrum]

The color sensation experienced by the eye depends on the spectral composition of the light received and the sensitivity of the eye.

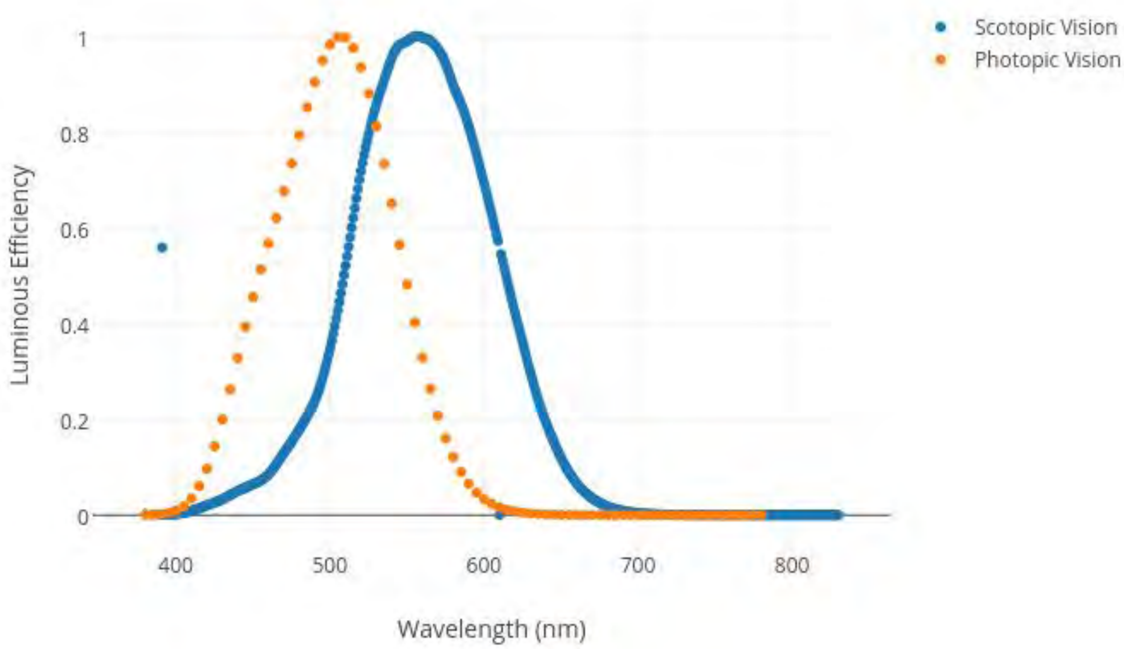


Figure 2.3: CIE luminous Efficiency curve [http://www.cie.co.at]

The quality and quantity of daylight change with location, time of day and weather conditions. Reliable daylight prediction method is developed by CIE (Commission International del'eclairage) after many years of luminance distribution measurement of real sky. According to CIE, three sky conditions, namely overcast sky, clear sky and blue sky, are investigated.

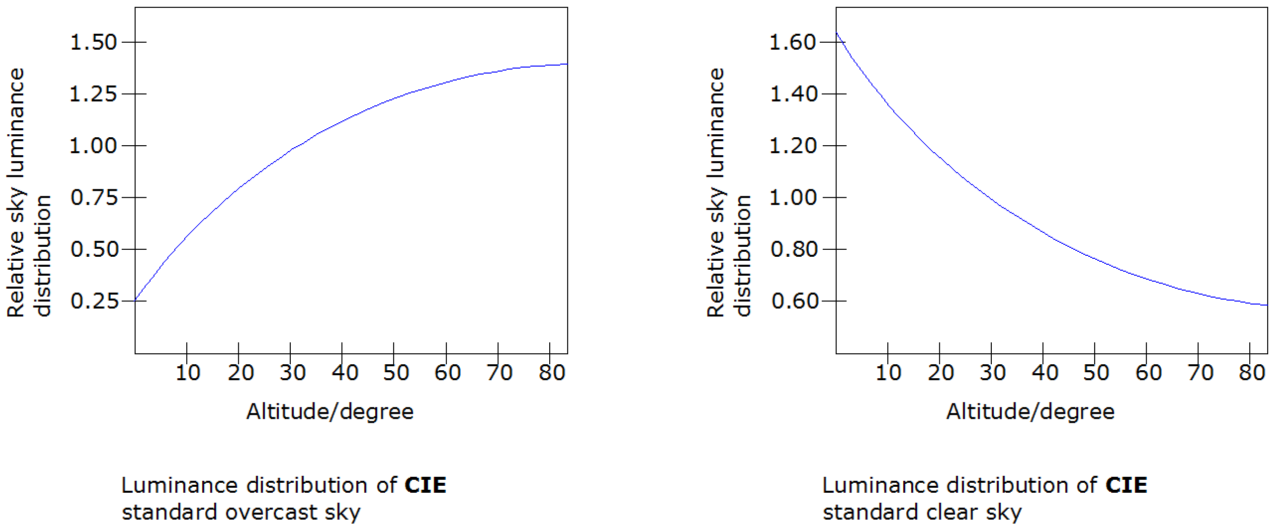


Figure 2.4: luminance distribution of CIE standard overcast and clear sky

2.2.2 LIGHT AND HEAT TRANSMISSION THOUGH GLASS FACADE

Heat exchange through building material is quantified by the thermal transmittance or **U-value** which is measured in W/m^{2}K. U-value is the rate of loss of heat per square meter, for a temperature difference of one Kelvin or degree centigrade between the inner and outer environment separated by the glazing. Heat loss is also quantified in terms of thermal resistance or R- value. R = 1/U-value or R= m^{2}k/w.

	U - value w/m^{2}k	R - value m^{2}k/w
Single	5.4 - 5.8	0.18 - 0.17
Double	2.8 -3.0	0.36 - 0.30
Double with low E coating	1.7 - 2.0	0.59 - 0.50

Table 2.1: U and R value for 4mm thick glass, with 12mm air space. (David button & Brian Pye, 1993)

The amount of solar radiation transmitted through the skin of a building is a function of the available radiation, area, orientation, and heat transmission characteristics of the exposed skin. Solar gain through glazing can be as high as 85% of the incident radiation. (G.Z.Brown and Mark D., 2001)

The thermal performance of a glass building is determined by its shading coefficient. The value indicates how the glass is thermally insulating (shading) the interior when there is direct sunlight on the panel or window. It is a value ranging from 1.00 to 0.00.The lower the rating, the less solar heat is transmitted through the glass, and the greater it's shading ability.

GLASS TYPE	**SHADING COEFFICIENT**
Glass + frame	
Single**, clear**	0.69 – 0.73
Bronze	0.53 – 0.62
Green	0.50 – 0.61
Gray	0.48 – 0.60
reflective	0.17 -0.28
Double**, clear**	0.60 – 0.70
Bronze	0.43 – 0.53
Green	0.40 – 0.52
Gray	0.38 – 0.51
HP green	0.33
Reflective	0.12 – 0.20
Double **– low E ,clear**	0.32 – 0.60
Bronze	0.23 – 0.48
Green	0.27 – 0.47
Gray	0.21 – 0.46
HP green	0.25 – 0.39

Table 2.2: Shading coefficient for typical windows (ASHRAE, 1997)

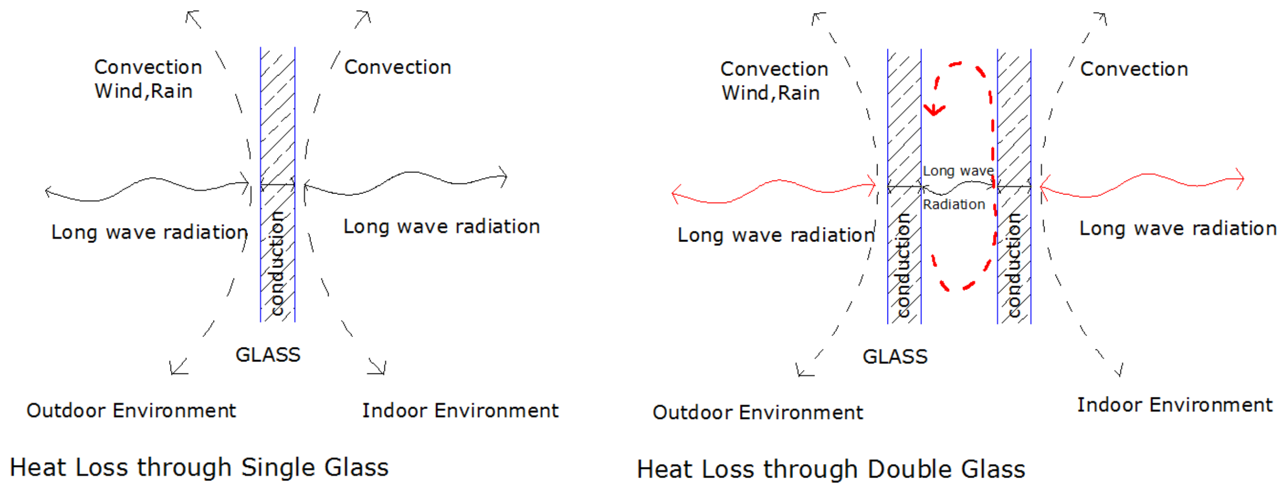


Figure 2.5: Heat loss through single and double glass

There are emerging researches and laboratory experiments which shows thermal performance optimization through modifications in transmission, reflection and absorption properties of glass. This is being achieved through tinted glass products which increases absorption, reflective coating, and combination of the two methods. There are also other techniques in contemporary design and construction where laminated glass panel is used in combination with solar responsive shading panels.

2.2.3 GLASS TYPE AND PERFORMANCE

Current researches and technologies aimed at maximizing the performance of glass in terms of **light transmission**, **heat blocking** and **safety issues**.

There are three glass categories in different strength. These are Annealed glass, heat-strengthened glass and fully tempered glass. Of all the three, Annealed glass is commonly used due to its good surface flatness and not heat- treated.

In terms of thermal performance and safety glasses are classified as:

Laminated glass - a transparent sheet of polymer is sandwiched between two or more layers of glass to protect ultraviolet rays and reduces vibration.

Insulating glass - glass layers are separated by sealed dry air or gas space for thermal insulation & condensation control.

Coated glass - covered with low- emissive (low – E) coatings which reflects radiation.

Tinted glass - composed of minerals which colors the glass to absorb radiation.

Wire glass – a wire mesh is inserted between glass plates to enable the glass stick together during crack.

2.2.4 BENEFITS OF DAY-LIGHT

Physiological benefits of day-lighting

Ultraviolet radiation is essential to human health. It prevents rickets, helps keep the skin in a healthy condition, is responsible for the production of vitamin D in the body (thus reducing the incidence of broken bones in the elderly), and it destroys germs. Ultraviolet widens the capillaries of the skin, reduces blood pressure, quickens the pulse rate and appetite, stimulates energetic activity, produces a feeling of well-being, reduces fatigue, and may even increase work output. (Boubekri M., 2008)

Psychological benefits of day-lighting

Sunshine - direct sunshine in the interior environment is one of the strongest psychological benefits. Although direct sun on a visual task may produce excessive brightness differences, Some direct sun in proper location and quantity is stimulating and desirable.

View - a view to the exterior is another psychological benefits to building occupants. Numerous studies have shown that tenants usually are willing to pay more for offices space with windows than for windowless space. (Boubekri M., 2008)

2.2.5 THE NEED FOR SOLAR CONTROL

The two most important climatic factors that influence indoor environment are air temperature and solar radiation even though wind and humidity also have an effect. Solar radiation may cause severe overheating which dramatically increases air conditioning load in addition to occupant discomfort.

"One of the first tasks of an architect is to determine when solar heat input is desirable and when solar radiation is to be excluded. The next step will then be to provide the appropriate solar control mechanism. A prerequisite of designing the solar control is to know the sun's position at any time of the year and then to relate it to the building."(Donald Watson, et al, 1997)

Recently, there are a number of non-geometrical solar control technologies like photo-chromatic or thermo-chromatic glasses. These however rarely provide the desired control, always reducing the day lighting of the interior spaces. (Wurm, J., 2007). The most effective method of solar control is the use of external shading device, which provides a barrier to solar radiation before it would reach the glass window. This was explained well in the 2nd international conference on sustainable and healthy buildings, in Korea. (kim, J.T, 2009).

2.3 VISUAL COMFORT

Visual comfort is a condition where human eyes receive a suitable amount of light without making an effort to visualize some tasks, which strongly relate to the illumination levels inside the space either artificial or natural light sources (David, 2011). The main focus on visual comfort has traditionally been light levels, contrast, and glare. In the first case, the more intense the task, the brighter the light required. This is the main reason operating rooms are much brighter than offices, which are in turn much brighter than living rooms. The second pertains to contrast: the greater the contrast, the easier the comprehension. The final point is that glare is undesirable, as it makes it difficult to see the object of attention. There are also other effects beyond light levels, contrast, and glare. Color relates to a particular frequency of light, and color can have an effect on one's comfort. Though it is has not been established whether the influence is from the color itself or derived from cultural and historical associations, people react differently to various segments of the spectrum.

2.3.1 MAIN PARAMETERS OF VISUAL COMFORT

The visual environment must allow people to see objects clearly, without strain, in pleasantly toned surroundings. The parameters of visual comfort for which architects play a dominant role are: the level of illumination of visual tasks, the harmonious distribution of light within a space, the ratios of illuminance within a building, the absence of unwanted shadows, an exterior view, good color interpretation, pleasant tones of light, and the absence of glare. (Derek Phillips, 2004)

2.3.2 VISUAL DISCOMFORT/GLARE

Glare is visual noise that interferes with visual performance. Two main types of glare exist, direct and indirect (reflected), and each can have very detrimental effects on the ability to see (Lechner, 2015). Direct glare is caused by a light source in the field of the view that is sufficiently bright to cause annoyance, discomfort, or loss in visual performance. Reflection of light sources on glossy surface usually cause indirect glare.

2.3.3 VISUAL COMFORT VS HUMAN PERFORMANCE

Lighting quality is one of the determinants of human performance in indoor environment. Various study has been conducted to compare the effects of different lighting conditions on health, productivity, and well-being and alertness level. With regards to human perception, correlated color temperature (CCT) and illuminance level are the two most important characteristics of light to be considered (van Bommel, 2004).

2.4 THERMAL COMFORT

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ASHRAE Standard 55). The **PMV** model was developed by P. O. Fanger using heat balance equations and empirical studies about skin temperature to define comfort. This model was developed by taking the mean value for thermal satisfaction which is normally above 85% vote. Studies show that the human body has a thermos- regulating system which maintain its temperature at 37 ^{0}c. Thermal comfort depends on this metabolic system being in balance with the surrounding environment.

2.4.1 MAIN PARAMETERS OF THERMAL COMFORT

According to ASHRAE standard 55, thermal comfort is affected by two factors, personal factor and environmental factor. The former are metabolic rate and clothing level, the latter are air temperature, mean radiant temperature, air speed and humidity.

Metabolic rate - ASHRAE 55-2010 Standard defines metabolic rate as the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism. It varies based on activity level, body shape and environmental conditions.

Clothing insulation - Thermal comfort is affected by the amount of clothing insulation because it influences the heat loss and consequently the thermal balance.

Air temperature - The air temperature is the average temperature of the air surrounding the occupant. It is measured with a dry-bulb thermometer and it is also known as dry-bulb temperature.

Mean radiant temperature - The radiant temperature is related to the amount of radiant heat transferred from a surface, and it depends on the material's ability to absorb or emit heat, or its emissivity. So the mean radiant temperature experienced by a person in a room with the sunlight streaming in varies based on how much of his/her body is in the sun.

Operative temperature - It is the average of the air dry-bulb temperature and of the mean radiant temperature at the given place in a room.

Air speed - According to ASHRAE Standard 55, it is the average speed of the air to which the body is exposed, with respect to location and time.

Relative humidity – it is the ratio of the amount of water vapor in the air to the amount of water vapor that the air could hold at the specific temperature and pressure.

2.4.2 SOLAR GAIN AND HEAT FLOW THROUGH BUILDING ELEMENTS

Solar gain refers to the increase in temperature in a space, object or structure that results from solar radiation. The amount of solar gain increases with the strength of the sunlight, and with the ability of any intervening material to transmit or resist the radiation. Heat flow through any building element (e.g. wall, floor ceiling, and window) is directly proportional to the temperature difference on either side of that element. This is called the temperature differential (also referred to as delta T or ΔT). The greater the temperature differential, the greater the heat flow through the element due to the rule of thermodynamics (heat flows from higher temperature to lower temperature till it reaches equilibrium).

2.4.3 THERMAL COMFORT AND HUMAN PERFORMANCE

Thermal discomfort distracts occupants' performance in the workflow rate in the office. There is dramatic performance deprivation that has direct effect on production, since thermal discomfort is directly interpreted into money loss. As stated by (Wargochi, et. al., 2006), a reduction of performance by 5% to 15% could occur if occupants feel discomfort in their workplaces.

2.5 THE IMPORTANCE OF BUILDING ENVELOPE

Building envelope is the interface between the interior of the building and the outdoor environment. By acting as a thermal barrier, the envelope plays an important role in regulating interior temperature and helps to minimize the amount of energy required to maintain thermal comfort. Improvement to the building envelope have the potential to reduce GHG (greenhouse gas) emissions from new and existing buildings in the residential, commercial and industrial sectors. However, careful study of the local climatic conditions is very important to identify the appropriateness and cost effectiveness of many decisions in terms of envelope design and material selection. As noticed by (David,2011), the implementation of shading devices is mostly effective in case of tropical climates, which tends to have the highest building operation energy.

2.5.1 TYPES OF SHADING DEVICES

There are many different forms of solar shading; each has its own characteristics, advantages and disadvantages, and the architect must be sure of the criteria that should be taken into account when determining the nature of the shading required and whether some form of adjustability is desirable. The principal reasons for needing shading are; to reduce the effect of heat gain from the sun, and to cut down sun glare experienced through the windows which interferes both indoor and outdoor activities. In addition, shading devices also used as enclosures to provide privacy (Hammad, 2010). There are different shading device classification criteria, but according to (Derek Phillips, 2004), Solar shading solutions can broadly be divided into three, namely, External shading, Internal shading, and Alternative glazing. Moreover, nowadays a number of studies are being performed to enhance intelligent day-lighting and shading techniques, which effectively influence thermal gains as (Kim, 2009) studied.

2.5.2 ADAPTIVE SHADING DEVICE

In contemporary architecture, one of the significant and concerning studies involves dealing with surfaces that can be assembled to create adaptive geometry to certain environmental conditions (Picon, 2010). Environment responsive components attached to facade is a primary interest in building sustainable and adaptive architecture. Adaptive systems are engaged in the surface generation scheme and are most likely connected to digital architecture and computational fabrication design. The feature of these systems consists of three-dimensional layers to operate the two-dimensional skin elements. These operational components are embedded in the skin and attached to the material system used. The skin works according to the natural properties of the material, and hence it is possible for the skin to perform only one type of response per system, such as shading or ventilation.

2.6 SIMULATION TOOLS FOR SOLAR ANALYSIS AND ENERGY CALCULATION

Now a days, hand calculation of thermal and visual parameters becomes more complex for multi zone or buildings due to dynamic environmental conditions. This includes, variation of outside air temperature and solar radiation with time, shading by neighboring buildings, self-shading, and thermal capacity of the building. Computer-based simulation tools are now available to do quick and accurate assessment of a building's thermal and day lighting performance. These tools can estimate the performances of different designs of the building for a given environmental condition. From these results, a designer can choose the design that consumes minimum energy.

A number of tools are available for simulating the thermal performance of buildings. A brief description of a few simulation tools is presented in the research in order to identify their capacity and use for local case study and design proposal.

1. TRNSYS

TRNSYS is a dynamic simulation tool for estimating the performance of any solar thermal system. For example, it can estimate the performance of a building, and a solar photovoltaic system. It is one of the most widely used commercially available tool for building simulation. It uses a menu driven interface to provide the building description (building geometry, materials and their properties, scheduling, heating and cooling system, etc.).The weather data, simulation run time, and output types can be provided by using PRESIM interface, or manually edited using any text editor. TRNSYS can be used with a general purpose CAD software called SimCAD, to integrate the architectural design and simulation. The output of a building's thermal performance in terms of temperature and loads, can be obtained both graphically and in text format.

2. Autodesk Ecotect Analysis

The intelligent objects in the building information model enable the advanced functionality of the desktop and web-based tools that are included with Autodesk Ecotect Analysis software. Using Autodesk Ecotect Analysis, architects and designers can gain better insight into building performance earlier in the process, helping to achieve more sustainable designs, faster time to market, and lower project costs.

3. ENERGY PLUS

Energy Plus is a modular, structured software tool based on the most popular features and capabilities of BLAST and DOE-2.1E. It is primarily a simulation engine; input and output are simple text files. This tool grew out of a perceived need to provide an integrated simulation for accurate temperature and comfort prediction. The Energy Plus building systems simulation module calculates the heating and cooling system, and plant and electrical system response. This integrated solution provides more accurate space-temperature prediction, crucial for system and plant sizing, and occupant comfort and health calculations. Integrated simulation also allows users to evaluate realistic system controls, radiant heating and cooling systems, and inter zone air flow. It has two basic components: a heat and mass balance simulation module, and a building systems simulation module.

4. RELUX

Relux is a software for dynamic light simulations based on pre-calculated HDR images. When a scene with several luminaires is calculated separately according to control groups, with only one group of luminaires switched on for each individual calculation, HDR images can be added afterwards in different scale factors. This can almost be done in real-time, since the time-consuming Retracing calculation has been performed beforehand. Thus, dynamic light control can easily be simulated, as if the luminaire groups were actually being dimmed.

Daylight can, of course, be incorporated in the process, such as through a sequence of calculations for a certain time and state of the sky. An important additional aspect is that the Relux simulation includes energy information in the calculation. In this way, the energy consumption of a lighting set can be readily simulated in dynamic operations. It is possible, for example, to determine the energy savings achieved by cutting back on the use of artificial light through the availability of sufficient daylight.

2.7 WEATHER DATA FOR ADDIS ABABA

Sunshine and daylight hours

There is an average of 2439 hours of sunlight per year (of a possible 4383) with an average of 6:40 of sunlight per day. It is sunny 55.6% of daylight hours, the remaining 44.4% of daylight hours are likely cloudy or with shade, haze or low sun intensity.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Sunlight Hours/ Day	08:05	07:09	07:17	06:06	07:36	05:48	02:48	03:05	05:24	08:05	09:00	09:42	06:40
Average Daylight Hours & Minutes/ Day	11:39	11:49	12:03	12:19	12:31	12:37	12:35	12:24	12:09	11:54	11:42	11:36	12:00
Sunny & (Cloudy) Daylight Hours (%)	70 (30)	61 (39)	61 (39)	50 (50)	61 (39)	46 (54)	23 (77)	25 (75)	45 (55)	69 (31)	78 (22)	85 (15)	56 (44)
Sun altitude at solar noon on the 21st day (°).	61	70.2	81.1	87.1	78.8	75.5	78.4	86.8	81.5	69.9	60.9	57.6	74.1

Table 2.3: sunshine and daylight hours in Addis Ababa [source: www.addis ababa.climatemps.com]

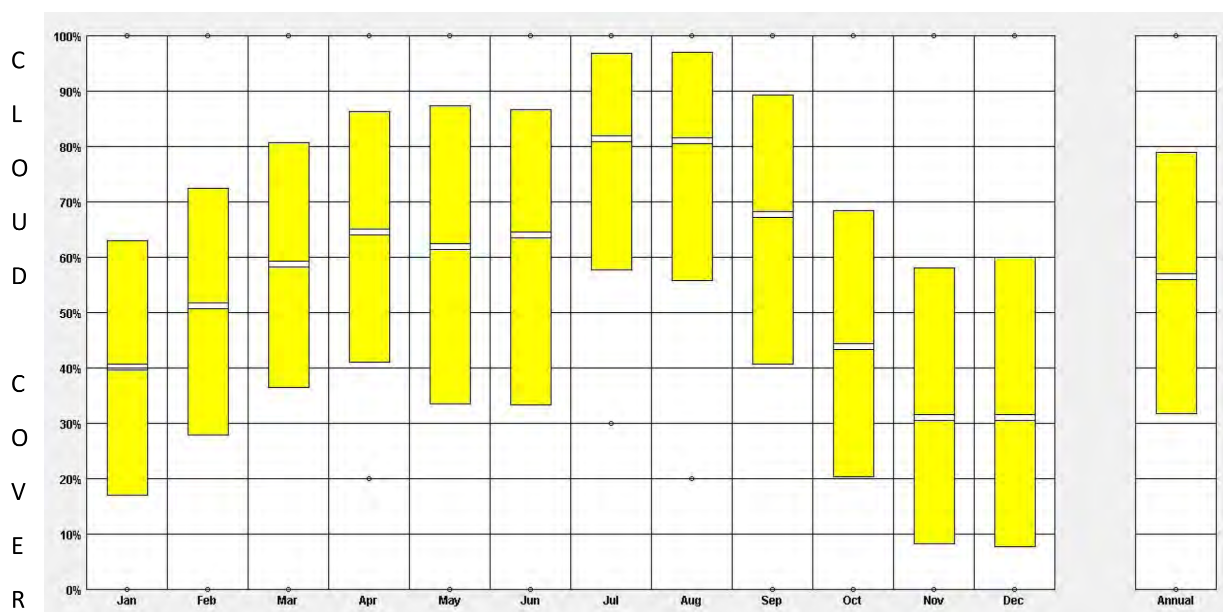
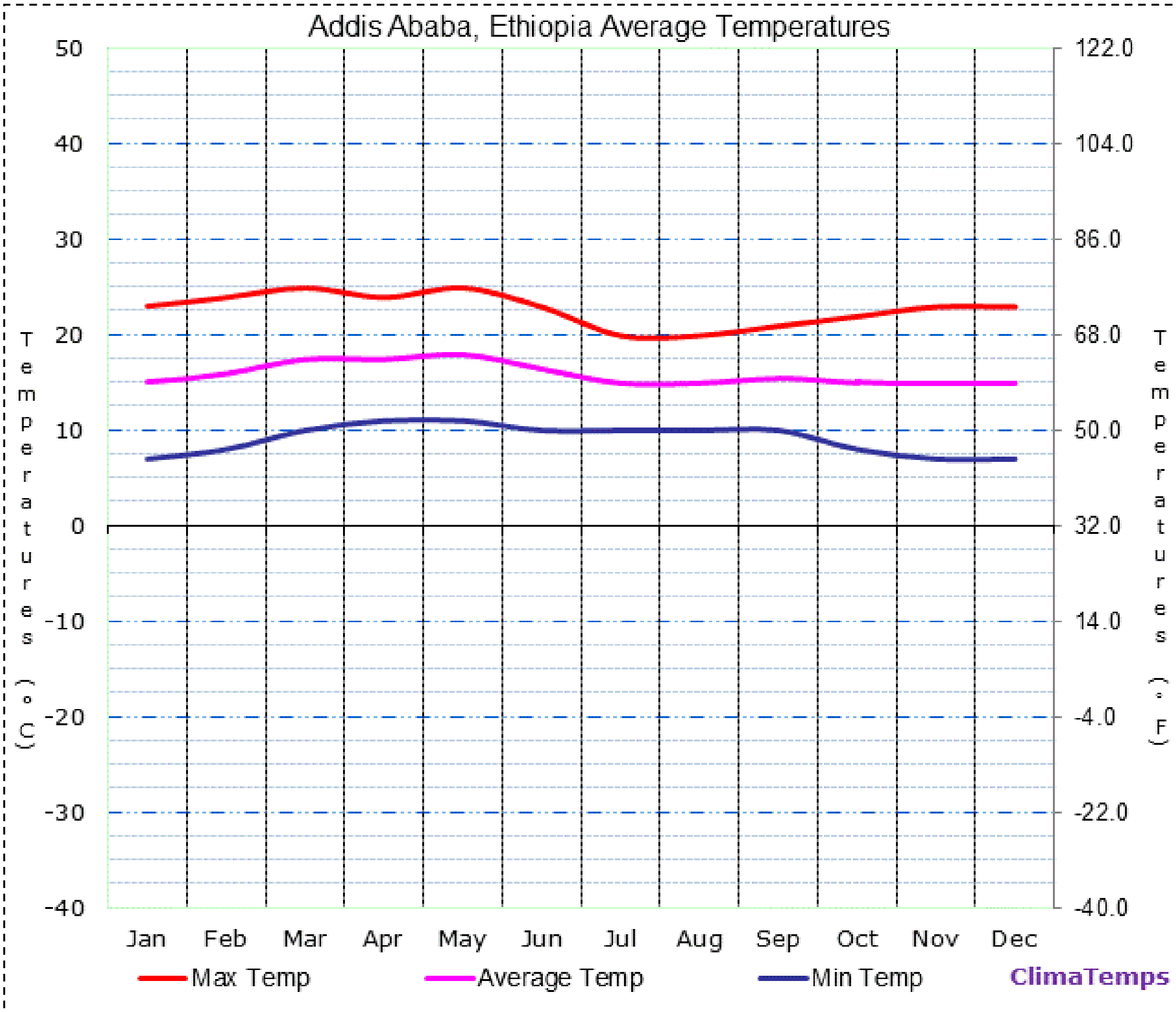


Table 2.4: sky cover range [source: climate consultant at SWERA 634500 WMO station number, elevation 2355m]

Average Temperature: The mean annual temperature in Addis Ababa is 15.9 degrees Celsius. The variation of average monthly temperatures is 3 °C which is an extremely low range. The hottest month (May) is somehow warm with an average temperature of 18 degrees Celsius. The coolest month (January) is slightly cold with a mean temperature of 15 degrees Celsius.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max Temperature °C	23	24	25	24	25	23	20	20	21	22	23	23	22.8
Average Temperature °C	15	16	17.5	17.5	18	16.5	15	15	15.5	15	15	15	15.9
Average Min Temperature °C	7	8	10	11	11	10	10	10	10	8	7	7	9.1

Table 2.5: Average Temperature in Addis (source: www.addis-ababa.climatemps.com/sunlight.php)



Chapter

3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

The work plan and sequence of activities are presented in detail to clear out the scientific process of the study. The method of the study is divided into two major parts.

PART ONE: The first part is literature review that has been presented in details in Chapter 2. The review was developed based on scientific journals, research papers and books, to have a strong base, knowledge and experience about the field of study.

PART TWO: The second part, which is briefly elaborated in this chapter, consists of Identification of **constant** and **variable parameters** to be studied, followed by determining the most common methods used for conducting similar researches, comparing them, selecting and justifying the most appropriate method depending on the availability and suitability to the local context. Afterwards, simulation tools are selected and justified. Finally, research plan, required resources, method of data analysis and limitation of the study are discussed.

3.2 IDENTIFICATION OF PARAMETERS

Identifying the constant and the variable parameters is very important to get exposed to all possible parameters that could influence the performance of facade systems. The variable parameters are tested, while others are kept fixed in order to achieve the required outputs which are the constant parameters.

3.2.1 CONSTANT PARAMETERS

- **WEATHER DATA AND LOCATION**: The emerging central business district (CBD) area of Addis Ababa, from Lideta up to Stadium has been chosen. Weather data of the city has been collected which defines the sun position (solar altitude and azimuth angles) and the sky conditions. The climatic details would be imported which includes all relevant information about the dry bulb temperature, the wet bulb temperature, the relative humidity, and prevailing winds with their frequency and strength.

- **SAMPLE OFFICE MODEL**: Open plan offices were chosen as their design is very critical in terms of the large space, how the daylight is distributed in the space, the solar radiation heat effect due to perimeter and interior workstation location distance from the facade.

ROOM HEIGHT – the height of the room were kept constant, hence change in room height would affect the volume of the space which in turn directly related to thermal comfort.

INTERNAL HEAT GAIN: During thermal simulation of individual office spaces, information regarding elements responsible for the internal heat gains such as: number of occupants per square meter, number of equipment found in the office, and the floor area and volume of the office space were kept constant.

FACADE MATERIAL: Properties and layers of glass materials (single leaf or double leaf) were identified and kept constant throughout the simulation process.

OFFICE FURNITURE: All furniture located in the sample office model where set to be similar with the real office material properties and color, to avoid significant difference in reflection/ luminance.

3.2.2 VARIABLE PARAMETERS

BUILDING ORIENTATION: The building will be tested in all orientations in order to investigate the effect of the sun position to the building facade and how it would influence the indoor and outdoor environment.

TIME OF SIMULATION: the simulation would be conducted in different times of the day, days of the month and months of the year in order to get an overview about the influence of changing time.

LOCATION OF OFFICE FLOOR: the location of the office floor would be variable in order to explore the effect of nearby buildings' influence in terms of shading (blocking of view and sunlight).

3.3 IDENTIFICATION, SELECTION AND JUSTIFICATION OF RESEARCH METHOD

Investigating the effect of facade systems has been performed by various methods throughout the research history in this field. However, there were five commonly used methods by the researchers, which are the **real simulation**, **numerical & experimental methods**, **questionnaires**, **case studies** and **computer simulation**. These were the different methods used by the studied papers during the literature review.

Real Simulation, which is often considered as accurate methodology, consists of a real sun and sky simulators that could be adjusted in existing building. The main advantage of this method is that a physical real model is very close in feeling to real conditions with a high precession accompanied by output photos to document the results. Numerical and experimental methods consists of mathematical formulas and equations to calculate and obtain the relationship between attributes, following it with an experiment to verify the results. The experiment could be done with different measuring equipment, in this case, light meter and temperature meter could be used. However, a researchers' percentage of error should be taken into account. Questionnaires are often used to collect raw data about the topic which could be further analyzed into useful information. Case studies are the conventional methods to measure and analyze existing buildings performance. Computer simulation is the most advanced method to obtain the required output values and give quantitative results.

	Research cost	Time needed	Accuracy	Experience needed
Real simulation	very expensive	time consuming	Accurate result	High experience
Experimental	Expensive	time consuming	Most accurate	Adequate experience
Questionnaire	Affordable	Minimum time	Less accurate	Less experience
Case study	Affordable	Time consuming	Least accurate	Adequate experience
Computer simulation	Affordable	Minimum time	Nearly accurate	Software experience

Table 3.1: Common research methods comparison

After comparing the advantages and disadvantages of the five commonly used methods in terms of cost, time, accuracy and experience needed, four of them are selected to deal with. These are **computer simulation**, **experimental**, **case study** and **questionnaires**.

3.4 SELECTION AND JUSTIFICATION OF SIMULATION TOOLS

According to study made during the literature review, a number of building simulation software have been developing rapidly to enhance options that are more flexible and accurate. Referring to a study done by (Attia, S., et al, 2012), which mainly discusses about Selection criteria for building performance simulation tools: contrasting architects' and engineers' needs, the most important parameters that architects and engineers focus on are found to be, usability and graphical visualization of the interface, accuracy of the tool and interoperability of building model. Familiar Simulation tools namely, **ECOTECT** and **RELUX** are used in this study because of their interoperability, ease of operation and better accuracy in terms of data analysis and interpretation.

3.5 METHOD OF DATA ANALYSIS

The analysis stage is basically transforming the input data into output quantitative and qualitative results. It has been concluded from the type of quantitative data collected and the variety of parameters that the best analysis comparisons would be performed through ECOTECT software.it produces graphical output data and gives minimum, maximum and average values of several parameters of different cases. In addition, RELUX software is used in order to evaluate daylight penetration through facade systems. Excel sheets is also used for further analysis of the data from questionnaires and numerical results of actual measurement tools (light meter and temperature meter). Finally, the output data from the above different tools is compared and discussed in chapter five.

3.6 COMPUTER SIMULATION

Volumetric model of the city from Lideta up to Stadium is prepared on sketch up and exported to Ecotect to proceed on solar analysis. Weather data of Addis Ababa is downloaded from a site called 'energyplus.com' to set daily and annual sun path. Then, annual cumulative solar access analysis is done for vulnerable surfaces of the buildings. Finally, special emphasis is given to five offices to study their overall facade concept, shading systems and its visual and thermal effect on the indoor environment.

3.6.1 OVERALL SOLAR EXPOSURE STUDY OF SELECTED CBD ZONE IN ADDIS ABABA

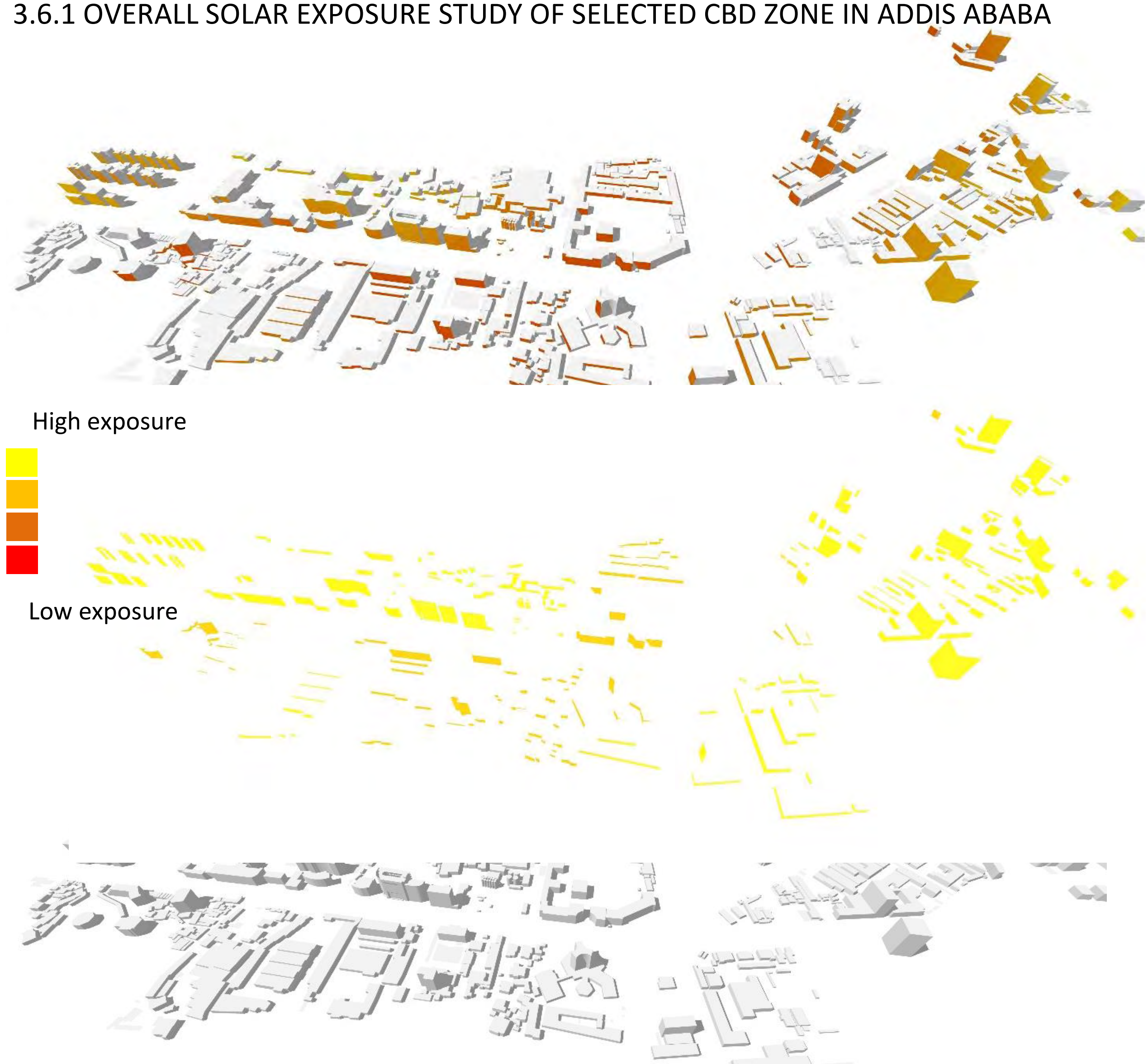


Figure 3.1: Overall solar exposure map of selected CBD area (west and south facade)

3.6.2 SOLAR ACCESS ANALYSIS OF SELECTED VULNERABLE OFFICE BUILDINGS

The study focuses on concerns related to incident radiation, overheating periods and thermal discomfort conditions in the building. The computer simulations were undertaken with the use of various lighting simulation software such as Relux and Ecotect to determine the likely daylight illuminance distributions and daylight factors across open plan office spaces. Finally, the computer simulation output is compared with some of the findings of observations and questionnaire inputs.

AWASH INSURANCE COMPANY

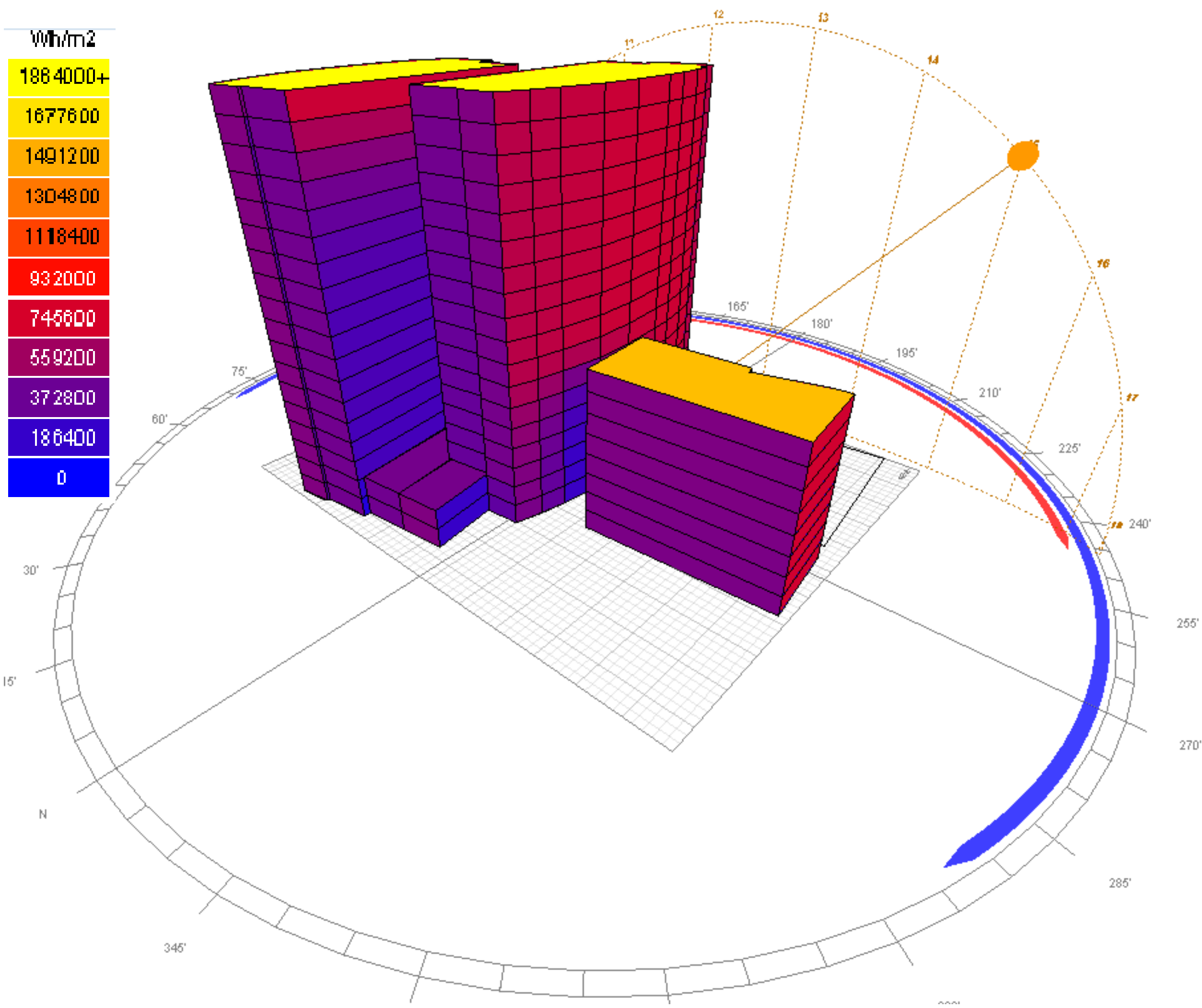


Figure3.2: Awash Insurance Annual cumulative solar access analysis in Wh/m^2

AWASH INSURANCE COMPANY

Evaluation of Day-lighting

Awash insurance company is a 16th story building which was designed for the insurance's administrative office. It consists of two transparent semicircular wings which are connected with pedestrian bridge at different stories. The investigation was carried out in levels consisting primarily of open plan office spaces such as the 10^{th}, 11^{th} and 12^{th} floor.

Figure 3.3: Interior and Exterior feature of awash bank

During sunny days the large glazed facade causes glare effect to the outside environment. High differences in internal illuminance on working positions during the time of intensive sunshine cause discomfort. Additionally, computer simulations are carried out to examine some of the findings of observations throughout the walk around survey conducted.

CHELELEK ALSAM BUILDING

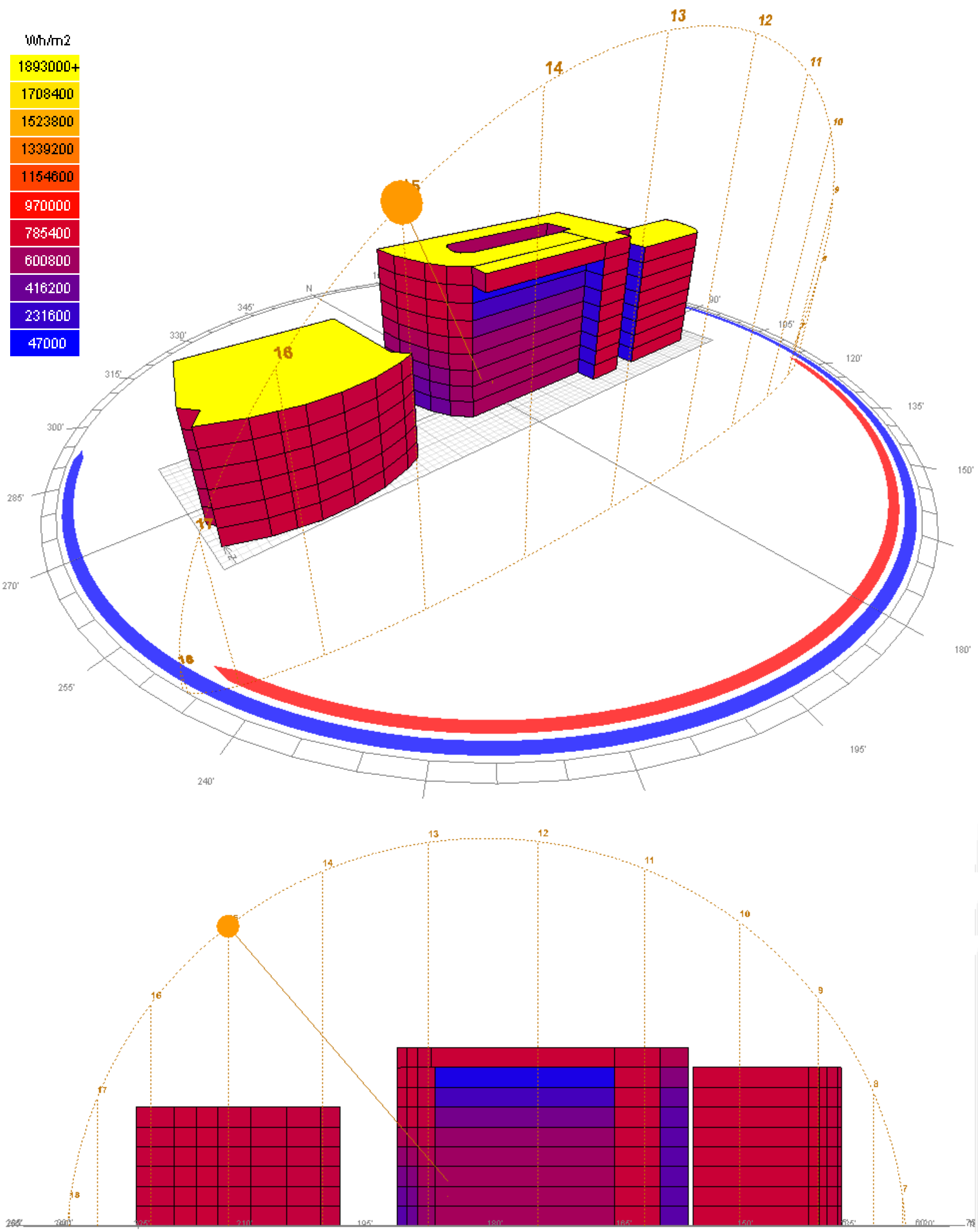


Figure 3.4: Chelelek Alsam, Annual cumulative solar access analysis in Wh/m^2

ALSAM BUILDING

Evaluation of Day-lighting

In the investigated building, the spaces located on the ground and first floor are dedicated for mixed use facilities, while the rest of the building is dedicated for office purposes and the investigation was carried out in levels consisting primarily of open plan office spaces such as the second and fifth floor.

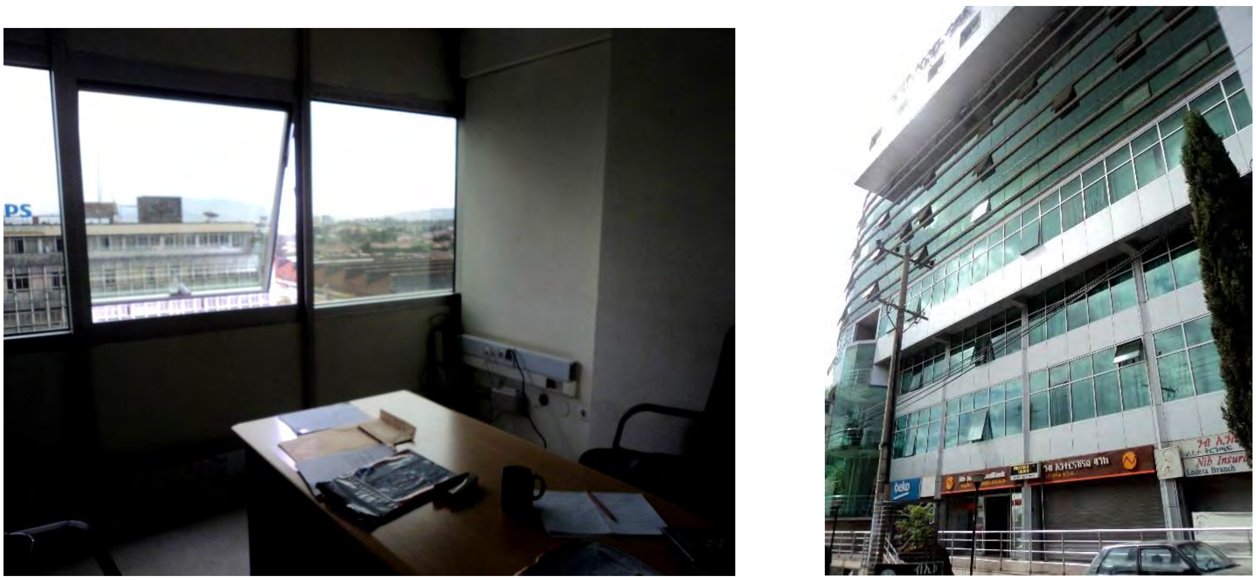


Figure 3.5: Interior and Exterior feature of Chelelek Alsam building

The large glazed facade causes glare effect to the outside environment. High differences in internal illuminance on working positions during the time of intensive sunshine cause discomfort. Additionally, computer simulations are carried out to examine some of the findings of observations throughout the walk around survey conducted. The computer simulations were undertaken with the use of various lighting simulation software such as Relux and Ecotect to determine the likely daylight illuminance distributions and daylight factors across open plan office spaces. Finally, the computer simulation output is compared with some of the findings of observations and questionnaire inputs.

DEBREWORK TOWER

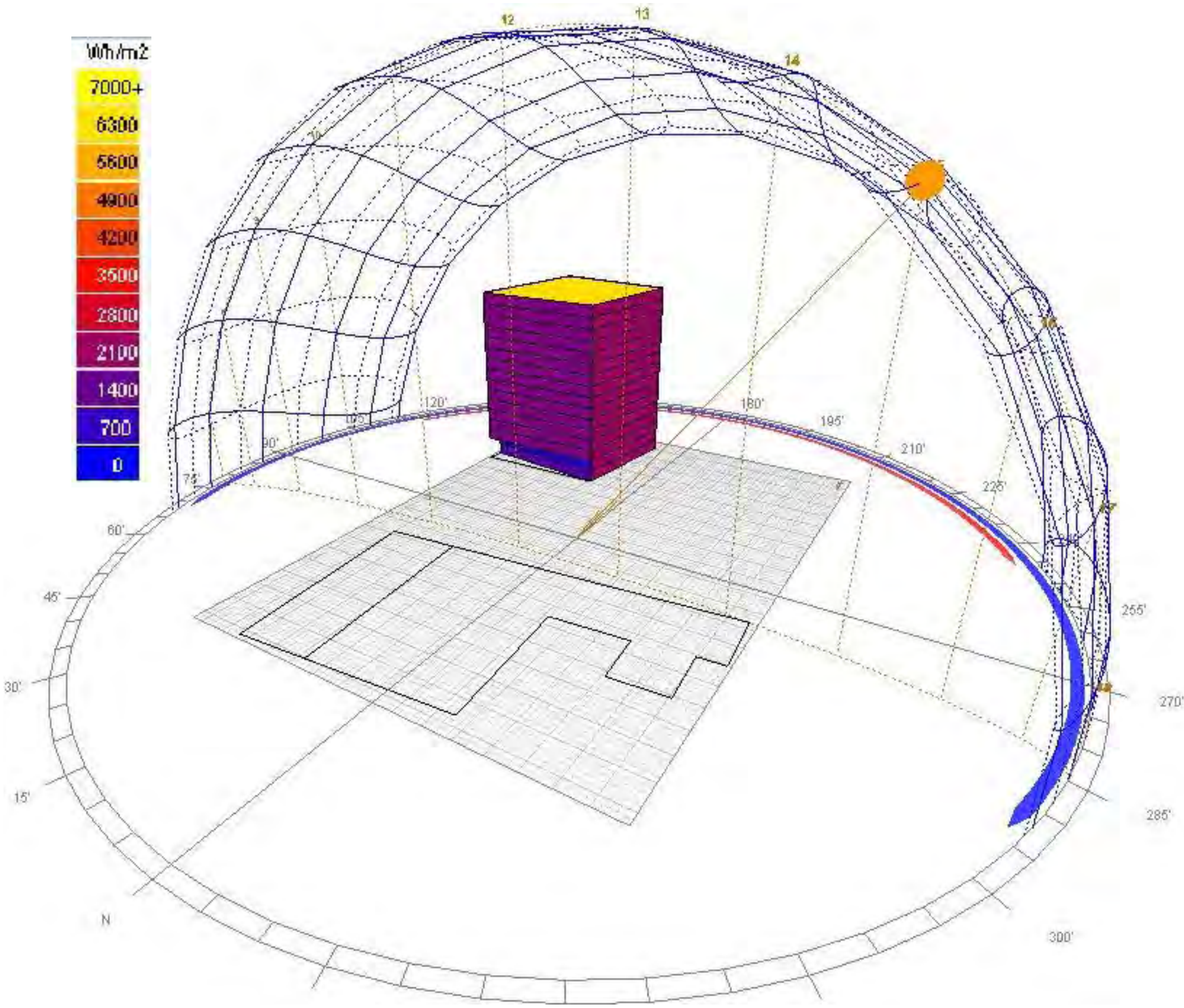


Figure 3.6: Debrework Tower- Annual cumulative solar access analysis in Wh/m²

DEBREWORK TOWER

Evaluation of Day-lighting

The building has 15 floors and designed for office use. The investigation was carried out in 3rd level, which consists of open plan office spaces for commercial bank of Ethiopia. The simulation was made on North West and west facade of the building.

Figure 3.7: Interior and Exterior feature of Debrework Tower

The color of the glass window is highly reflective and also has exclusive golden color. The computer simulations were undertaken with the use of various lighting simulation software to determine the likely daylight illuminance distributions and daylight factors across open plan office spaces. Finally, the computer simulation output is compared with some of the findings of observations and questionnaire inputs and became input for the final result.

3.7 QUESTIONNAIRE AND OBSERVATION /QUALITATIVE DATA

Questionnaires were structured based on the objectives of the research in order to measure the satisfaction of office occupants and street users. The draft is Pre-tested to find out how respondents understand the questions. The questionnaire basically contains closed questions which allows respondents a number of defined response choices as well as open-ended questions that allow respondents freedom to respond in their own way. The content was classified into two parts, namely, the effect of facade choices on indoor visual and thermal comfort, and the effect of facade choices on outdoor environment and drivers.

3.7.1 STUDYING THE EFFECT OF FACADE CHOICES ON INDOOR VISUAL AND THERMAL COMFORT

The questionnaire was formulated to investigate the relationship of visual and thermal comfort in relation to occupant performance. Around 4 radiation vulnerable offices in Addis Ababa were investigated during the survey.

The questions were structured based on:

- Section 1: Basic Information
- Section 2: General Comments
- Section 3: **Thermal Comfort** assessment
- Section 4: **Visual comfort**/natural light assessment

3.7.2 STUDYING THE EFFECT OF FACADE CHOICES ON NEARBY BUILDINGS, STREETS AND DRIVERS

The questionnaire was formulated to investigate the impact of glare and high contrast over nearby buildings and street activities.

The questions were structured based on:

The effect of nearby building facade over the neighborhood facade
The effect of facade choices on drivers and streets.

3.8 QUANTITATIVE DATA MEASUREMENT

The illuminance at the working plane (table) is measured using lux-meter (light-meter). This measurement is usually taken at 0.85 meter above the floor. The illumination level at the working plane ranges from 750 lx (near the exterior wall) to 250 lx at the central space. However, studies show that, a horizontal illuminance of 500 lx on the working plane is appropriate for office work.

The dry-bulb temperature (DBT) recording equipment is used on the survey to measure indoor air temperature. DBT is the temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture. It is the temperature that is usually thought of as air temperature, and it is the true thermodynamic temperature.

Light meter

Figure 3.8: Light meter and temperature meter

The measurement was taken in May/2016, from 2:00pm up to 4:00pm in every 30 minutes interval. The equipment were put on the same place for every measurements, in order to register constant output data.

Chapter

4

INTERNATIONAL CASE STUDY & PRIOR STUDY

4.1 INTERNATIONAL CASE STUDY

The case study was undertaken to support the basic idea of the research. It was mainly concerned with adaptive solar facade (ASF) performance. Both of the projects explore the geometry and dynamic pattern of building surfaces and components in relation to solar radiation.

4.1.1 AL BAHAR TOWERS RESPONSIVE FACADE (AEDAS ARCHITECTS, ABU DHABI)

The dynamic nature of solar radiation angle make possible architects to look for adaptive skins which responds accordingly. The intense heat and glare in Dubai generates uncomfortable indoor environment which is harsh to work without air conditioning. For Abu Dhabi's newest pair of towers, **AEDAS architects** have designed a responsive facade which takes cultural cues from the "mashrabiya", a traditional Islamic lattice shading device.

Completed in June 2012, the 145 meter towers' Masharabiya shading system was developed by the computational design team at Aedas. Using a parametric description for the geometry of the actuated facade panels, the team was able to simulate their operation in response to **sun exposure and changing incidence angles during the different days of the year**.

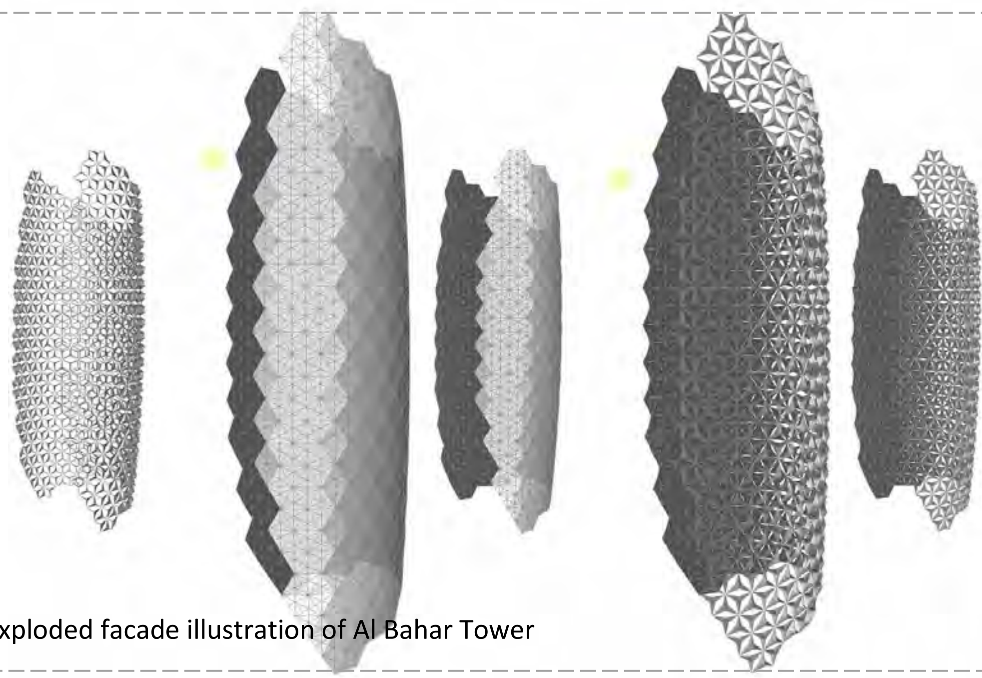


Figure 4.1: Exploded facade illustration of Al Bahar Tower

The screen operates as a curtain wall, sitting two meters outside the buildings' exterior on an independent frame. Each triangle is coated with fiberglass and programmed to respond to the movement of the sun as a way to reduce solar gain and glare. In the evening, all the screens will close.

Figure 4.2: Automated Opening and Closing illustration of shading system – real photo

The solar screen will reduce solar gain by more than 50 percent, and reduce the building's energy need for cooling. Plus, the shade's ability to filter the light has allowed the architects to use more transparent glass, which lets more light in and less need of artificial light and better views.

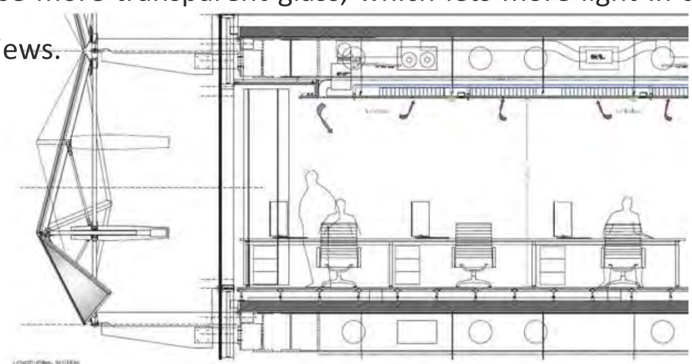


Figure 4.3: facade section and shading components' photo

For the project's sustainable engineering and sensitive cultural and urban approach, the towers were awarded the 2012 tall building innovation award by the Council of Tall Buildings and Urban Habitat. The facade on Al Bahar, computer-controlled to respond to optimal solar and light conditions, has never been achieved on this scale before. In addition, the expression of this outer skin seems to firmly root the building in its cultural context.

4.1.2 B5 BUILDING (BARRECA & LA VARRA STUDIO, MILANO, ITALY)

The B5 Building is located in the north-eastern outskirts of Milan. The facade, one of the main design elements, is composed of vertical alternating shades of white, gray and black, staggered in respect to the adjacent floors of the buildings. The glass panels sometimes appear transparent and other times opaque, depending on the light. Windows are placed between the opaque glass elements, and a shading system, perpendicular to the facade, is incorporated. Designed as a "class A" (the equivalent of a LEED platinum) certified structure.

Figure 4.4: Exterior facade view of B-5 building

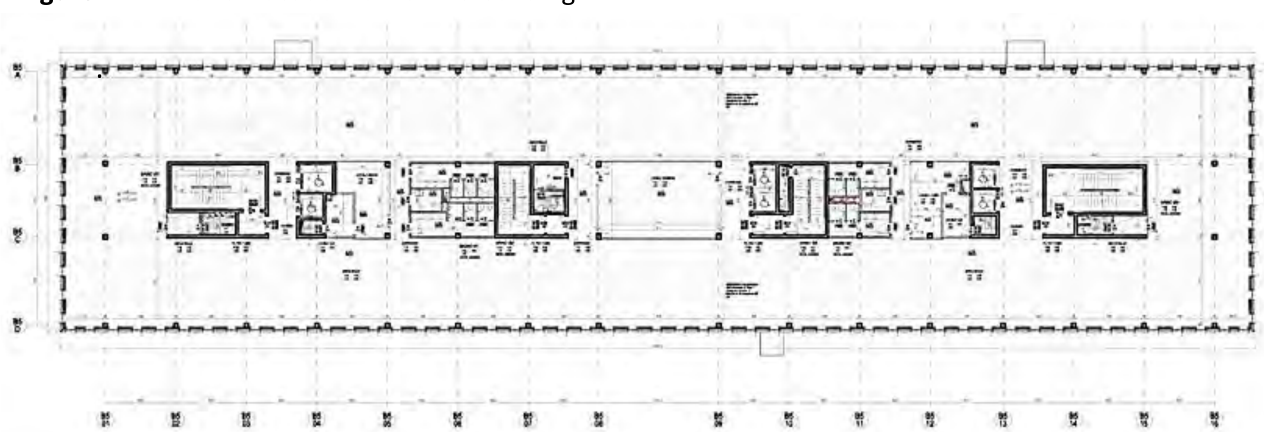


Figure 4.5: Typical plan showing circulation core and pool office spaces.

The attempt was to define the facade in a greater sense than is usually required, creating a surface that is much more responsive to its surroundings. The surrounding cityscape and context are in fact reflected from the glass as if the building were able to "read" the site, tracing on its surface the history, ideas and stories that give the place its current shape.

Figure 4.6: Automated Opening and Closing illustration of shading system

The vertical elements create a 'color texture' for the exterior, resulting in a dynamic skin that shifts in its transparency depending on the time of day and available light. The new office building is surrounded by a collection of large scale structures but still faces a spacious inner court that serves as a free-flowing outdoor space between buildings.

Figure 4.7: Exterior facade view of B-5 building 4.2

PRIOR STUDY

Two intensive researches are selected and studied to investigate research toolboxes and methodologies during data collection and analysis process of the study. Both of the researches are concerned about indoor environmental quality such as, visual comfort, thermal comfort, air quality and acoustics and its relationship with human comfort and performance. The studies are held in USA and Hong Kong. These researches were also valuable for the study in terms of understanding comfort parameters and how human performance is related with the immediate work environment.

4.2.1 OFFICE BUILDINGS INDOOR ENVIRONMENTAL QUALITY (IEQ) RESEARCH, USA

Indoor Environmental conditions in USA was investigated on 29 office buildings which contained around 492 occupants. Participants filled out questionnaires to rate their satisfaction with indoor air quality, thermal, visual and acoustic environment and overall satisfaction with IEQ. The analyses were then performed to find the correlation between satisfactions with each environmental condition and the overall satisfaction with IEQ.

The result of the data analysis showed that, the highest correlation was found between the overall satisfaction with IEQ and satisfaction with air quality followed by satisfaction with thermal, visual and acoustics. The ranking of environmental conditions slightly differed between females and males. Women valued lighting higher than acoustics compared to men. Those sitting in the interior zone ranked lighting higher than thermal conditions compared with those sitting in the perimeter zone, who ranked thermal conditions higher than lighting.

4.2.2 OFFICE BUILDINGS INDOOR ENVIRONMENTAL QUALITY (IEQ) RESEARCH, HONG KONG

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China has investigated indoor environmental quality in different office buildings. The research has used subjective evaluation as a methodology to collect data from individual occupants. An air conditioned office building, which contained around 293 occupants, was investigated with its indoor environment. Participants judged satisfaction with air quality, thermal, visual and acoustic conditions and overall satisfaction with IEQ. The contribution of satisfaction with single environmental conditions to the overall satisfaction with IEQ was estimated.

Good IEQ (90% acceptance)—It represents a Grade 'A' office which has an indoor environmental performance better than average. It requires more attendance to achieve compliance with relevant standards for each of the basic IEQ components (air quality, thermal, visual and acoustic conditions).

Average IEQ (80% - 90% acceptance)—It represents an average grade office. It can normally be achieved by traditional competence when the appropriate standards for each of the basic IEQ components are complied with.

Bad IEQ (<40% acceptance)—this represents a below average grade office which is often the result of an investment plan based on assumption.

Satisfaction with the thermal environment was found to be the most important for overall satisfaction with IEQ, followed by satisfaction with air quality, noise and visual quality. If a particular environmental condition was judged to be more unacceptable, it contributed to a larger extent to overall satisfaction with IEQ.

Chapter 5

ANALYSIS AND INTERPRETATION

5.1 RESULTS

Daily and monthly discomfort period of the indoor environment is identified. The discomfort time interval of the day and duration of the month is generated out of the occupants' feedback and careful study of the simulation output.

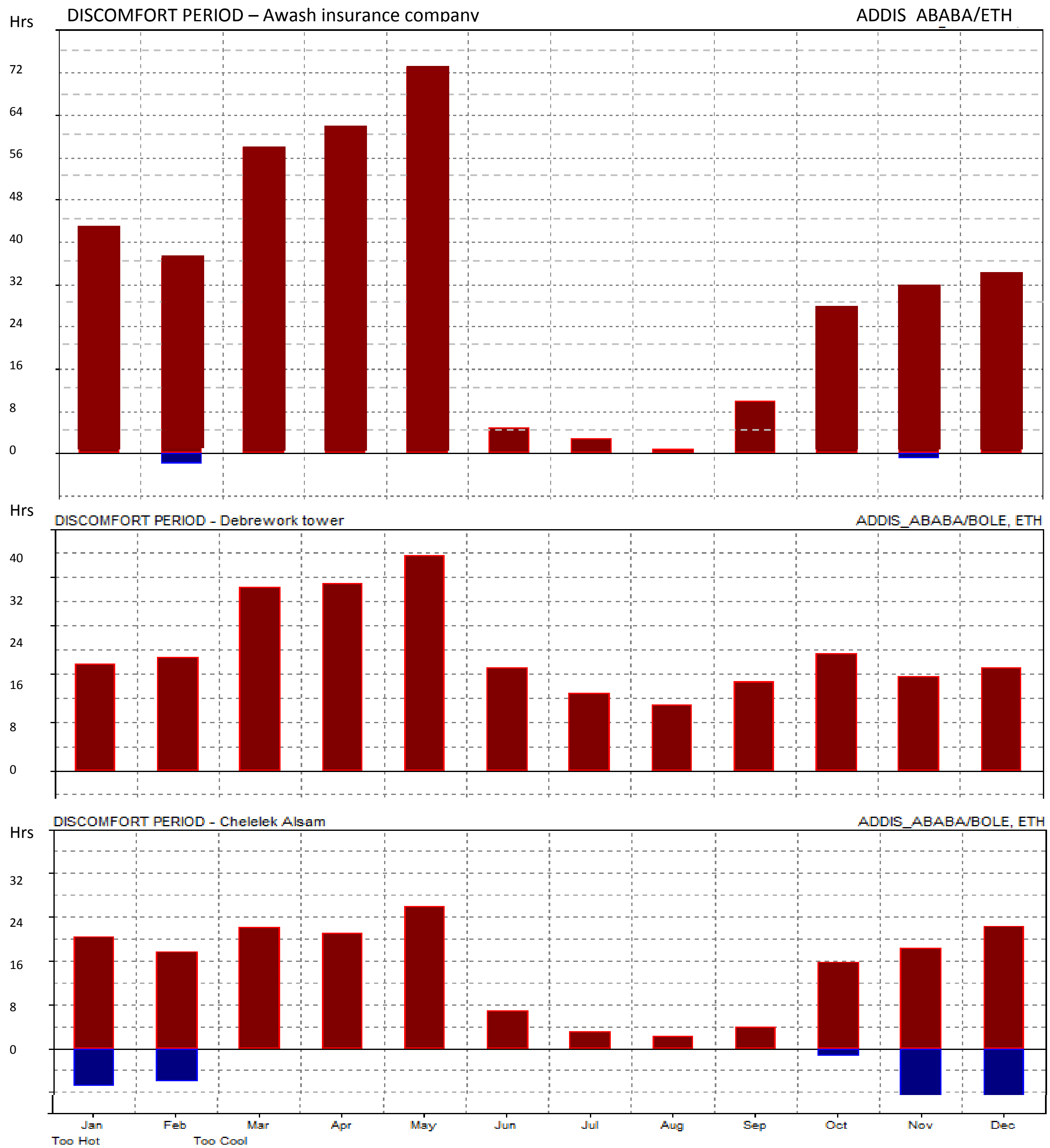


Figure 5.1: Monthly discomfort period comparison of three offices [Ecotect]

The thermal simulation is done considering two conditions. The first thing is **internal design conditions** such as clothing, lighting level, humidity, and air speed .These values are used to define indoor conditions in thermal comfort and lighting calculation. The second thing is **occupancy and operation** such as, number of people and activity (values for number of people and their average biological heat output), sensible and latent heat gain (values for both lighting and small power loads per unit floor area), and infiltration rate (values for the exchange of air between indoor and outdoor environment).

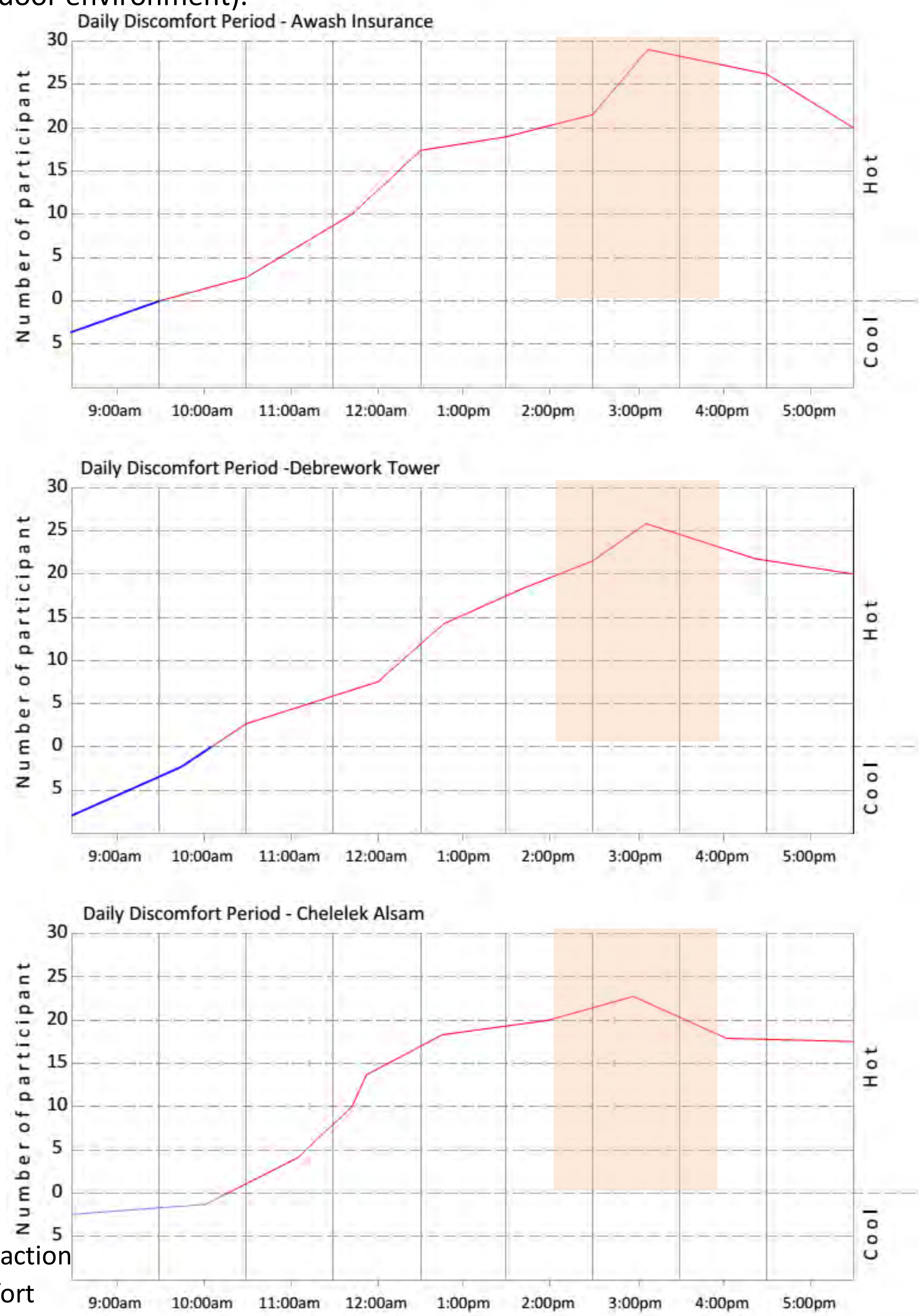
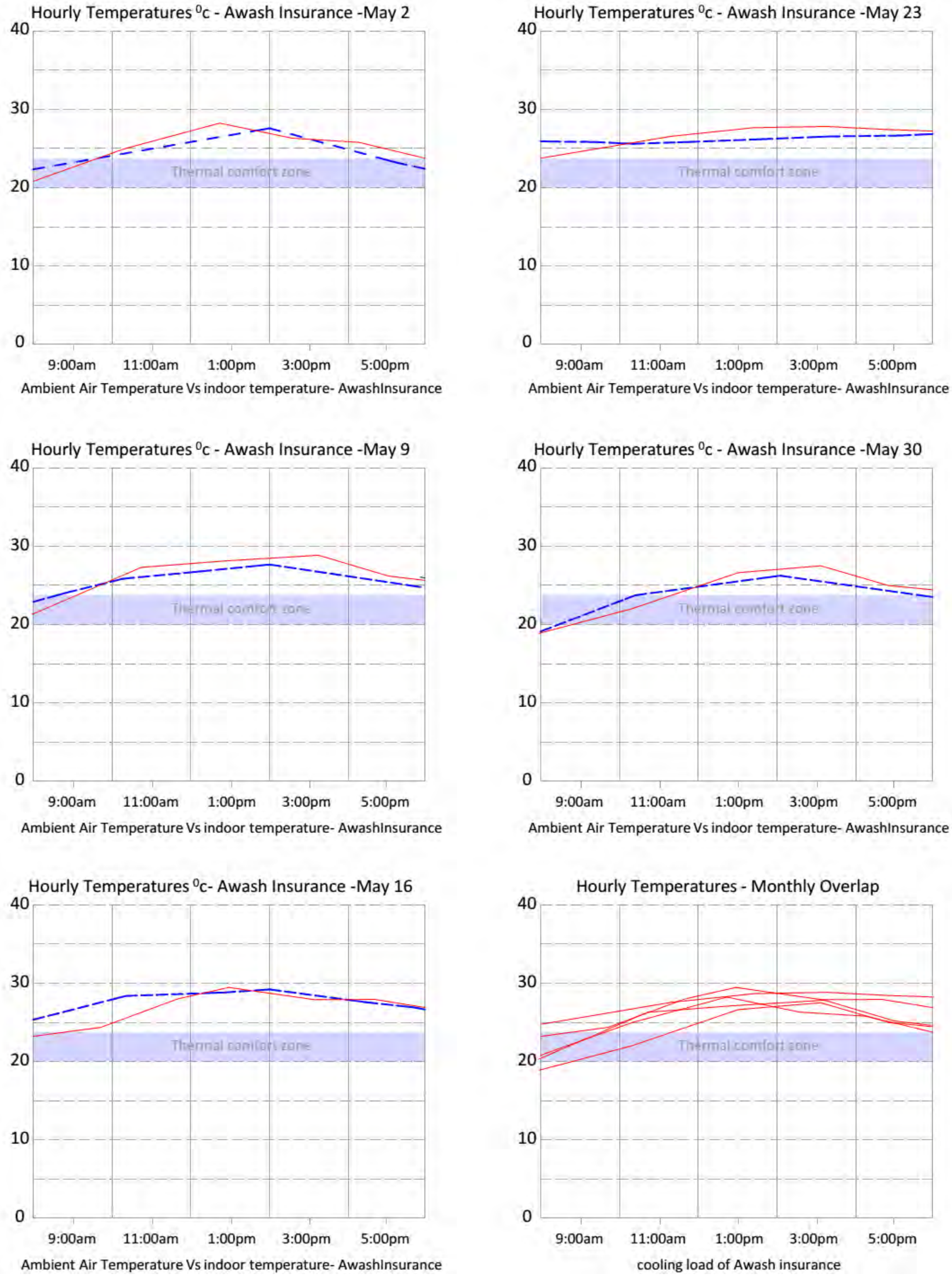


Figure 5.2: Occupants' reaction curve to thermal discomfort

STUDYING INDOOR AND AMBIENT AIR TEMPERATURE AT DIFFERENT TIME INTERVALS using temperature meter (Figure:5.3)



5.2 DISCUSSION

According to monthly indoor thermal environment analysis, **March**, **April** and **May** were found to be the hottest months of the year in all of the sampled office buildings. Of all the three, **May** was found to be the hottest month of the year with average discomfort period of **46hrs.** of total 180hours of occupancy. When this hour is divided by 8 (which is average daily occupancy),it becomes about **6 days of discomfort period** out of 22 days of monthly occupancy.

Of all the three sampled offices, **Awash Insurance** was found to be in the risk of long discomfort period. In one year of occupancy, (which is about 180hours x 10 months = 1800hours), there is **390hrs. (48 days) of discomfort period**. Debrework Tower has **300hrs. (37 days)** of discomfort period. Chelelek Alsam building exceptionally has both too hot and too cold situations. For the hot months, it has about **138hrs. (17days) of discomfort period**. For the cold months, it has 24 hrs. (1day) of discomfort period.

The questionnaire is also analyzed to evaluate occupants' feedback about the hot and cold months of the year and average discomfort time interval of the day. For each sample offices, 3 floors are selected with 10 participants each. 30 people are participated in each sample buildings. Total number of participants is around **90 persons** of which 65 are male and 25 are female. The analysis graph above shows that the time interval between 2:30 pm up to 4:30 pm is susceptible to overheating.

According to the simulation result and questionnaire feedback, the afternoon session from 2:30 pm up to 4:00 pm is taken as discomfort period of the day. During this time interval, the sun moves from east to west which as a result makes the west and south facade of the buildings vulnerable to direct solar radiation. The facade of the buildings, namely, Awash and Chelelek, are more than 90% glazed on their west and south facade. Whereas, Debrework tower is 60% glazed which somehow reduced the amount of direct radiation. All of the buildings use internal shading which is made of plastic fibers. The risk of glare is also observed during windy days because of the flimsy nature of shading devices.

Subjective evaluation was used as a methodology to collect data from individual occupants. The ranking of indoor thermal environmental conditions slightly differed between female and male, and between perimeter and interior zones. Women valued natural lighting higher than overheating. 78.33% of the participants dissatisfied with the thermal environment, 13.33% are comfortable, and 8.33% did not notice the thermal environment.

The luminance level, which strongly relate to the illumination level inside the space, became more intensive towards the perimeter. 44% of the participants complained about the visual environment. Too much light contrast is observed towards the perimeter whereas the interior zone showed up too dark. Due to this, artificial light is used in the interior zone of the open floor office space in order to balance the light distribution.

During outdoor environment analysis, out of 30 drivers, 80% valued the risk of glare because of reflective glass facades and the rest 20% did not noticed the issue of glare.

Finally, computer simulation and questionnaire results were compared with Quantitative measurements of indoor air temperature and light intensity. However, the measurement varied with change of different parameters that contribute to internal heat generation, such as number of occupants, and time of the day. However assuming full occupancy, and equipment operation, the result showed relatively similar values with the computer simulation outputs.

5.3 DESIGN GUIDE LINE

This guideline is basically prepared to assist architects and planners in the early stage of the design process. It overviews major design considerations and strategies for radiation vulnerable streets and buildings in Addis Ababa. Moreover, the document hierarchically elaborate checkpoints from the general urban setup level up to detail fenestration design, glass material selection and shading device types and solar angle calculation strategies.

5.3.1 URBAN SETUP, SITE CONDITIONS AND ORIENTATION

- Consider the orientation of the streets and the building facade, which are likely to have the greatest solar exposure during critical hours. In most cases, these should be located towards the south and west side of the building.

- The orientation of the building should be North West / south east for the long facades. However, it could be slightly rotated either direction in order to allow dominant East west winds to improve natural ventilation without compromising the optimal orientation advantages.

- Calculate solar access analysis of the site using either a computer model of the site or by using a sun path diagram in order to understand the effect of neighborhood buildings on the site.

5.3.2 ROOM LAYOUT

- Areas of a building that has similar program should be grouped together so that areas of similar solar gains can share common design strategies.

- A daylight-optimized interior design shall consider furniture material, placement, and room surface finishes with respect to daylight performance.

- Office partition heights must be limited, and walls and ceilings shall be as highly reflective as possible, to help bounce and distribute the redirected daylight.

- By positioning work surfaces parallel to the building envelope, direct exposure of radiation on to occupants view direction shall be avoided.

5.3.3 GLAZING PROPORTION

- The simplest method to maximize daylight within a space is to increase the glazing area. However, architects and engineers shall understand at least two glass characteristics, namely U-value and Shading coefficient in order to optimize a fenestration systems. U-value which represents the rate of heat transfer due to temperature difference through a particular glazing material and Shading coefficient which represents the thermal performance of the glass material must be understood.

- Glazing should be as clear as possible and non-reflective to promote transparency and visibility. Non reflective coatings are acceptable to reduce heat gain while allowing in natural daylight.

- A selective use of transparency at key locations such as ground floor, entrance area and public spaces could be integrated in order to create a welcoming and legible built environment.

- Optimize window-to-wall area ratios per solar orientation to maximize daylight entry while avoiding overheating and glare. Provide total glazing areas per elevation within the following optimum percentages. (Remark: “wall” in this study represents opaque geometry which is optimized based on critical solar angles in order to shade the building.)

South orientation: 40% - 60% window to wall ratio (WWR)

North orientation: 60% - 85%

West orientation: 35% – 55%

East orientation: 55% - 75%

The above percentage is roughly calculated based on daily and annually solar exposure of a model building facade. The glazing percentage values differ due to various use of shading devices geometry and different performances.

5.3.4 GLAZING TYPE AND SHADING COEFFICIENT

The thermal performance of a glass building is determined by its shading coefficient. The value indicates how the glass is thermally insulating (shading) the interior when there is direct sunlight on the panel or window. It is a value ranging from 1.00 to 0.00.The lower the rating, the less solar heat is transmitted through the glass, and the greater it's shading ability.

GLASS TYPE	**SHADING COEFFICIENT**
Glass + frame	
Single**, clear**	0.69 – 0.73
Bronze	0.53 – 0.62
Green	0.50 – 0.61
Gray	0.48 – 0.60
reflective	0.17 -0.28
Double**, clear**	0.60 – 0.70
Bronze	0.43 – 0.53
Green	0.40 – 0.52
Gray	0.38 – 0.51
HP green	0.33
Reflective	0.12 – 0.20
Double **– low E ,clear**	0.32 – 0.60
Bronze	0.23 – 0.48
Green	0.27 – 0.47
Gray	0.21 – 0.46
HP green	0.25 – 0.39

Shading coefficient for typical windows (ASHRAE, 1997)

Low – emissivity glass: Radiant energy is one of the important ways heat transfer occurs with windows. Low-e coatings have been developed to minimize the amount of ultraviolet and infrared light that can pass through glass without compromising the amount of visible light that is transmitted. Therefore, reducing the emissivity of one or more of the window glass surfaces improves a window's insulating properties.

Solar control glass: Solar control glass is a high performance coated product that reflects and radiates away a large degree of the sun's heat while allowing daylight to pass through a facade. Solar control glass incorporates invisible layers of special materials which have the dual effect of allowing sunlight in, while repelling solar heat.

5.3.5 EXTERIOR SHADING AND SOLAR CONTROL DEVICES

- In an attempt to incorporate daylighting into a building, designers often make the mistake of simply increasing the glazing area as much as possible. Unfortunately, Large, unprotected areas of glazing can lead to discomfort to occupants through glare, and high solar gains. As glare effects vary over time and location, the ideal shading strategy should be relatively flexible and allow the building users to adjust the shade to suit the immediate situation.

- Exterior shading devices are preferable due to its capability in heat gain reduction and natural light diffusion before entering the work space.

- Selection of shading materials must consider materials reflective behavior, availability, ease of construction and cleaning.

South and north facade: generally vertical shading devices are more effective with little intervention with horizontal shading components.

East and west facade: generally horizontal shading devices are more effective with little intervention with vertical shading components.

Chapter

6

DESIGN PROPOSAL

6.1 INTRODUCTION

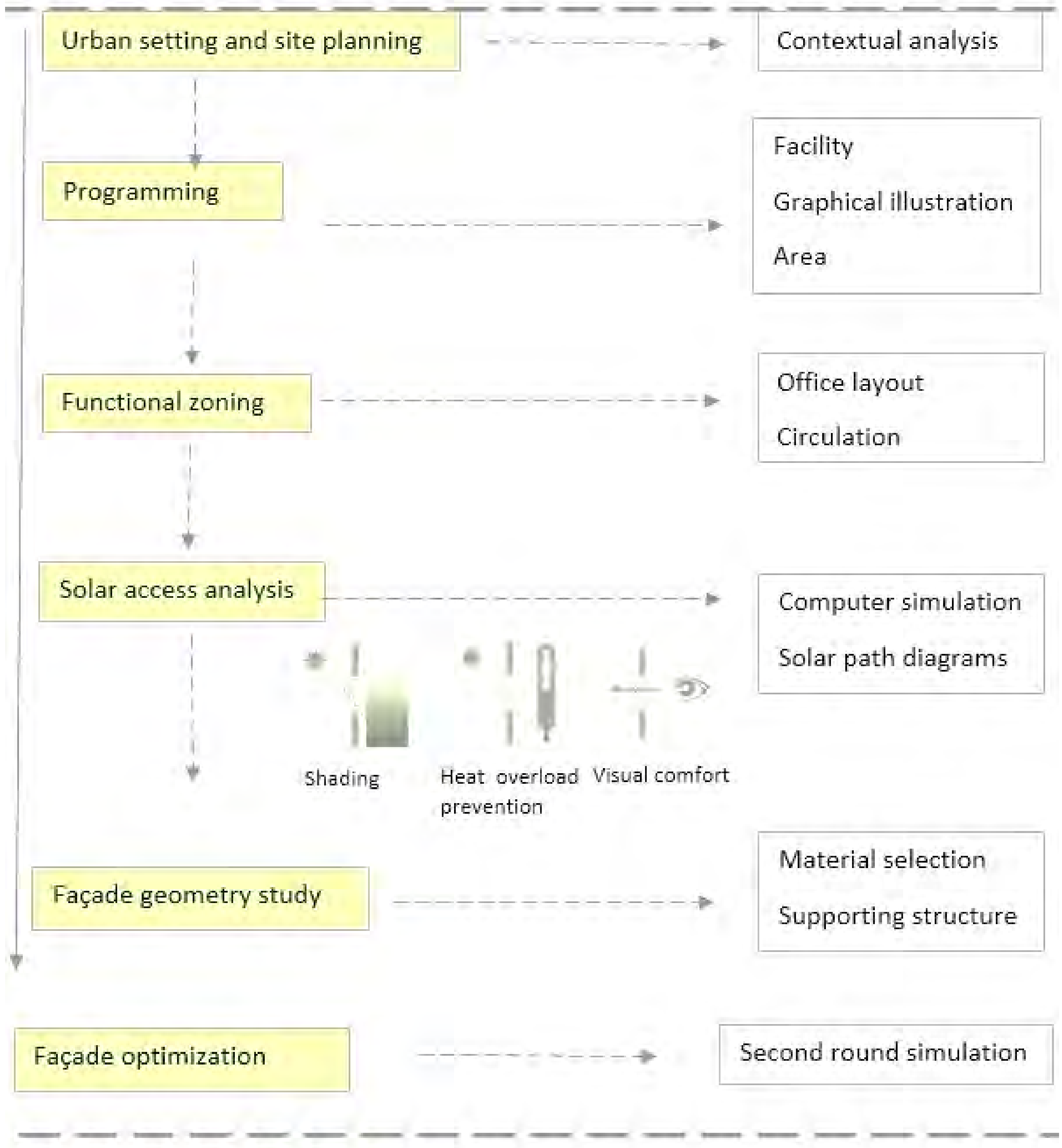
After analyzing the lack of research environment for architects and engineers in the building design and construction industry, a research lab and prototype fabrication building is proposed. The building accommodates architects, engineers, and other related professionals in multi-layer spaces to facilitate research and communication culture in the design and building fabrication process. The culture of research brings alternative and critical approaches to the production of knowledge. Such contextualized, experimental, and practice–based traditions have profound implications to understand and utilize local resources such as solar energy, pursuing sustainable architecture.

The design is proposed in the emerging central business district (CBD) area of Addis Ababa. The site is located near Mexico square, adjacent to the temporary taxi station. This location is primarily selected due to its vulnerability to harsh sun radiation even though it is visible and accessible from different points of the city. The longer face of the site is oriented to the west and east while the shorter side is to the south and north. The site is tilted 6^0 from north which makes it more susceptible to harsh sun. Streets with different orientation potentially affect the way the facade behaves in relation to drivers and pedestrian movement. The site has total area of 3,000m2, of which 1,150 m2 is built up area and around 14,000m2 of floor area.

6.2 DESIGN TASK

The proposal is intended to introduce an alternative local design strategy for envelope fabrication based on solar analysis. This parametric design process, unlike common design trends of fully glazed facade systems, wisely study the behavior and pattern of solar angles and paths. The facade, as interface between the interior and exterior environment, creates multitude patterns and geometry in response to different angles of solar exposures to facilitate visual and thermal comfort of occupants. In addition to radiation, the facade also responds to different street orientations and indoor seating arrangements. A design program is developed and a schematic office layout is produced in order to study solar path diagram and develop solar access analysis based on climatic data of Addis Ababa. Then, the solar analysis leads to facade design concepts which could be further developed through design program and special interest.

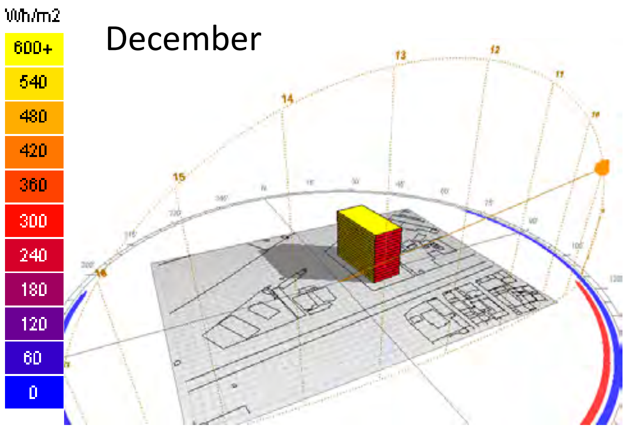
Design process

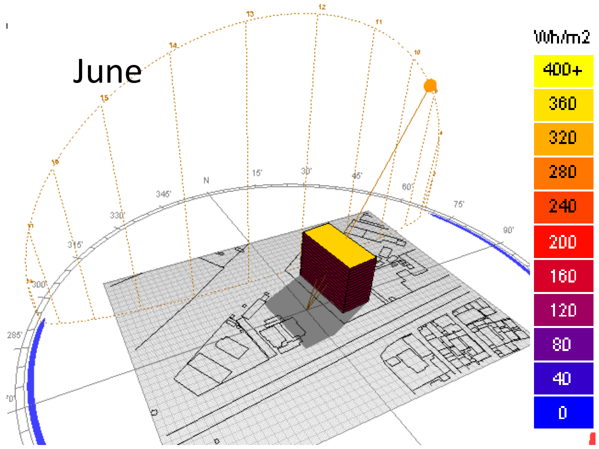


6.3 PROGRAMMING

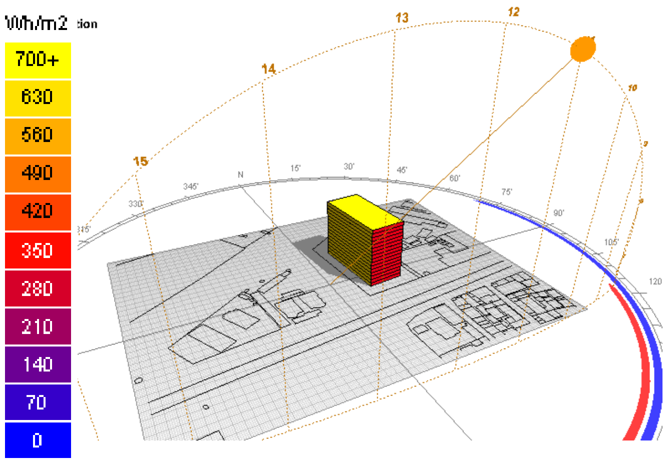
Story	Program	Area/m²	Category
Basement floor	parking	1150	Service
	Storage space	200	
	Machine room	50	
	Toilet and Janitor room	30	
Ground floor	Temporary exhibition space	400	Commercial
	Shopping hall	450	
	Plaza/outdoor display		
	Storage space	150	
	Lounge	200	
1st floor	Temporary exhibition space	500	Commercial
	Shopping hall	450	
	Storage space	600	
2nd floor	Presentation space	270	Research platform
	Research space	350	
3rd floor	library	210	
	Archive	250	
4th floor	Training center	400	
5th floor	office	500	
	Toilet & Janitor room	40	
6th floor	gallery	550	office & Entertainment
7th – 12th floor	Rental office	4800	
	Cafeteria /lounge	400	
13th floor - 15th floor	Restaurant	500	
	cafeteria	500	
	VIP rooms	500	

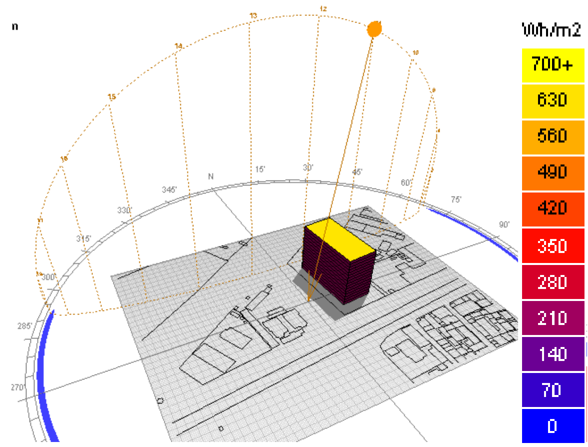
6.4 DAILY SOLAR ACESS ANALYSIS AND COMPARISON (December and June) – 9:00am



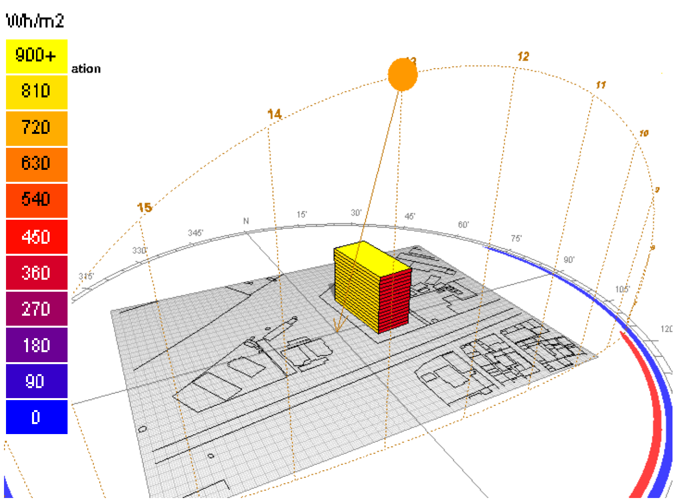


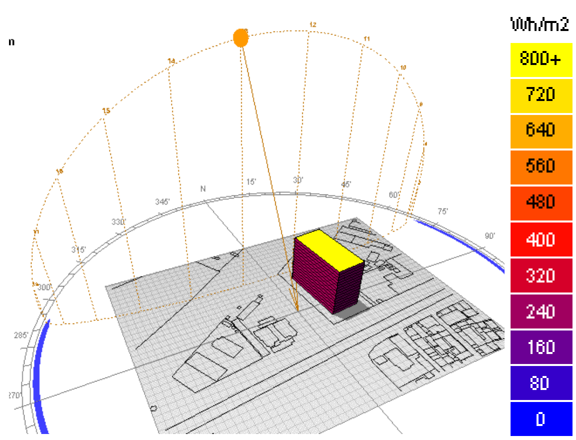
December and June – 11:00am



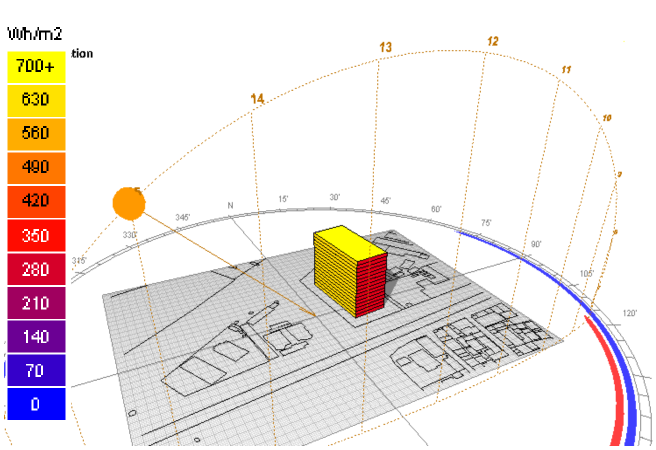


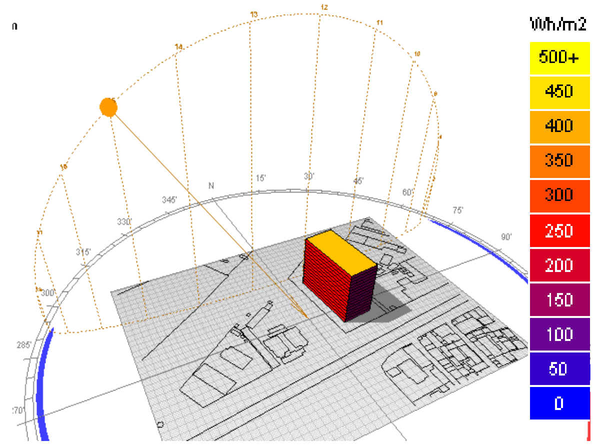
December and June – 1:00pm



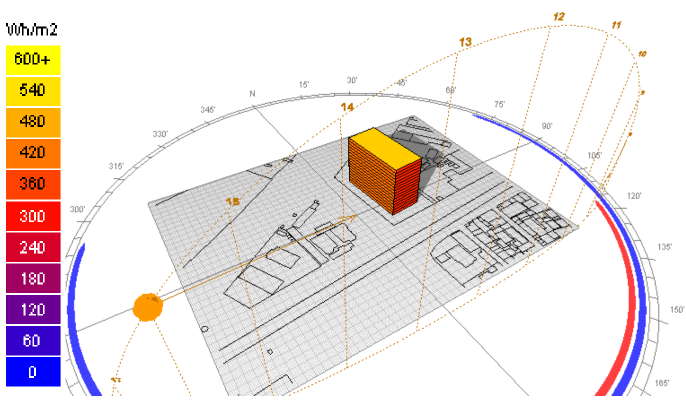


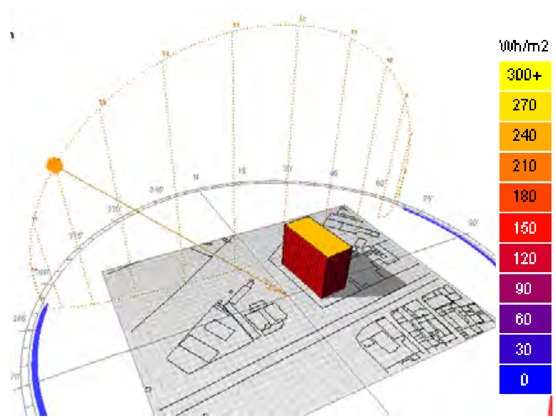
DAILY SOLAR ACESS ANALYSIS AND COMPARISON (December and June) – 3:00pm



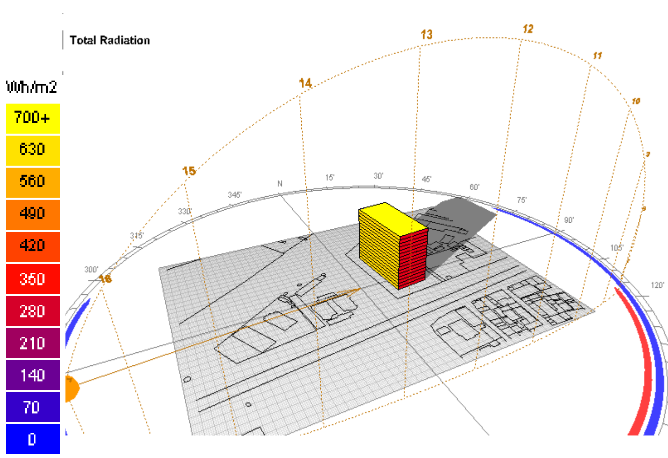


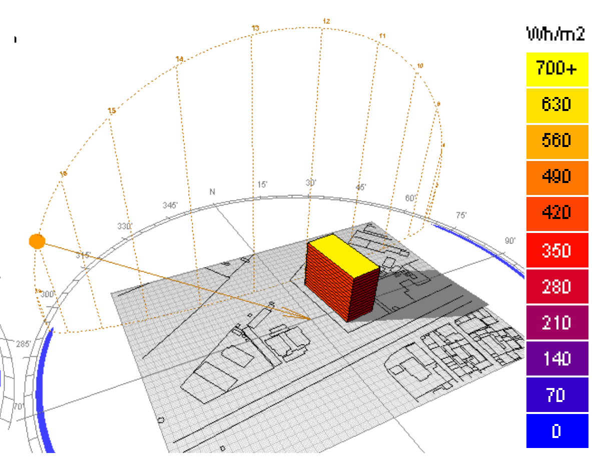
December and June – 4:00pm



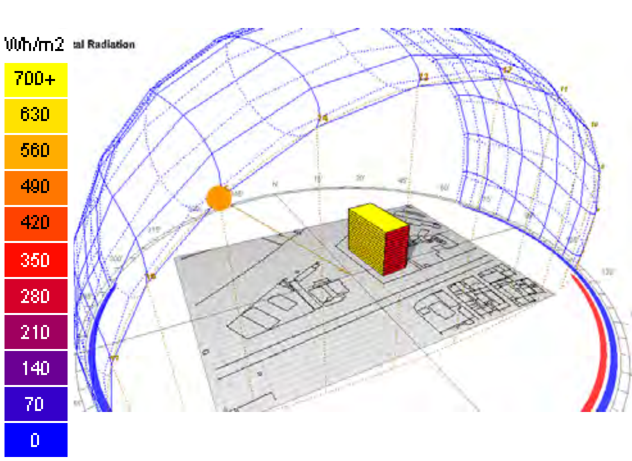


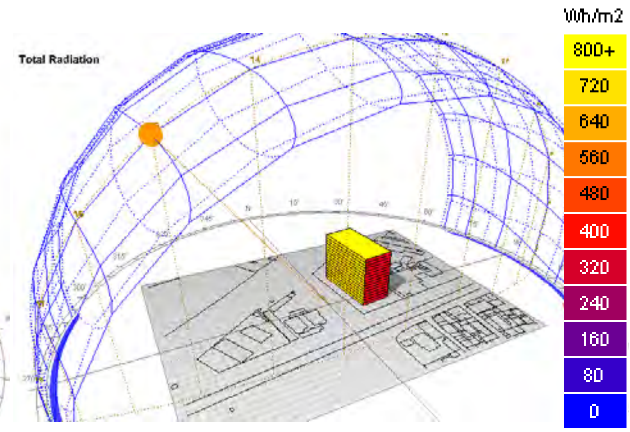
December and June – 5:00pm



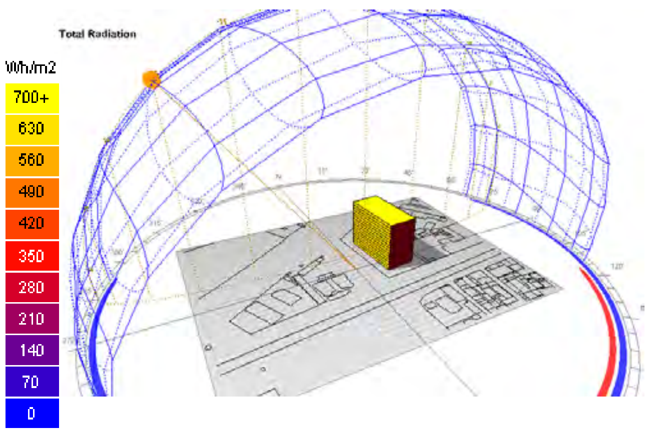


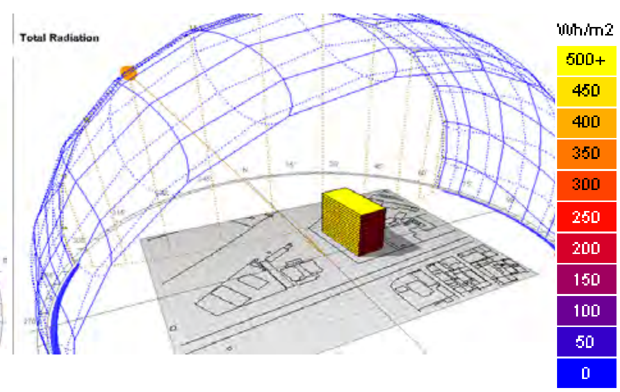
MONTHLY SOLAR ACESS ANALYSIS AND COMPARISON – January, March - 3:00 pm





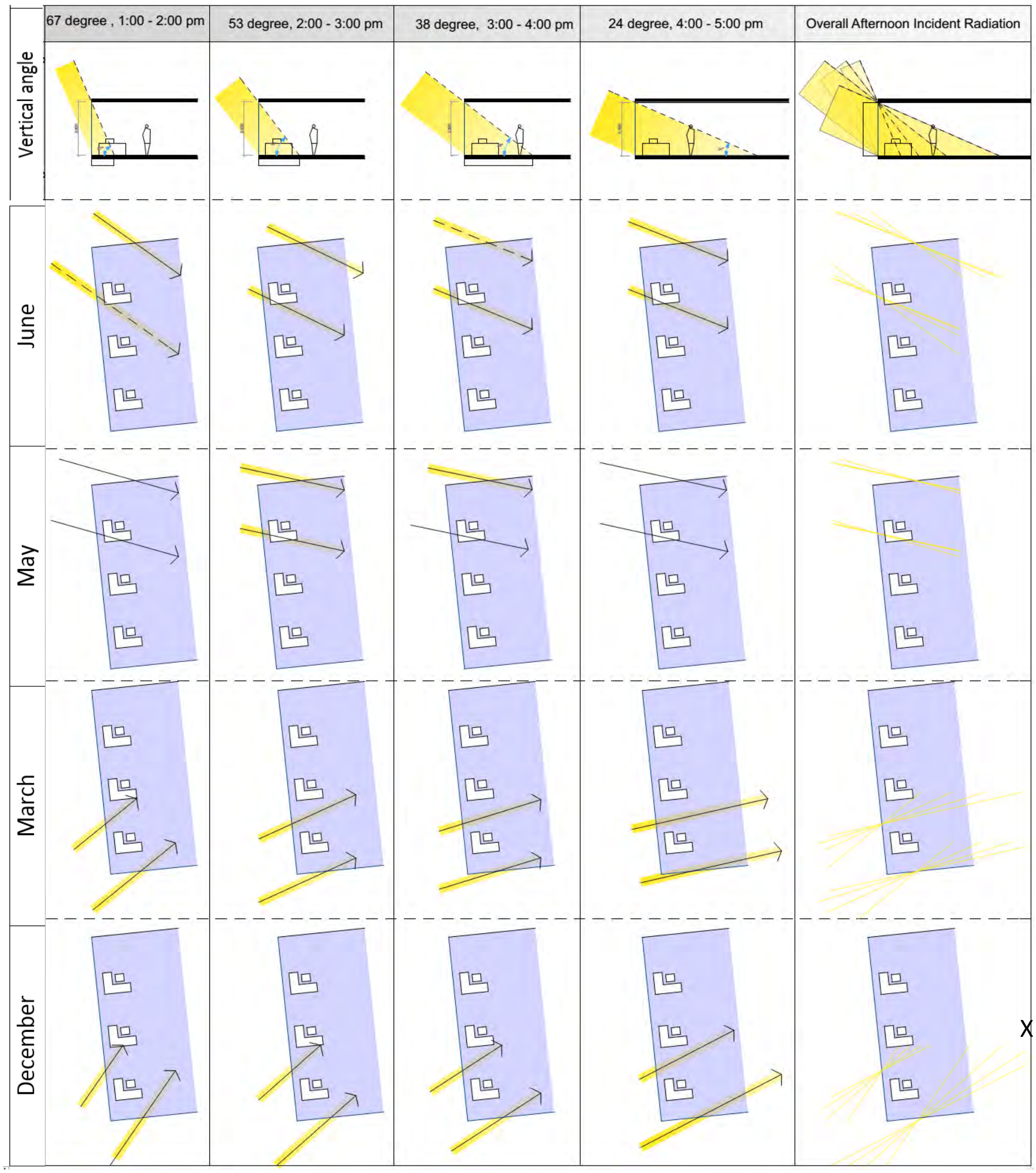
May, July - 3:00 pm





6.5 SOLAR ANALYSIS AND FACADE INTERPRETATION

The solar path diagram is well studied to investigate critical hours and days as well as to understand the position of sun in relation to the building orientation. Every other month is analyzed to find out critical vertical and horizontal component of solar ray.



Daily and monthly incident radiation of Addis Ababa

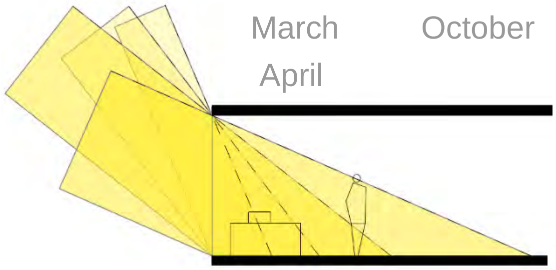
SOLAR ANALYSIS AND FACADE INTERPRETATION

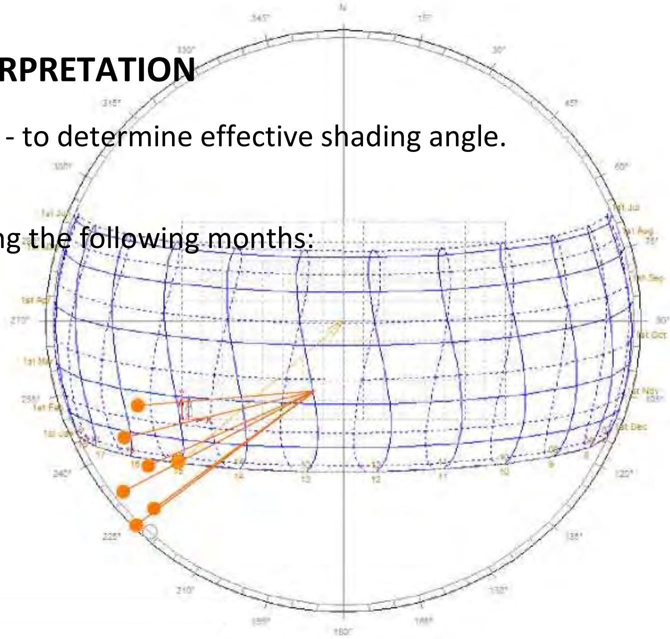
CRITICAL SOLAR ANGLE ANALYSIS (SOUTH) - to determine effective shading angle.

FROM 1:00 pm - 5:00 pm

Solar radiation protection from south during the following months:

January December
February November
March October
April

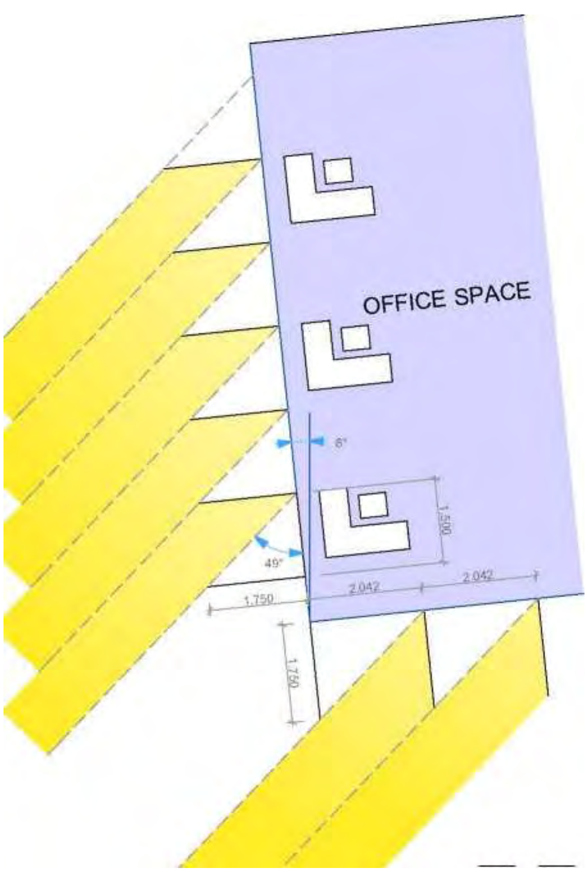




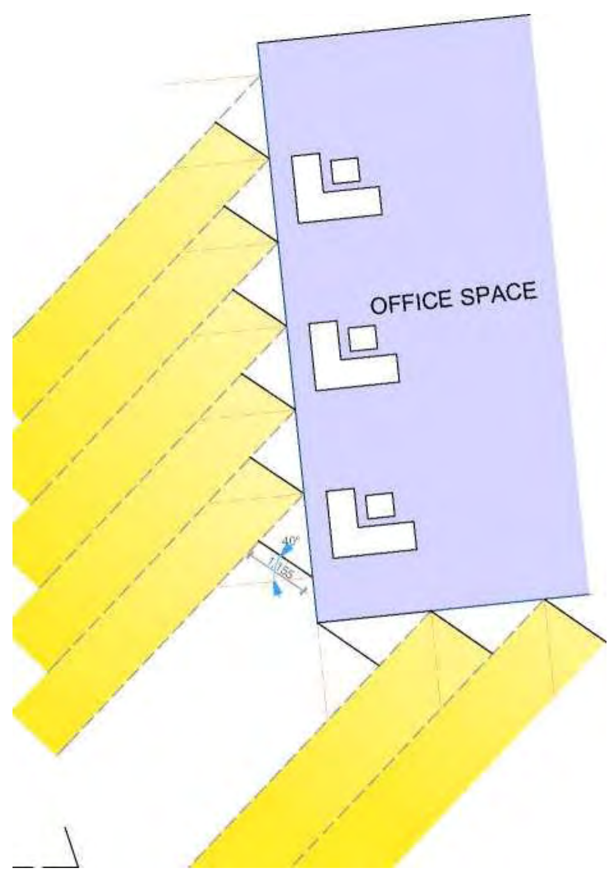
Vertical shading device size and spacing is calculated based on critical solar angle from south. The result shows that for the west facade, the devices shall be 1.75m long with 1.5 m spacing to protect direct light penetration. For the south facade, the devices shall be 1.75m long with 2m spacing.

Shading Device Optimization Strategy: The device is rotated 40^0 towards north in order to shorten the length from 1.5m to 1.15m as well as reduce the span to 0.9 m.

Initial shading device



optimized shading device

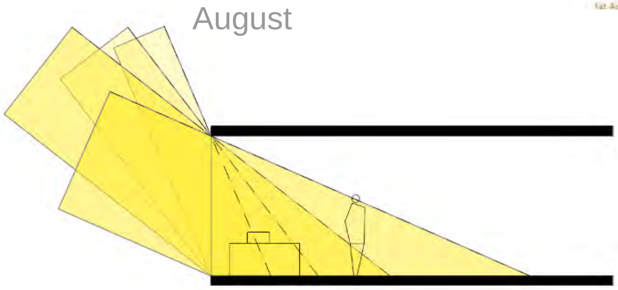


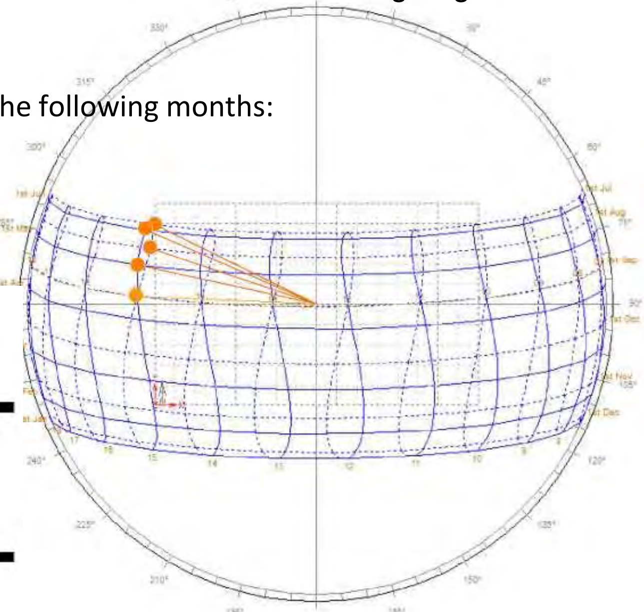
CRITICAL SOLAR ANGLE ANALYSIS (NORTH) - to determine effective shading angle.

FROM 1:00 pm - 5:00 pm

Solar radiation protection from North during the following months:

May September
June
July
August



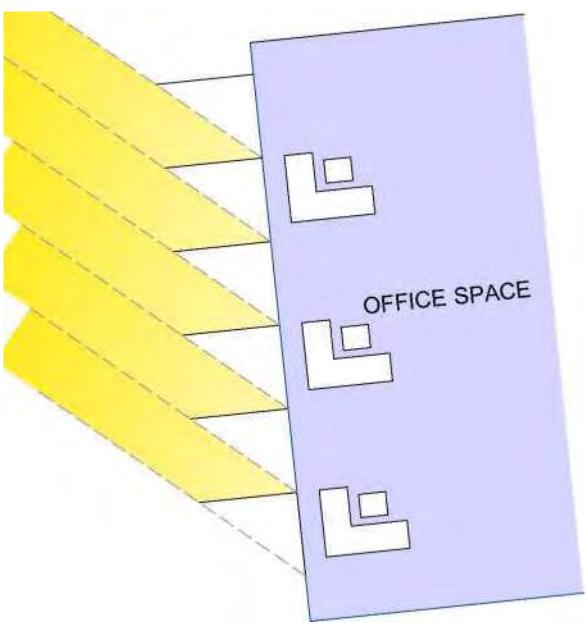


Vertical shading device size and spacing is calculated based on critical solar angle from North.

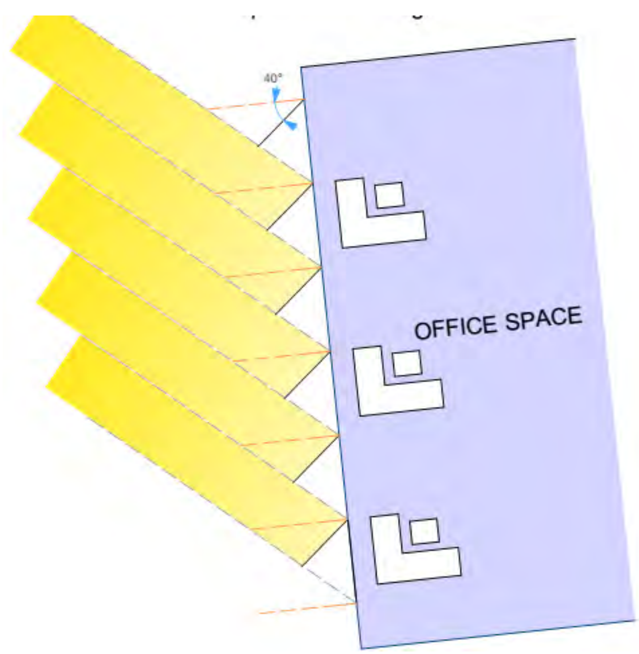
The result shows that for the west facade, the devices shall be 1.75m long with 1.5 m spacing to protect direct light penetration. The south facade is in the shade zone during this season due to the building orientation.

Shading Device Optimization Strategy: The device is rotated 40^0 towards South in order to shorten the length from 1.5m to 1.15m as well as reduce the span to 0.9 m.

Initial shading device



Optimized shading device

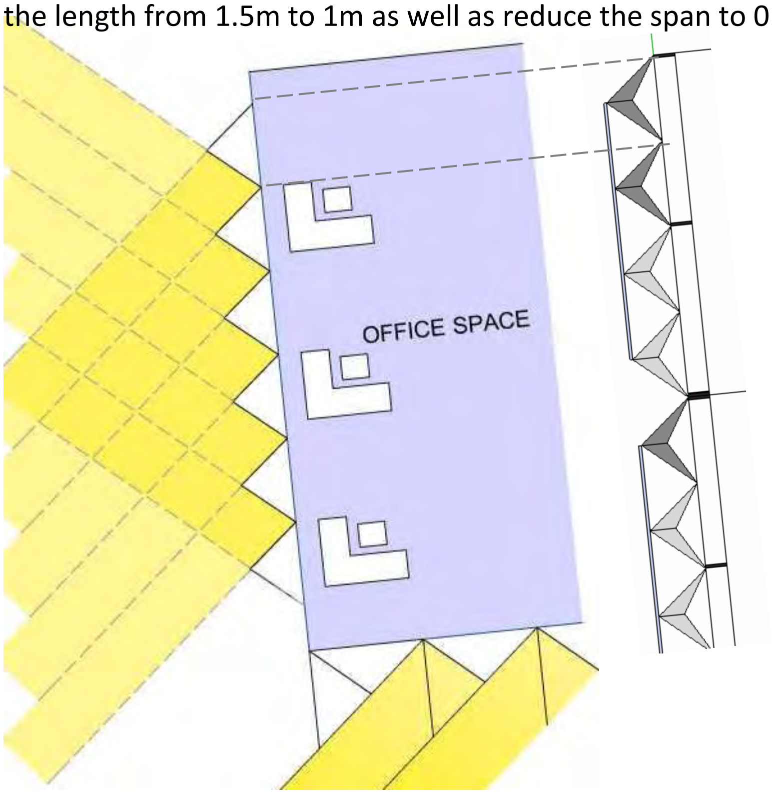


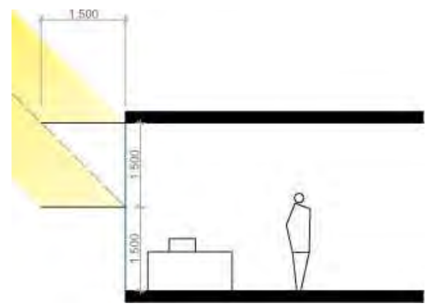
FROM 1:00 pm - 5:00 pm

Annual Solar radiation protection from North and South direction.

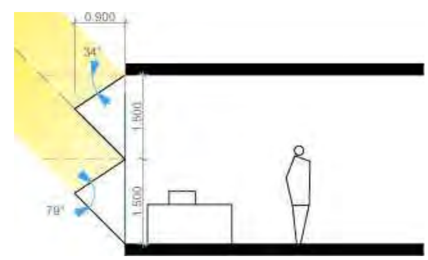
Horizontal shading device size is calculated based on critical solar angle. The result shows that for the west facade, effective shading devices shall be 1.5m long with 1.5 m spacing to protect direct light penetration.

Shading Device Optimization Strategy: The device is rotated 34^0 downward in order to shorten the length from 1.5m to 1m as well as reduce the span to 0.9 m.

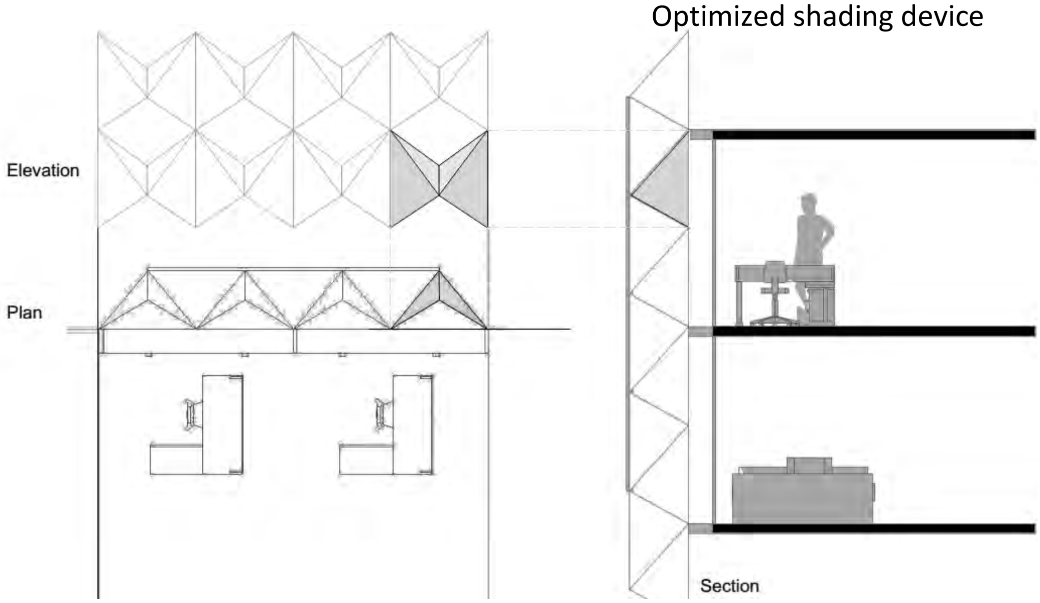




Initial shading device

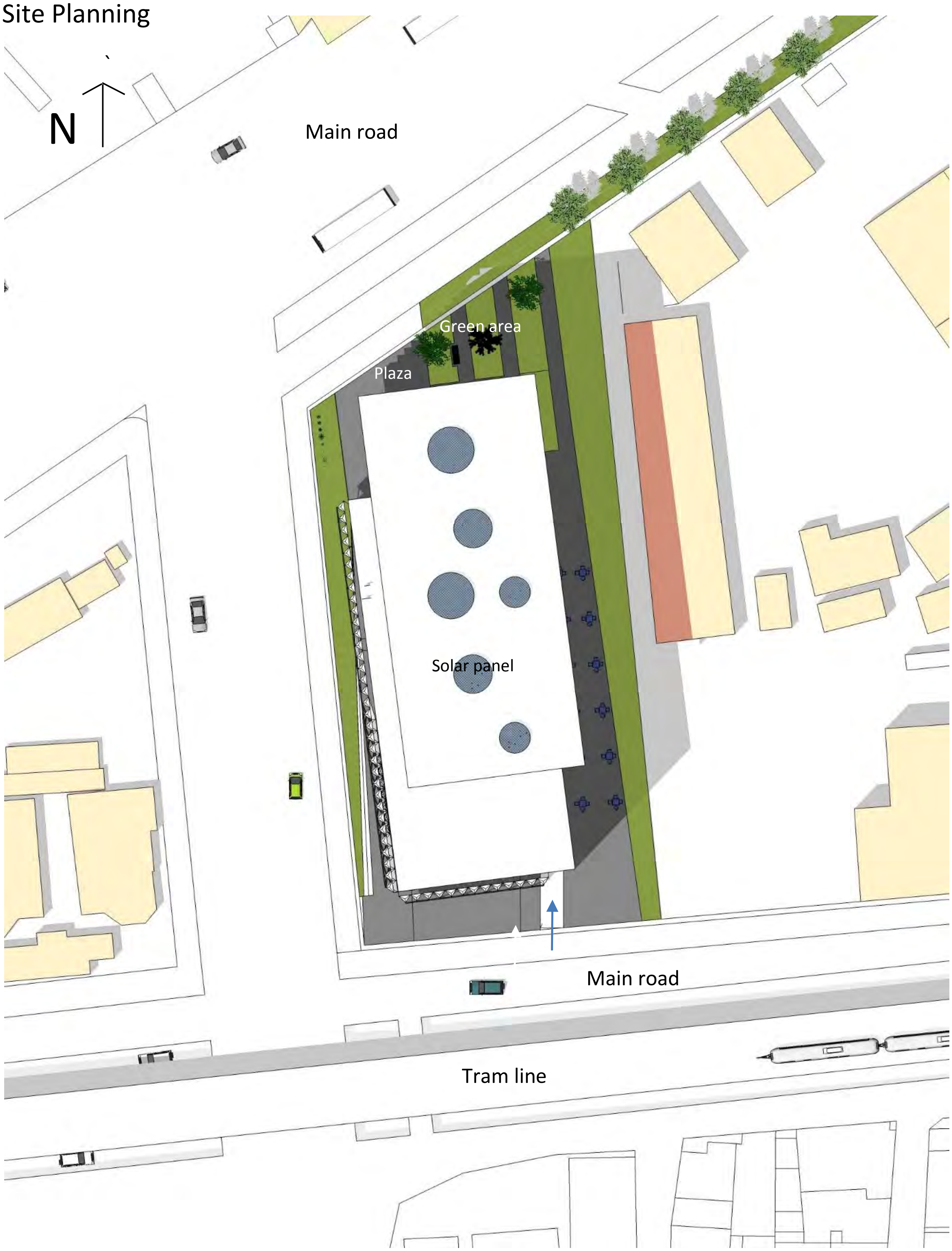


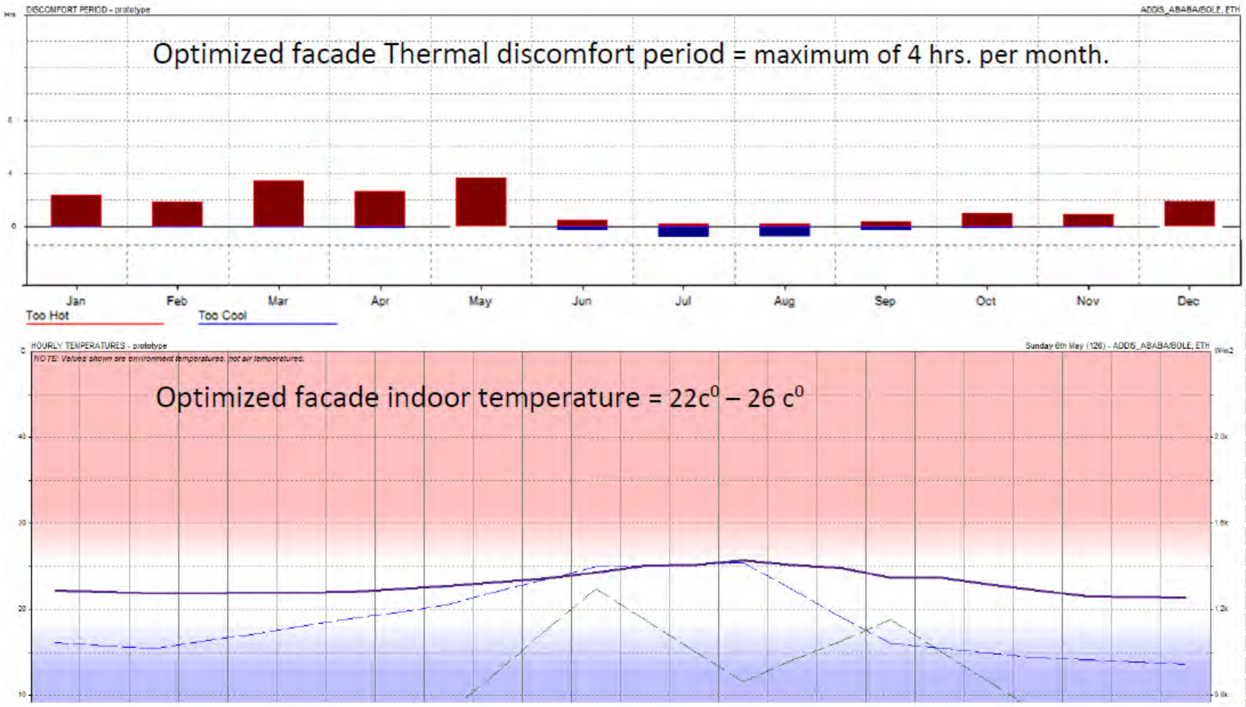
Optimized shading device



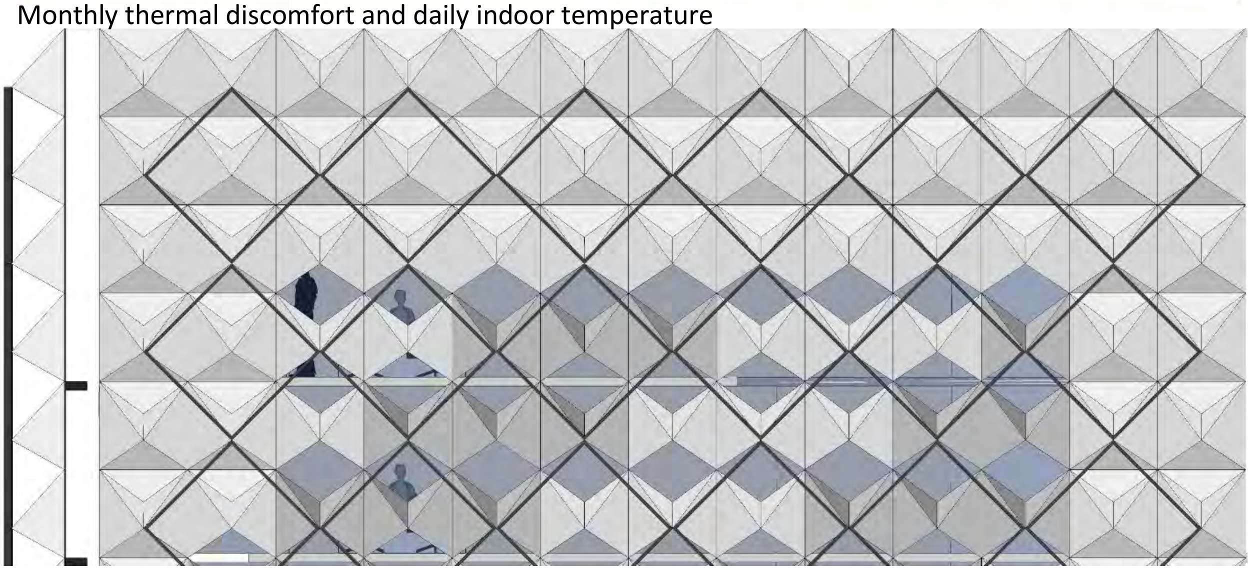
6.6 DESIGN OUTPUT

Site Planning



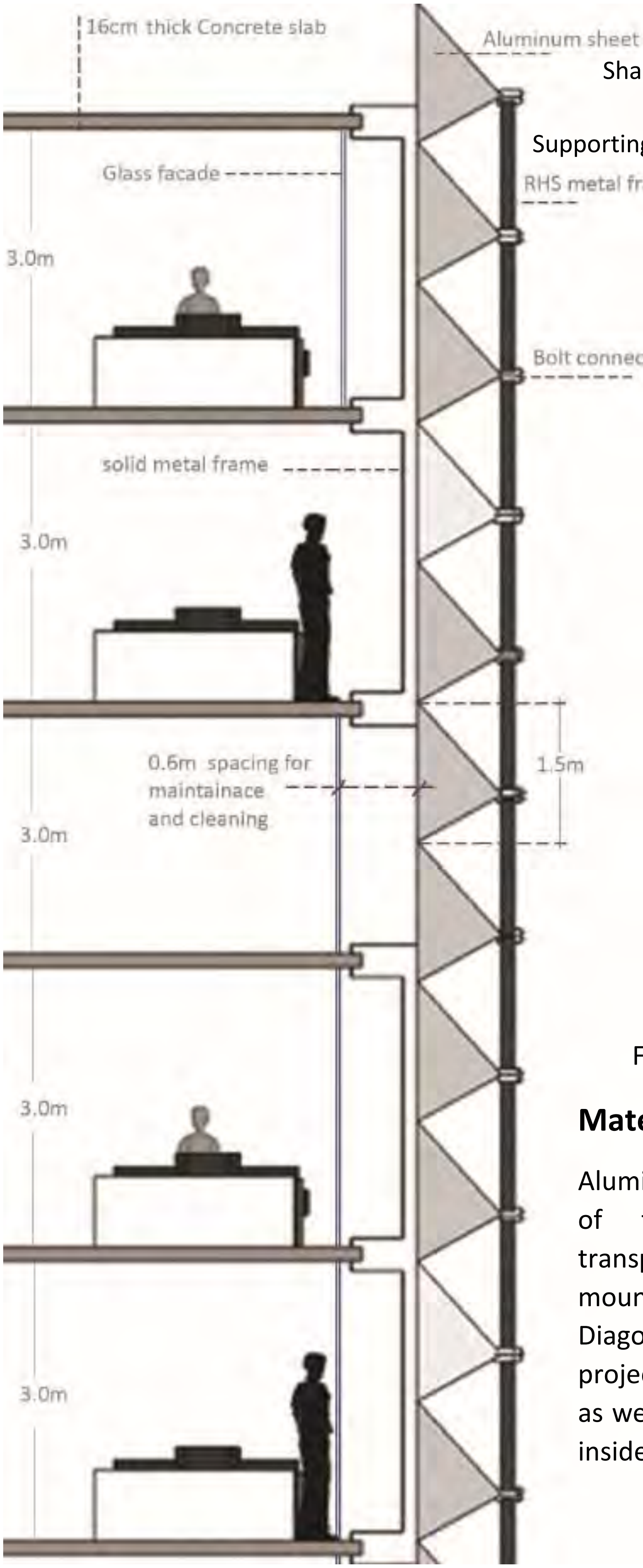


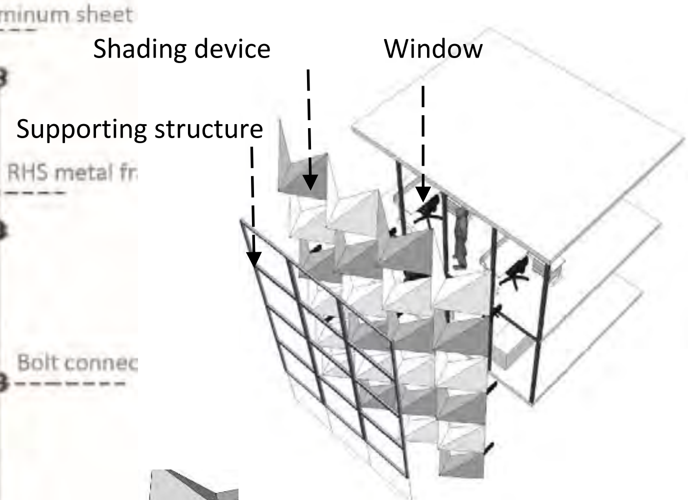
Monthly thermal discomfort and daily indoor temperature

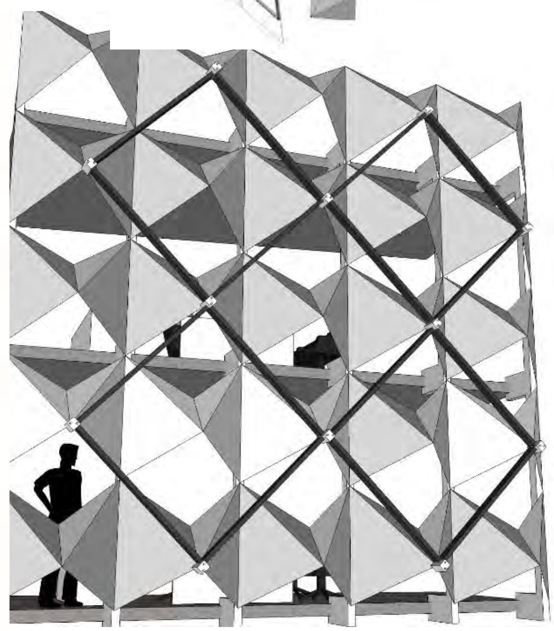


Exterior view of proposed facade

The openness and closeness of the components relies on the interior program and time of the day, even if the proposed geometrical configuration was set for the critical hours (2:30 pm- 4:00pm in the afternoon). The performance of the proposed skin geometry is tested in terms of direct radiation protection. Even if, the skin covers only 55% of the total façade surface, it protects 80% of direct solar radiation while allowing diffused light and view to the outside. This optimization is brought through solar path study during those critical hours and days of the year.





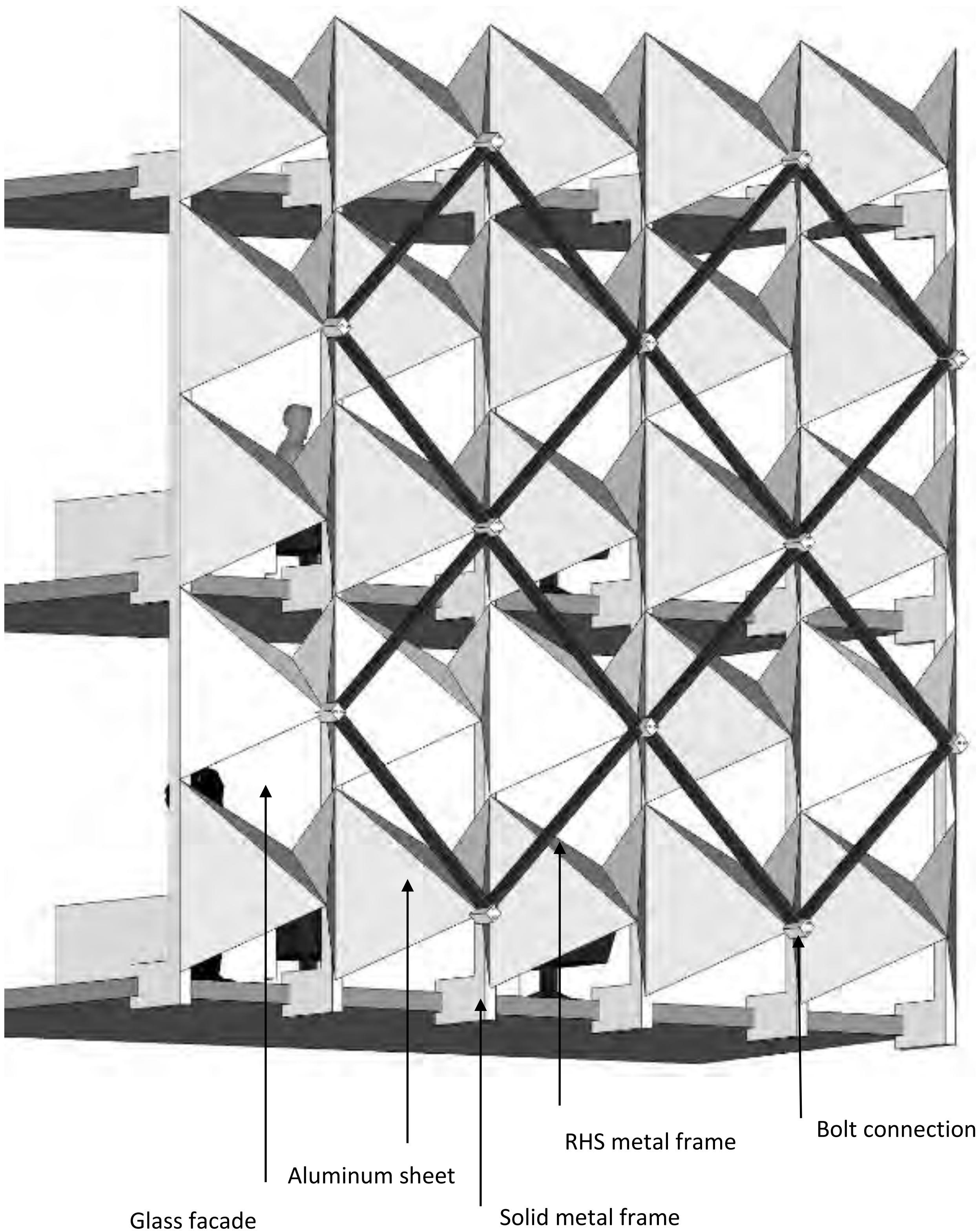


Facade View from outside

Material and method of construction

Aluminum sheet is chosen because of its ease of fabrication, workability, wait and transportation. The shading device is mounted on diagrid metal panels for support. Diagonal pattern is preferable to connect projected points on the shading components as well as allow clear view to the outside and inside the building.

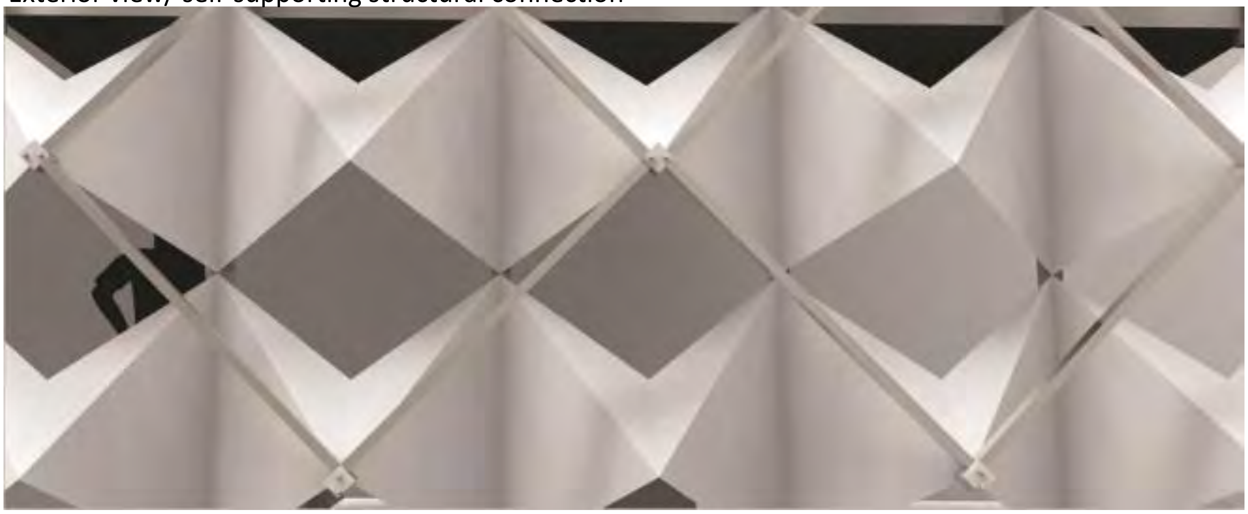
Facade construction

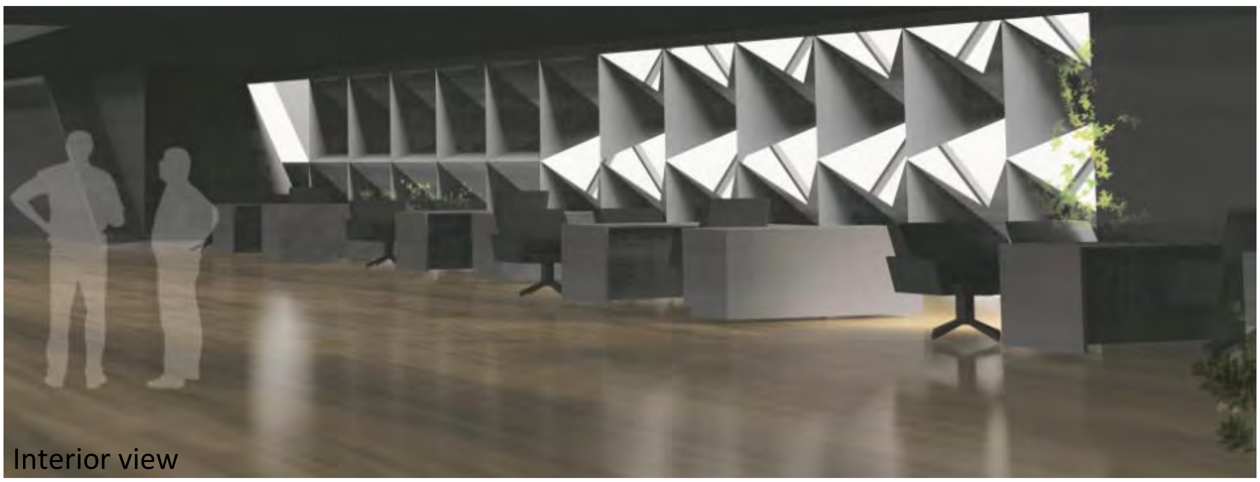


South west View

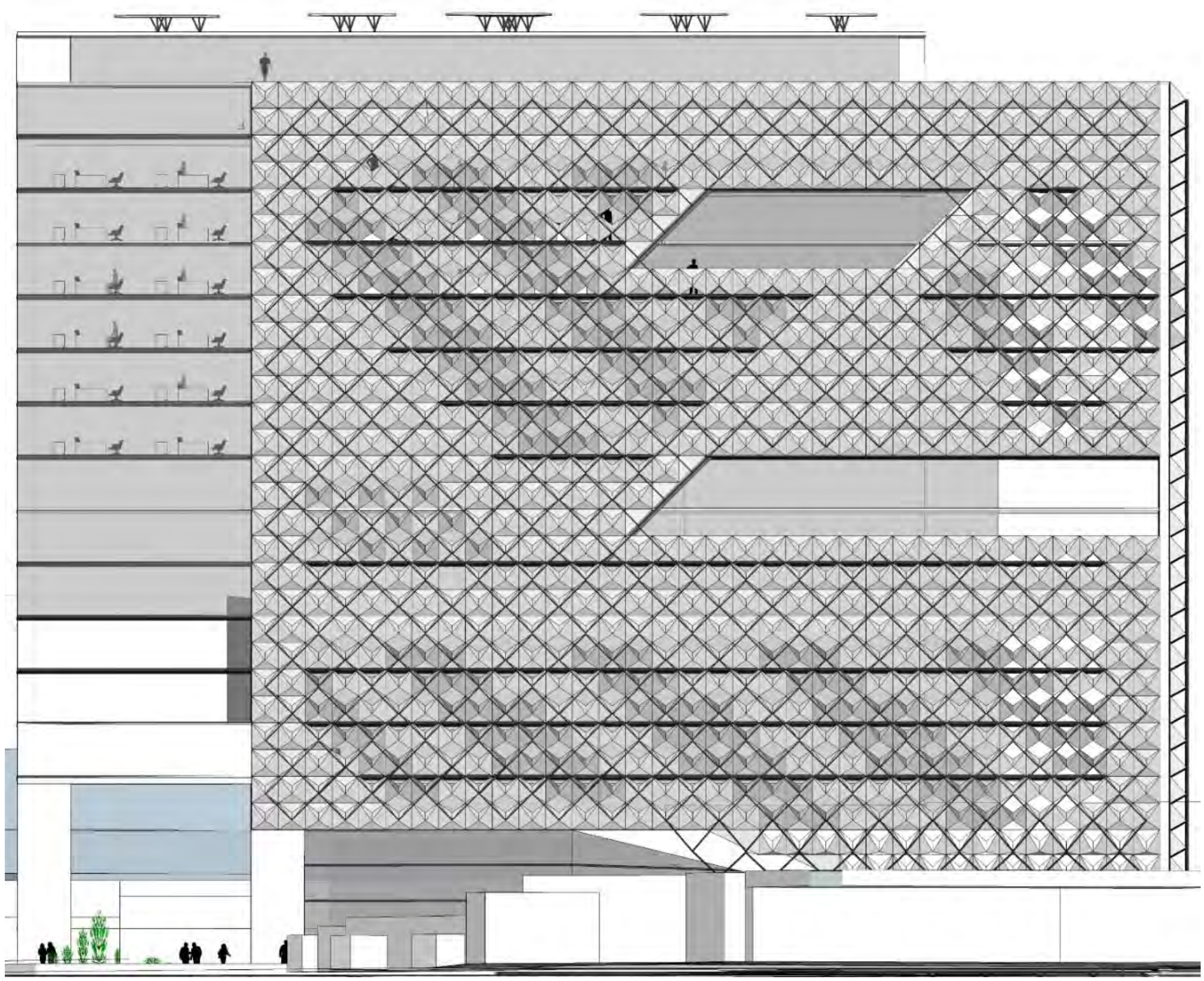
Aerial view

Exterior view/ self-supporting structural connection

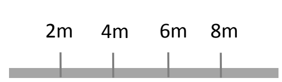


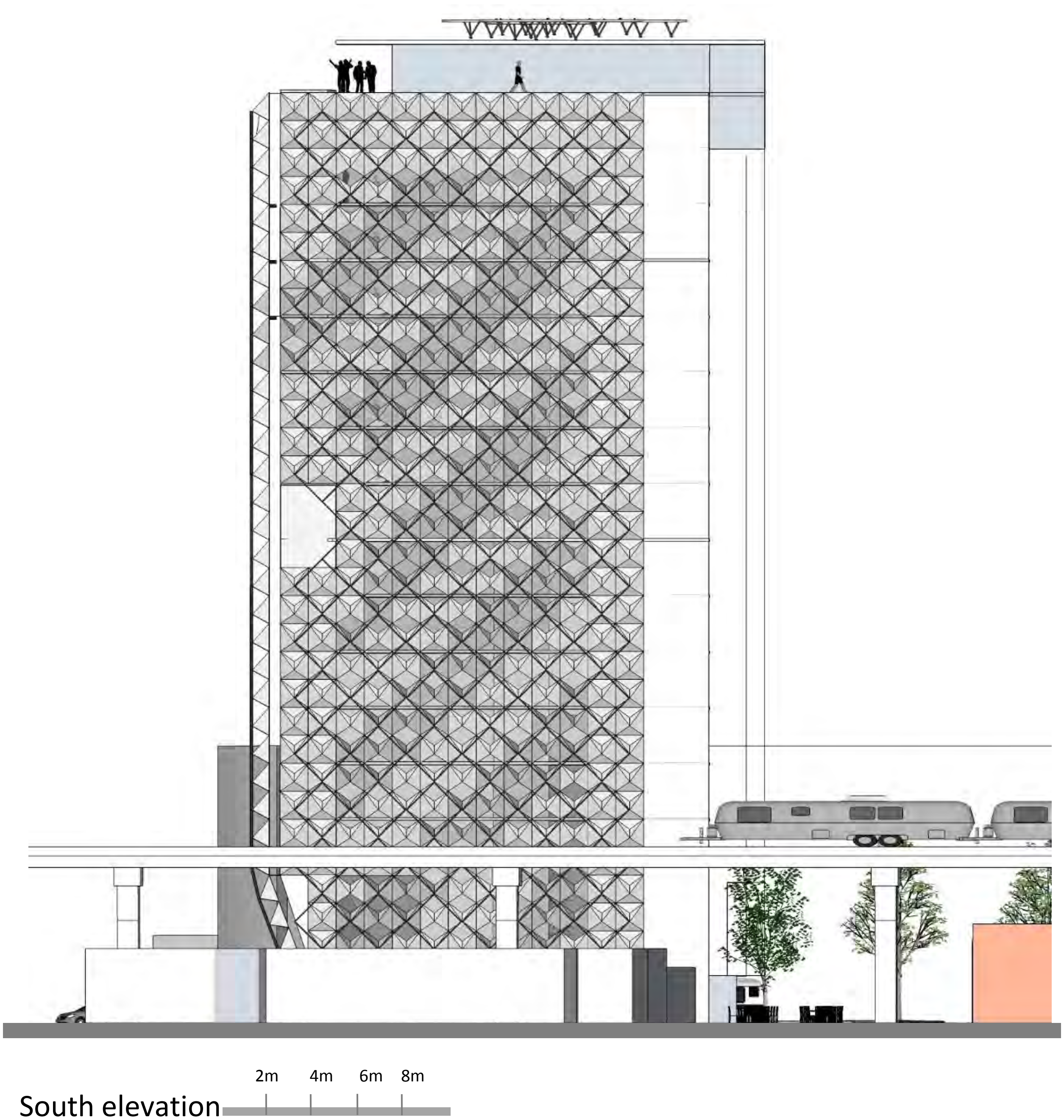


Interior view



West elevation



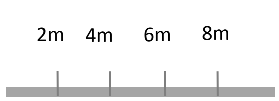


South elevation

Ground floor plan

Typical floor plan

2nd, 3rd, 4th floor



Chapter

7

CONCLUSION & RECOMMENDATION

7.1 CONCLUSION

The purpose of this study was to explore the impact of radiation on glazed office buildings and the effect of glass facade and shading choices on occupants' thermal and visual comfort. The research showed that, the sensation of comfort is mainly related to urban setup, site conditions, and orientation; room layout; glazing proportion; glazing type and shading coefficient; and exterior shading devices. However, the research was basically concerned with effective shading device experiment which controls the radiation before it strikes the glazing. For south and north facades, Vertical shading devices were found to be more effective with little intervention with horizontal shading components. Whereas, for east and west facades, horizontal shading devices were found to be more effective with little intervention with vertical shading components. As a matter of fact, recent glass technologies also brought an alternative approach in solar control mechanism. High performance coated glass products like, Low – emissivity glass and solar control glass are nowadays produced to replace external shading devices.

7.2 RECOMMENDATION AND FUTURE WORKS

The solar radiation could be controlled before it strikes the glass though calculated shading configuration in selected critical discomfort hours of the day and months of the year. This method optimizes the effectiveness of shading systems and brings better building performance through protection of the interior space from the unfavorable sunlight that results in overheating. The performance of the proposed skin geometry is tested in terms of direct radiation protection. Even if, the skin covers only 55% of the total facade surface, it protects 80% of direct solar radiation while allowing diffused light and view to the outside. This optimization is brought through solar path study during those critical hours and days of the year and finding appropriate geometrical configuration for the facade. Therefore I recommend architects and researchers to be engaged in comprehensive and holistic study of their environment before major facade design decisions. Climatic analysis and interpretation shall be integrated in the design and fabrication process starting from the schematic phase of the design. In addition, I suggest glass material importers to study the performance of the material in local context before supplying to the building industry.

I suggest future studies and experiments to be made on effective shading devices for existing radiation vulnerable buildings in the city. Type of glasses, shading devices and effective angles for different orientations could be studied to produce a general municipal guideline which evaluates upcoming facade designs in the city before construction permit. This would also create an opportunity for young architects and engineers to find alternative design solutions which optimizes the visual and thermal performance of local buildings as well as maximizes the productivity of building users. Such strategies would also save daytime energy demand of buildings while exploiting available energy resources such as sun lighting.

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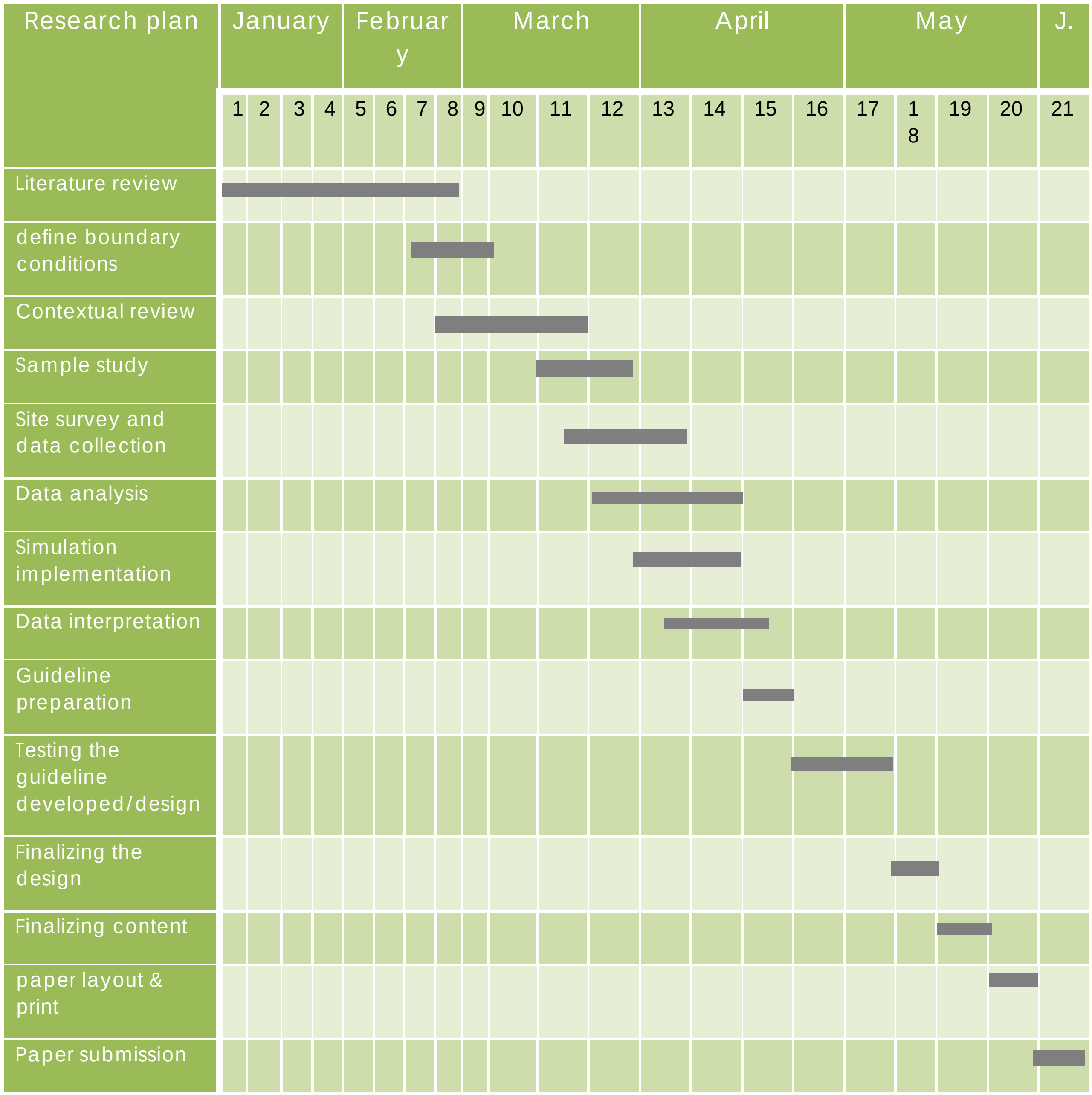
Appendix

Appendix

A

RESEARCH SCHEDULE


Research plan
January
Februar y
March
April
May
J.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 1 8 19 20 21
Literature review
define boundary conditions
Contextual review
Sample study
Site survey and data collection
Data analysis
Simulation implementation
Data interpretation
Guideline preparation
Testing the guideline developed/design
Finalizing the design
Finalizing content
paper layout & print
Paper submission

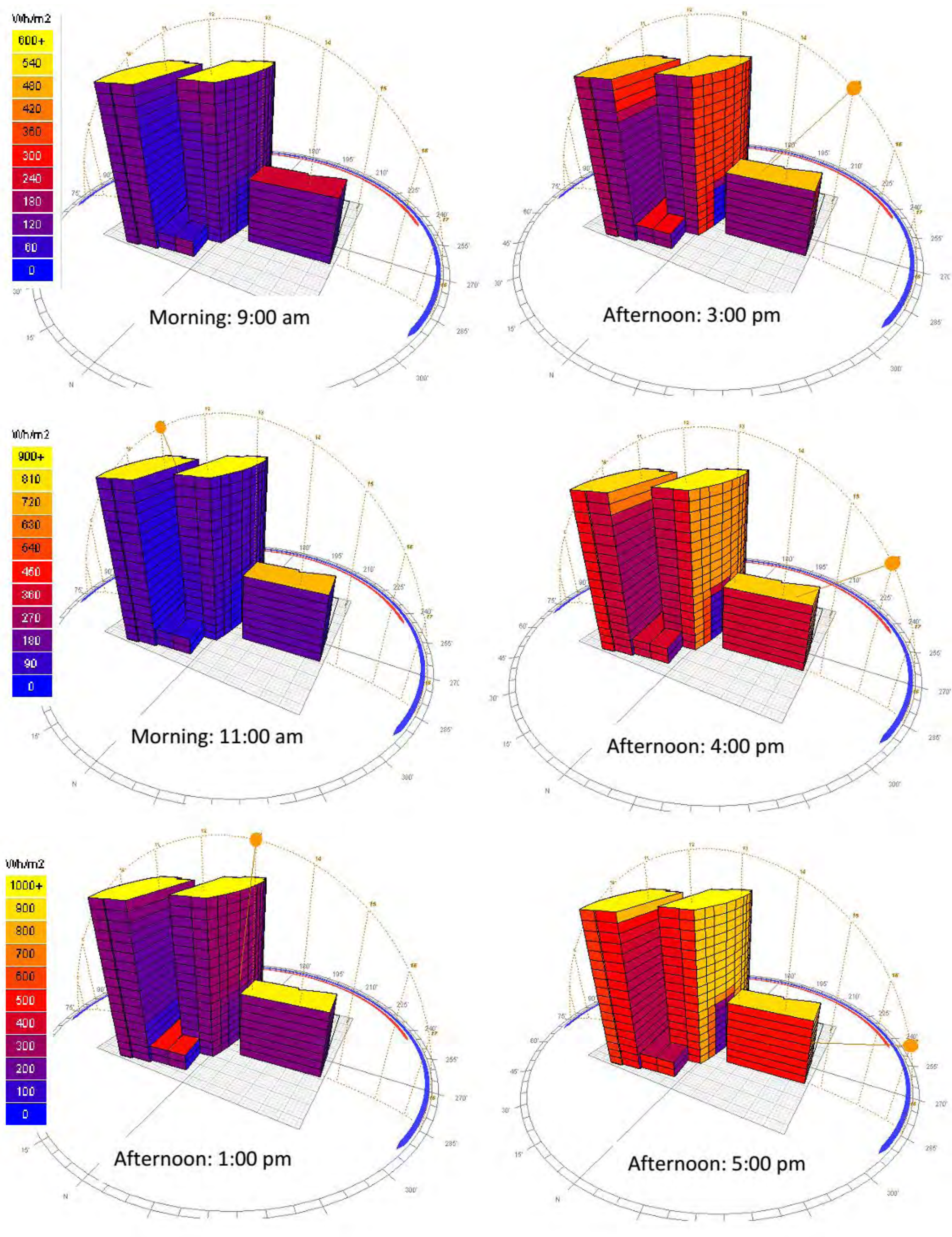
Appendix

B

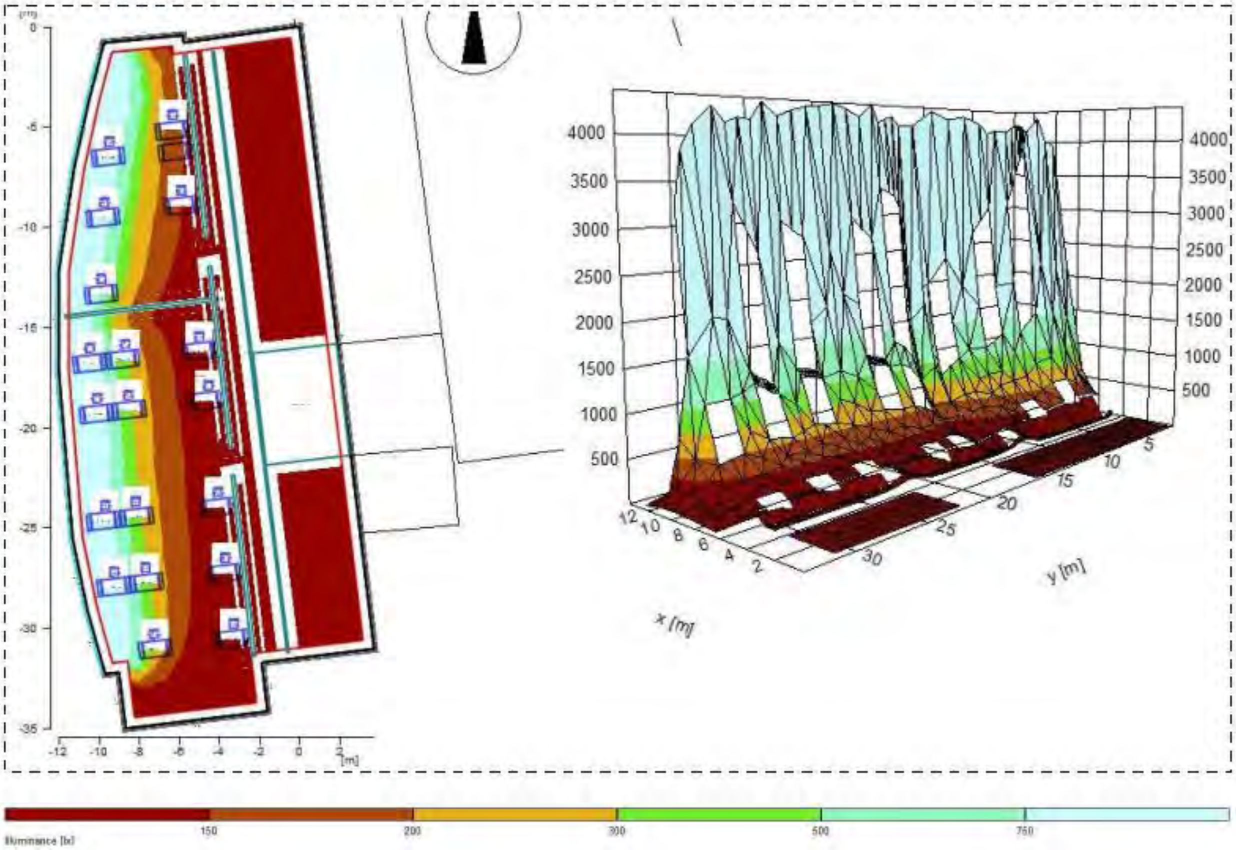
AWASH INSURANCE COMPANY

SOLAR ACCESS ANALYSIS

A.1 Daily cumulative solar access analysis in Wh/m^2, May



A.2 Indoor Space Natural light simulation, illuminance, Lx [Relux software]



A.3 Daylight factor calculation [Relux software]

General

Calculation algorithm used	Average indirect fraction
Height of evaluation surface	0.75 m
Calculation mode used:	Overcast sky acc. CIE
Date, Time:	21.03. 10:28 (TST 09:56)

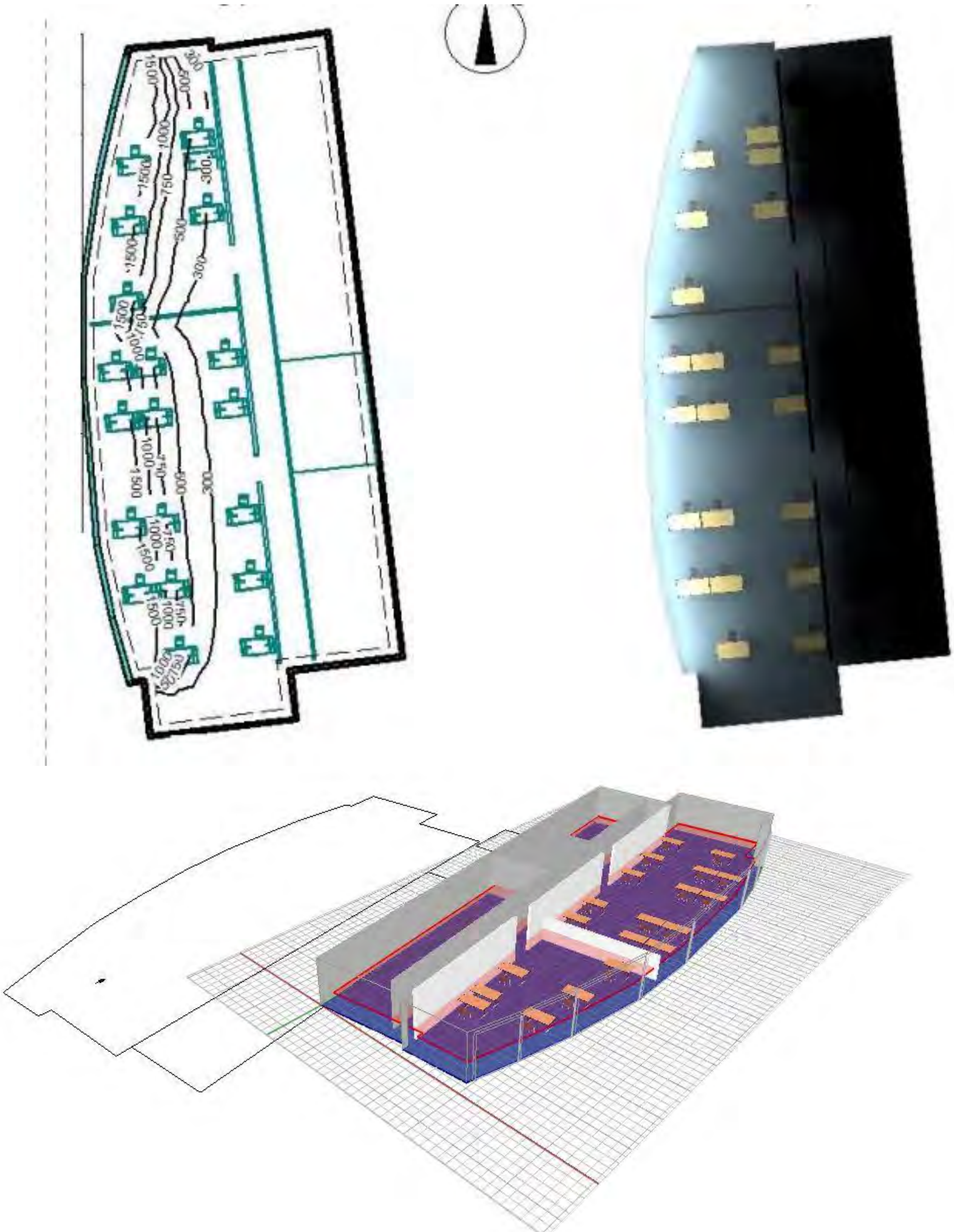
Geographical data:

Location	: Ethiopia
Latitude (degrees)	: 9.00 °
Longitude (degrees)	: 38.80 °
North angle	: 0.00 °

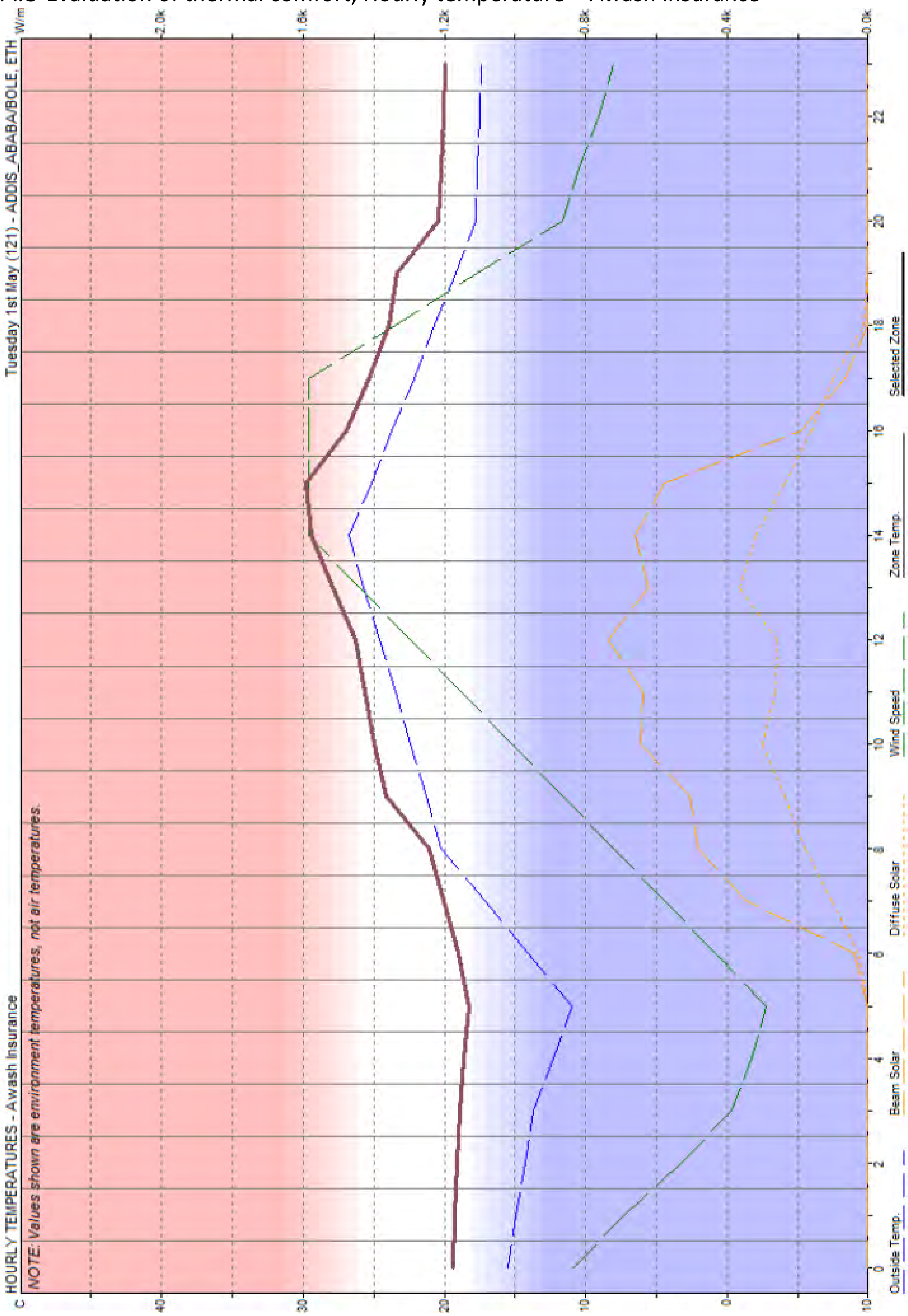
Daylight factor:

Average daylight ratio	Dav	: 3.5
Minimum daylight ratio	Dmin	: 0
Maximum daylight ratio	Dmax	: 23

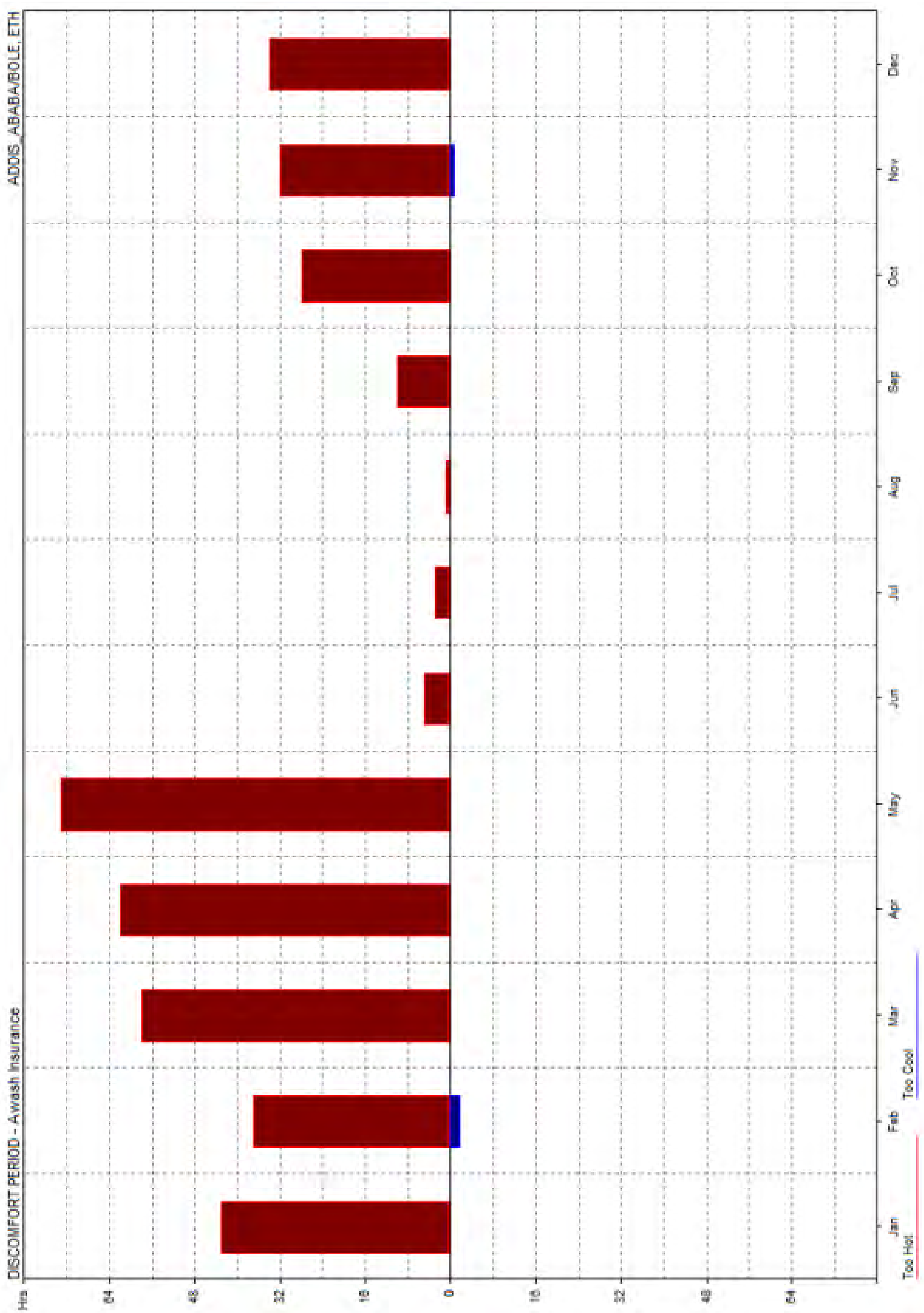
A.4 Daylight illuminance distributions (lux) across an open floor plan, 10th story



A.5 Evaluation of thermal comfort, Hourly temperature – Awash Insurance



A.6 Discomfort period– Awash Insurance

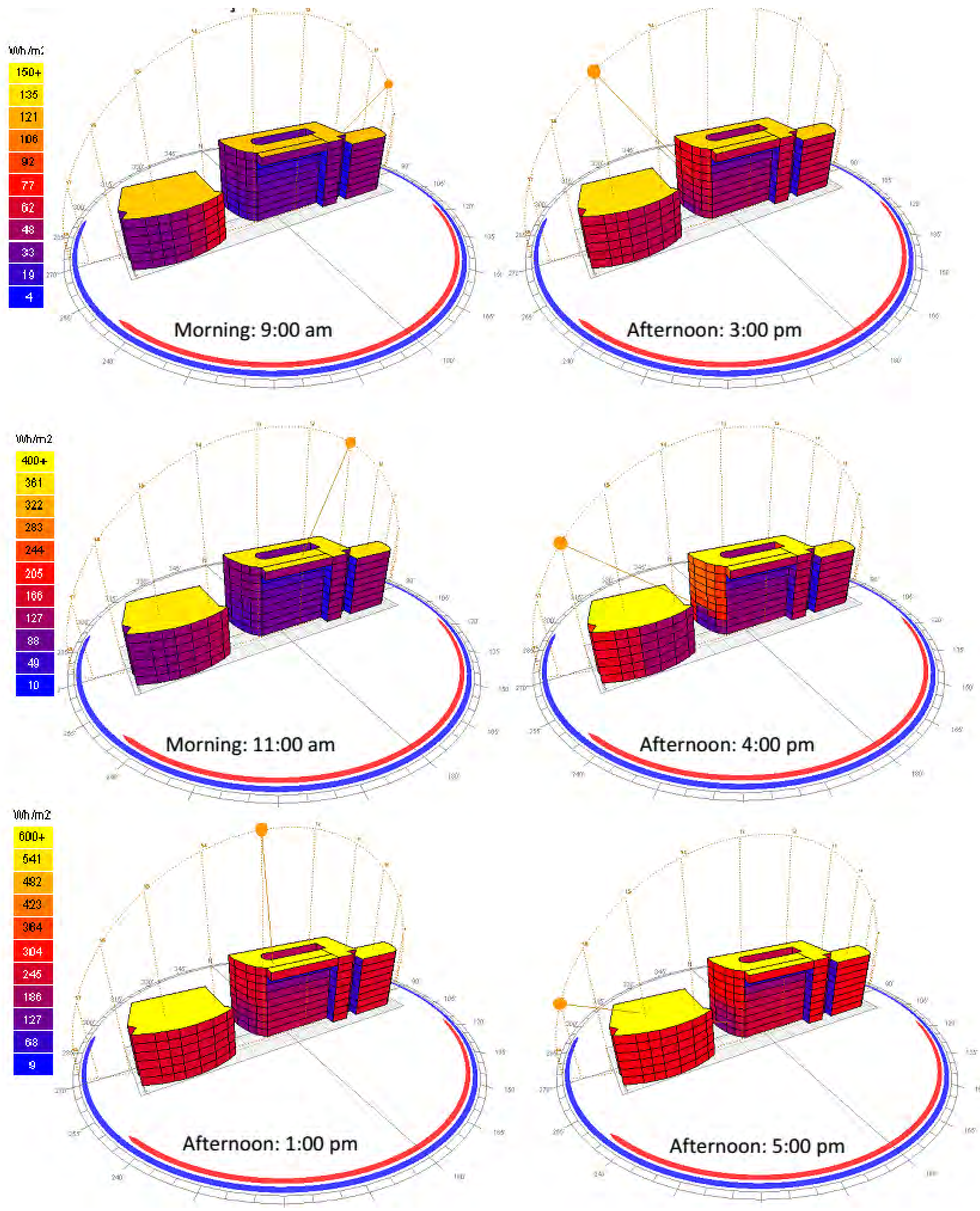


Appendix

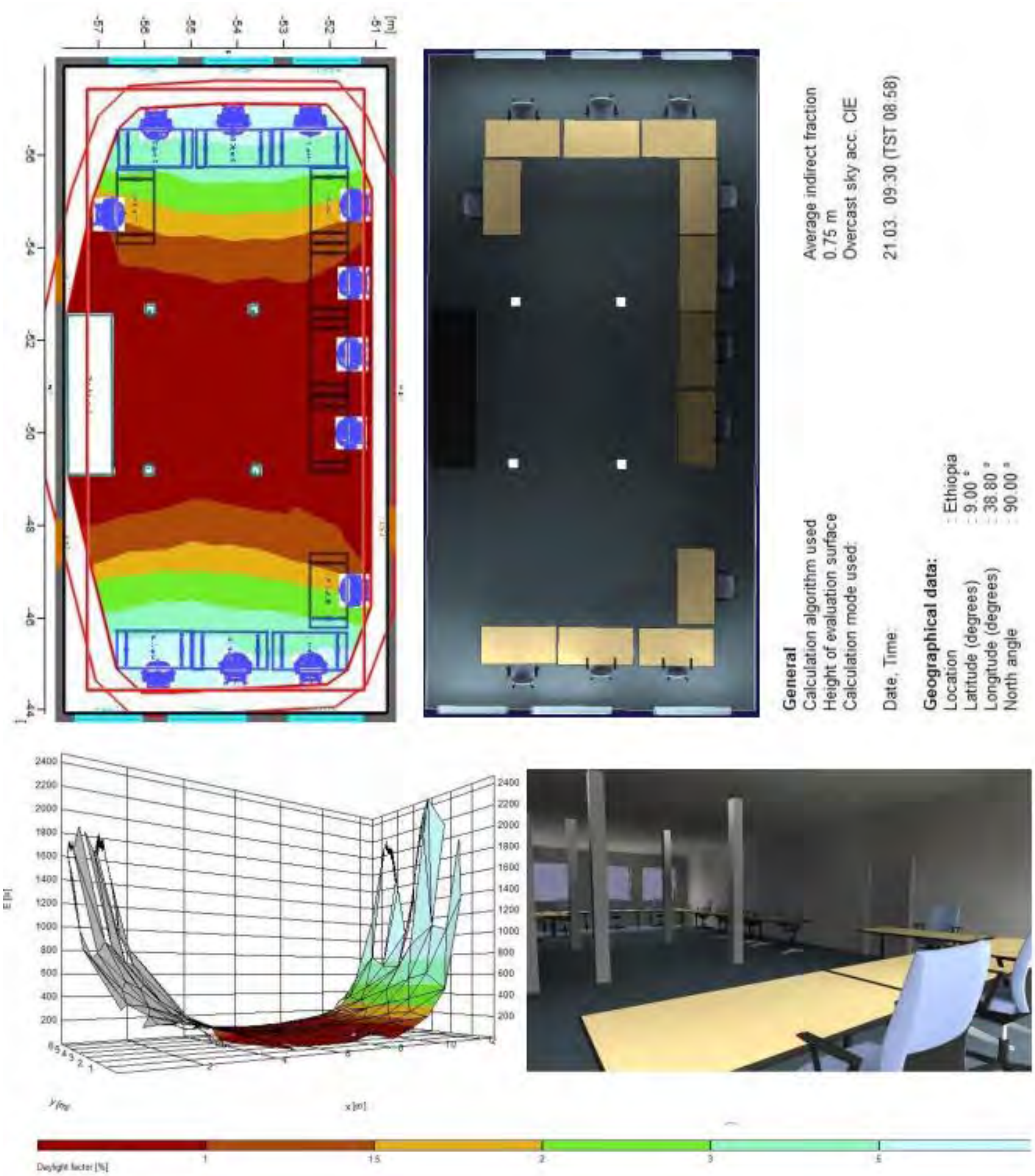
C

CHELELEK ALSAM SOLAR ACCESS ANALYSIS

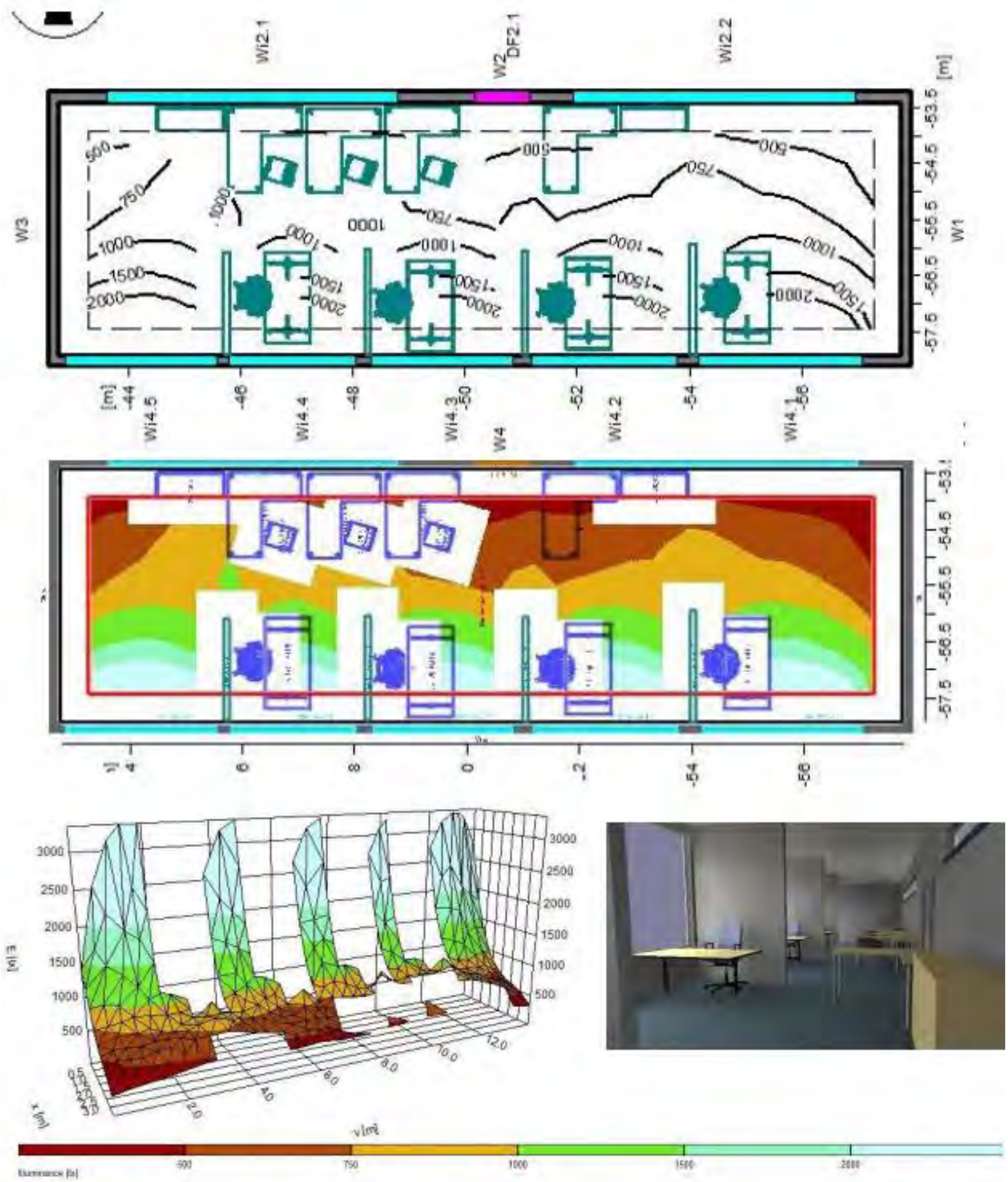
B.1 Daily cumulative solar access analysis in Wh/m 2



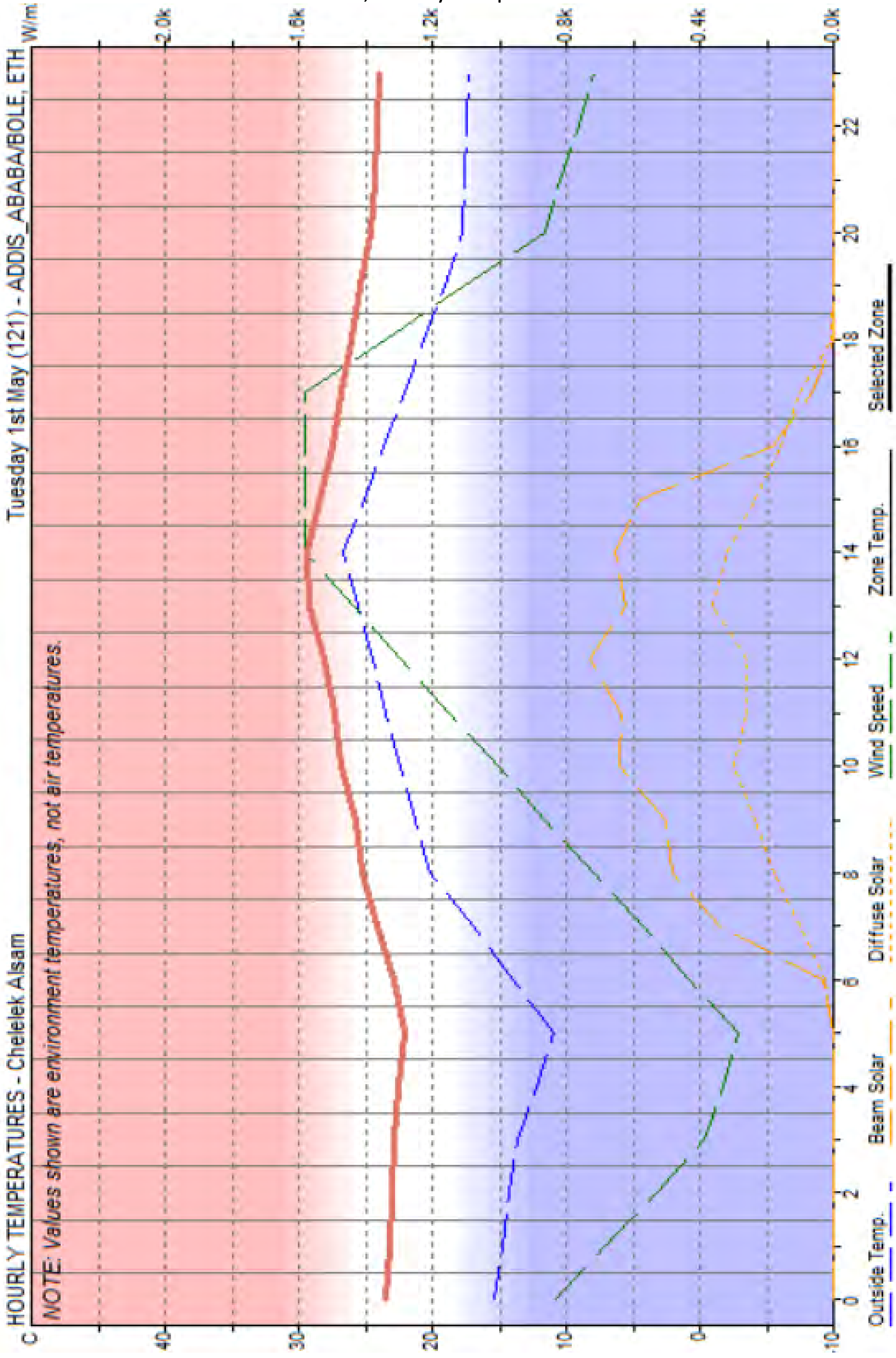
B.2 Indoor Environment Natural light simulation, illuminance, Lx), 2nd floor



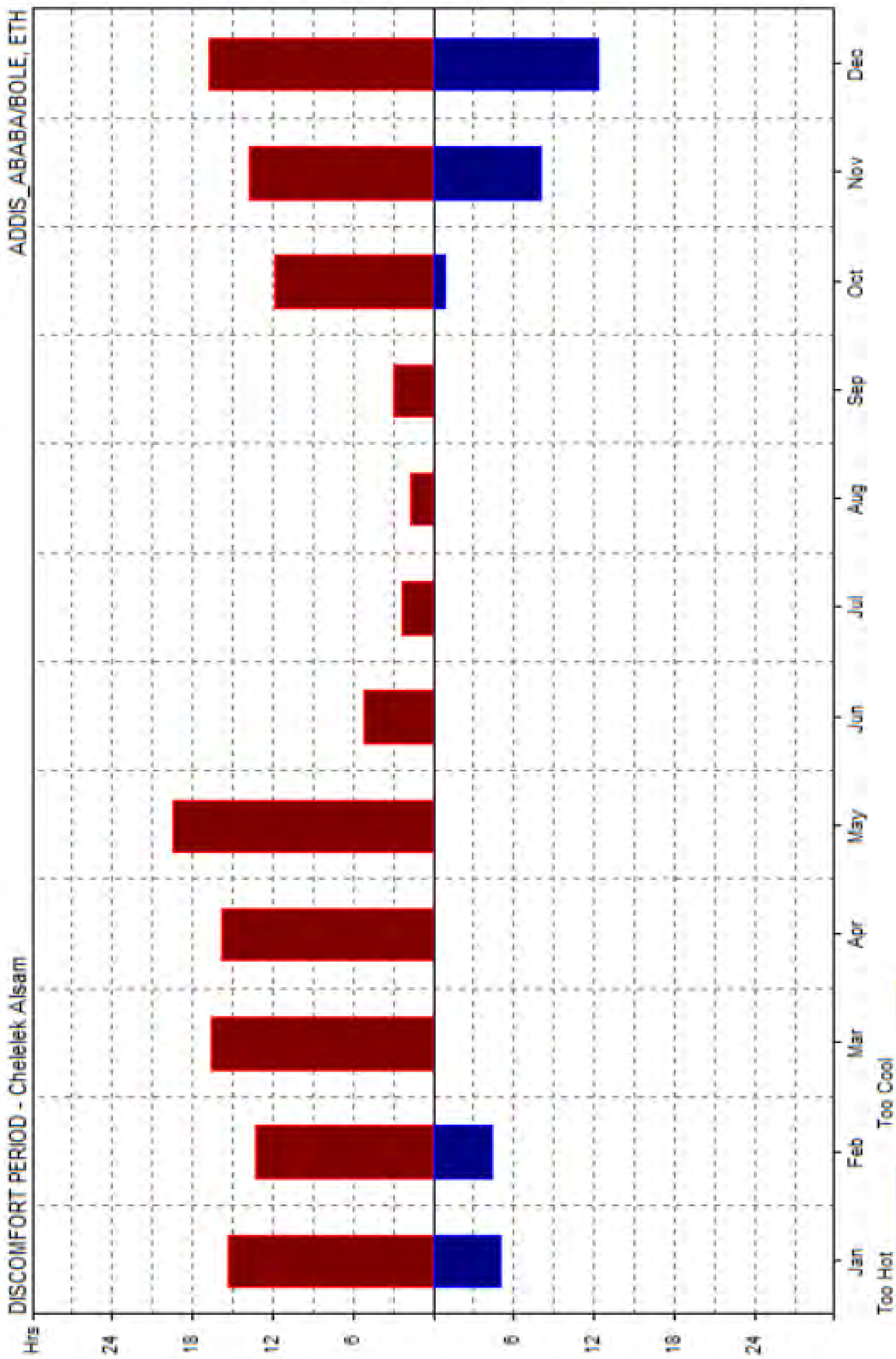
B.3 Indoor Environment Natural light simulation, illuminance, Lx), 5th floor



B.4 Evaluation of thermal comfort, Hourly temperature – Chelelek Alsam



B.5 Discomfort period - Chelelek Alsam

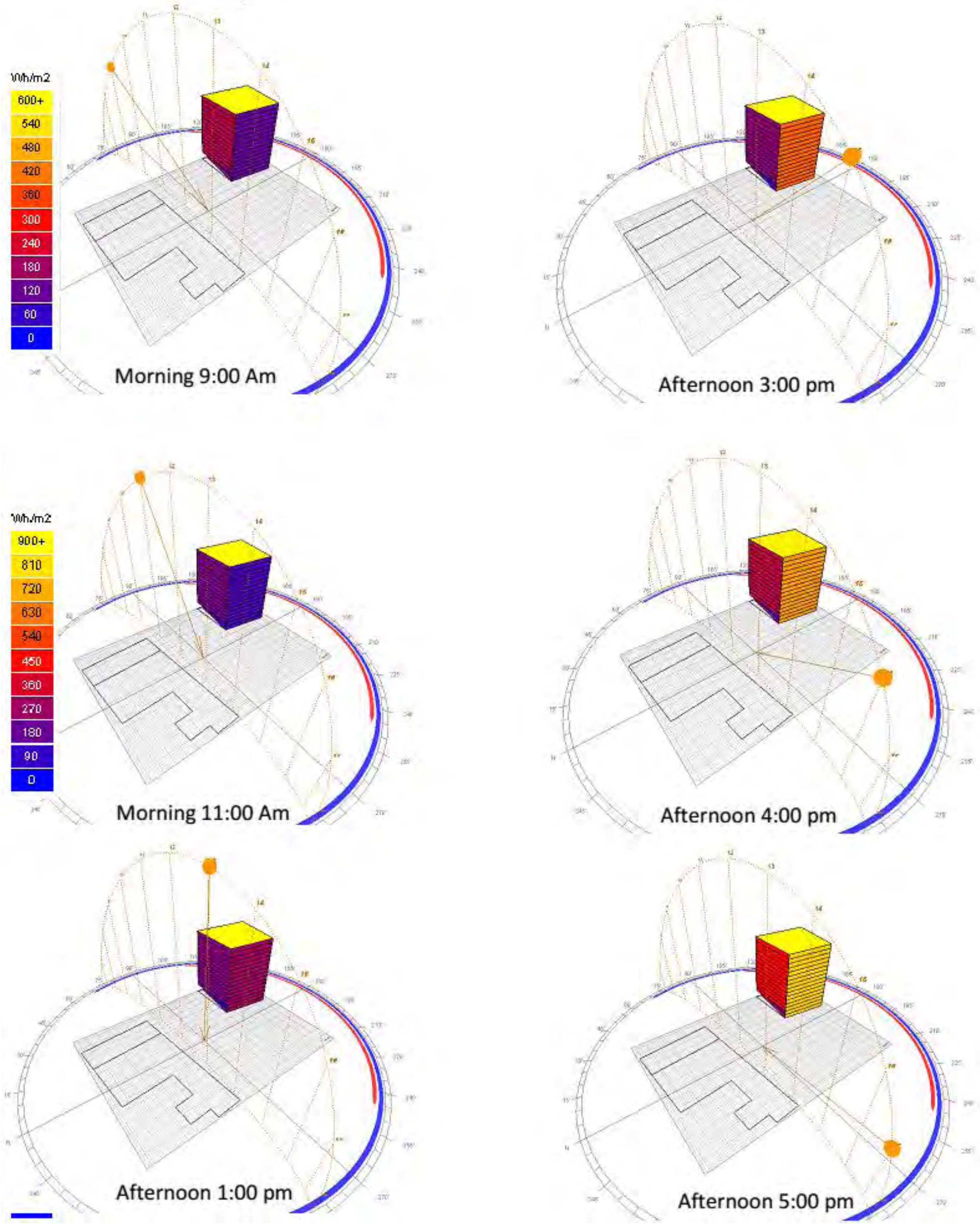


Appendix

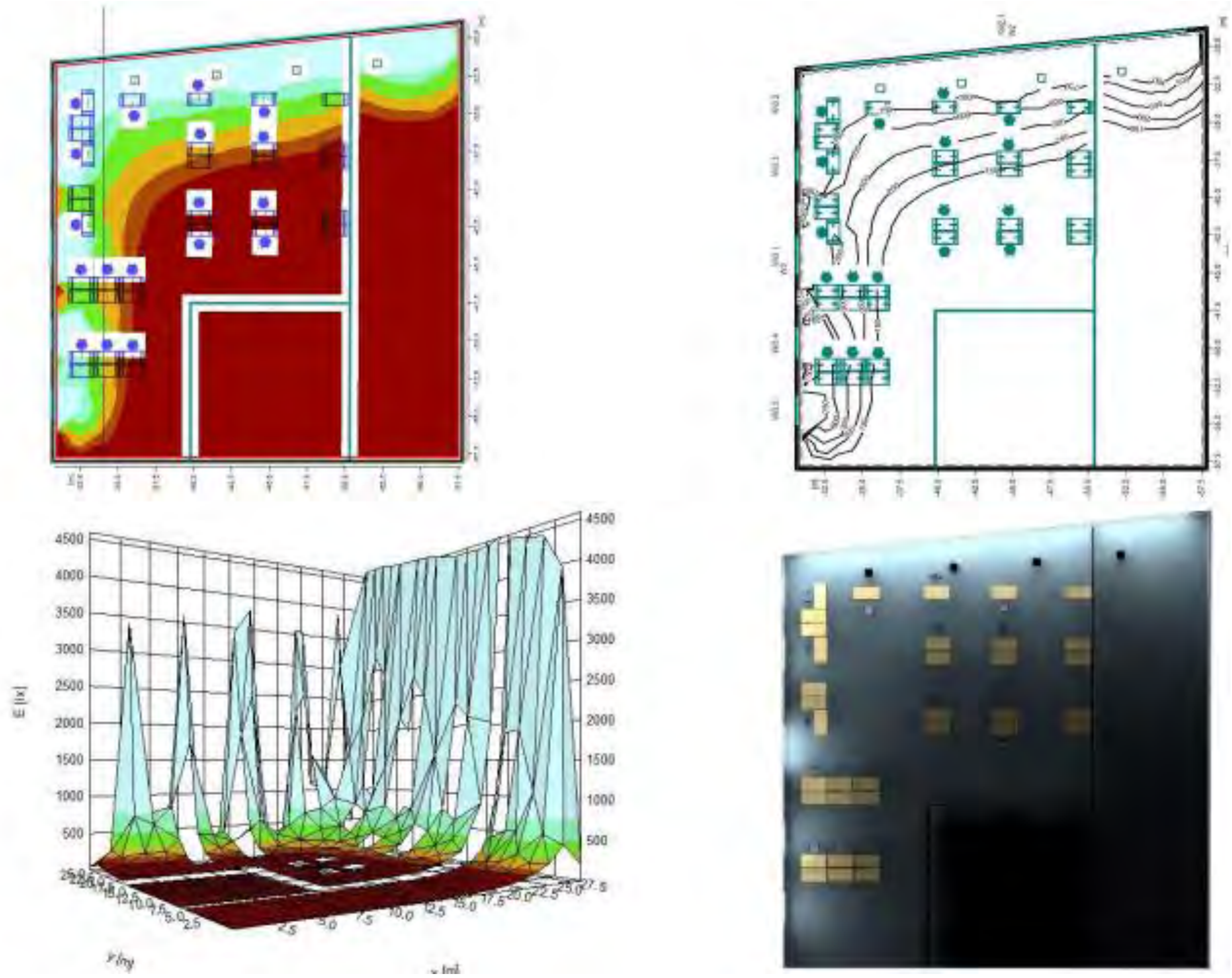
D

DEBREWORK TOWER SOLAR ACCESS ANALYSIS

C.1 Debrework Tower - Daily cumulative solar access analysis in Wh/m^2



C.2 Indoor Environment Natural light simulation, illuminance, Lx



C.3 Daylight factor calculation, Debrework Tower [Relux software]

General

Calculation algorithm used	Average indirect fraction
Height of evaluation surface	0.90 m
Calculation mode used:	Overcast sky acc. CIE
Date, Time:	21.03. 09:30 (TST 08:58)

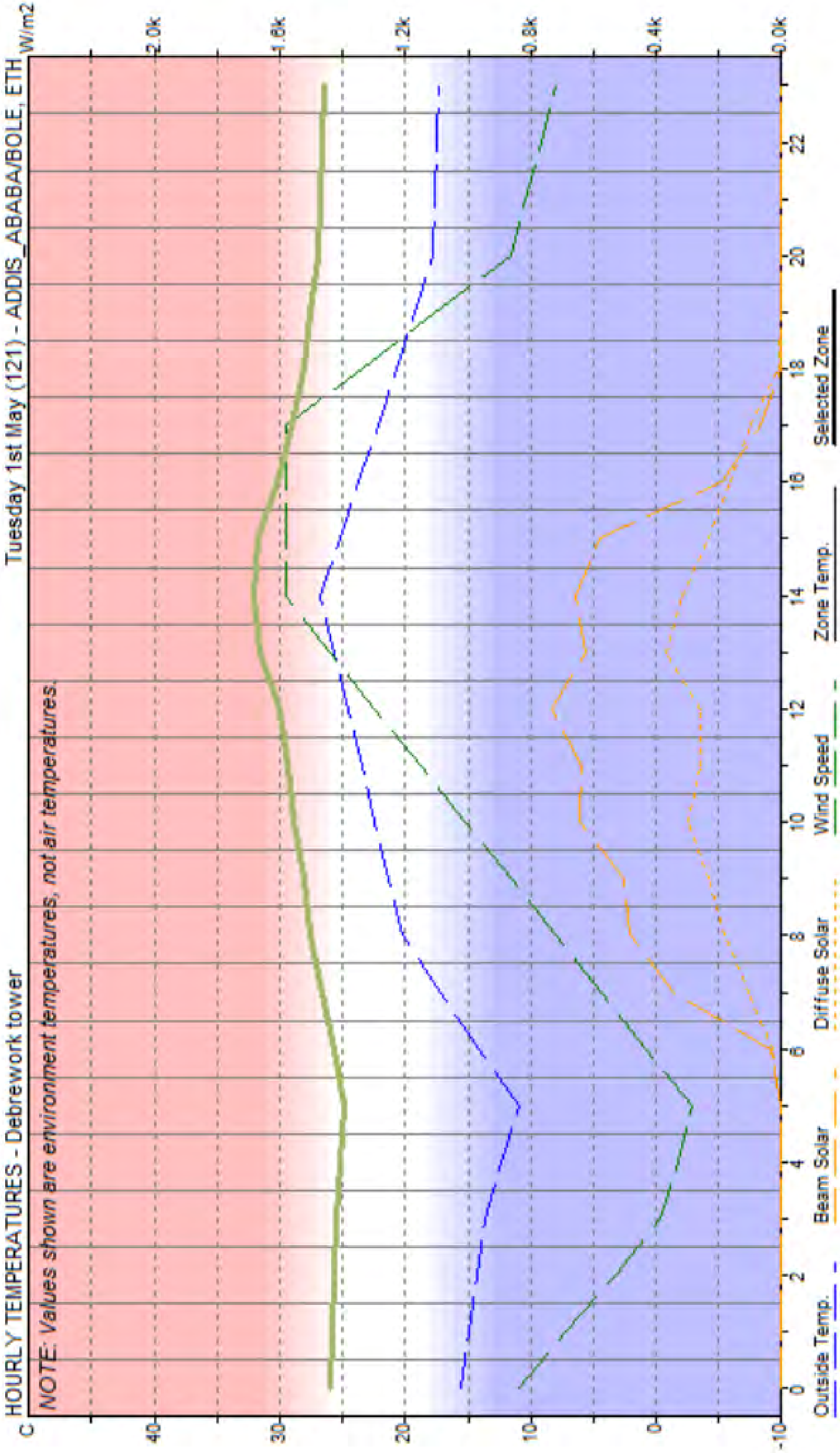
Geographical data:

Location	: Ethiopia
Latitude (degrees)	: 9.00 °
Longitude (degrees)	: 38.80 °
North angle	: 90.00 °

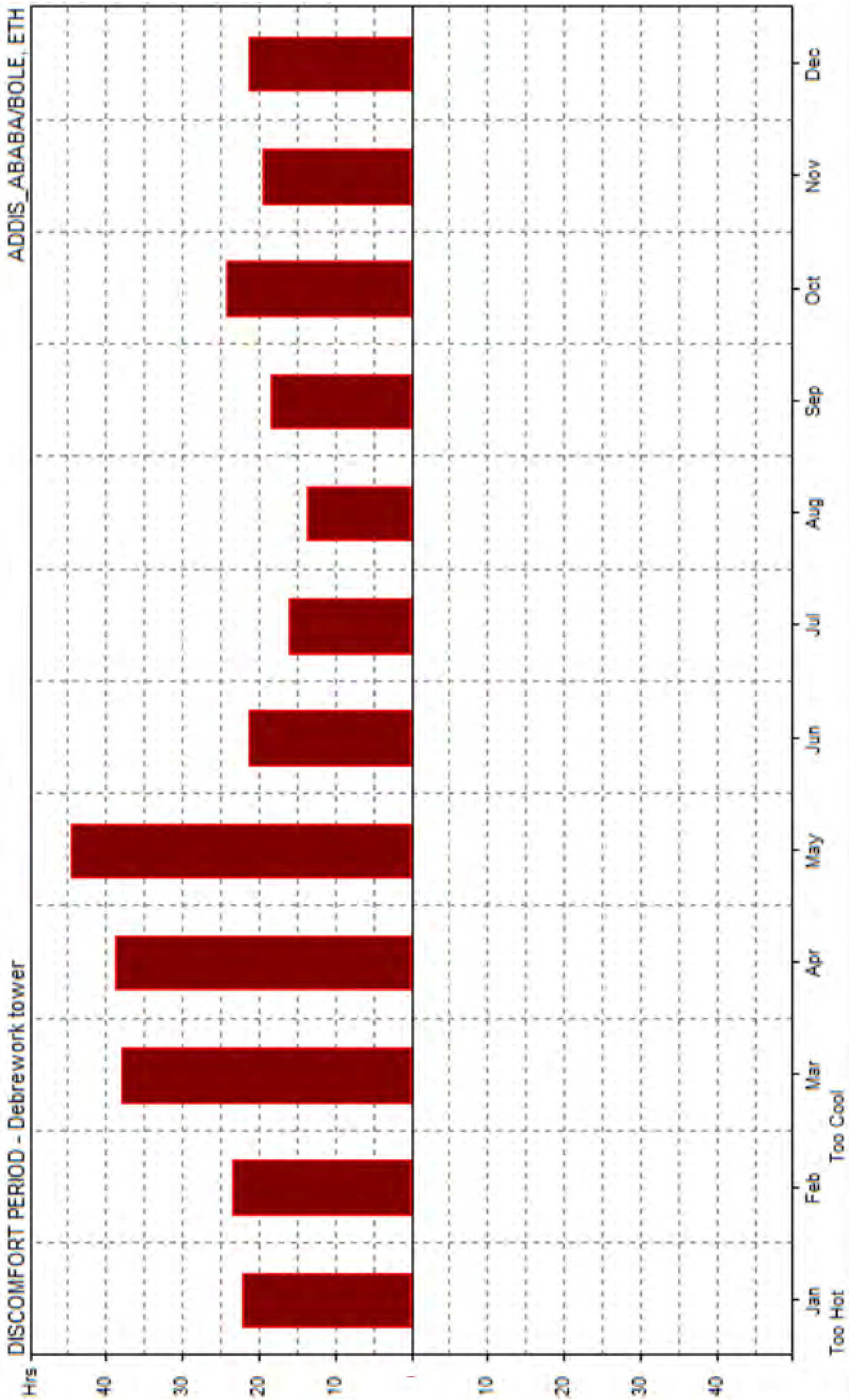
Daylight factor:

Average daylight ratio	Dav	: 2.4
Minimum daylight ratio	Dmin	: 0
Maximum daylight ratio	Dmax	: 29

C.4 Evaluation of thermal comfort, Hourly temperature – Debrework tower



C.5 Discomfort period – Debrework Tower



Appendix

E

THERMAL AND VISUAL COMFORT SURVEY

conducted in selected office buildings in Addis Ababa

PART ONE: STUDYING THE EFFECT OF FACADE CHOICES ON INDOOR ENVIRONMENT

Section 1: **Basic Information**

Basic information is needed since the amount of heat and moisture generated by people is a function of sex, age, activity and other factors.

1. What is your Gender?

○ Male ○ Female

2. What is your age?

○ 20-30 ○ 31-40 ○ 41-50 ○ Over 50

3. How many years have you worked in this building?

○ Less than a year ○ 1-2 years
○ 3-5 years ○ More than 5 years

4. How long have you been working at your present workspace?

○ Less than 3 months ○ 4-6 months
○ 7-12 months ○ More than 1 year

5. In a typical week, how many hours do you spend in your workspace?

○ 15 or less ○ 16-32 ○ More than 32

6. How would you describe the work you do?

○ Administrative support ○ Technical
○ Professional ○ Managerial/supervisory ○ other

Section 2: **General Comments**

1. How satisfied are you with the building overall service?

Very Satisfied ○ ○ ○ ○ ○ Very Dissatisfied

2. How satisfied are you with your personal workspace?

Very Satisfied ○ ○ ○ ○ ○ Very Dissatisfied

3. Any additional comments or recommendations about your personal workspace or building overall condition?

____
____

Section 3: **Thermal Comfort**

1. Which of the following do you personally adjust or control in your workspace? (Check all that apply)

- ○ Open and Close window
- ○ Window blinds or shades
- ○ Room air-conditioning unit
- ○ Portable fan
- ○ Ceiling fan
- ○ Adjustable air vent in wall or ceiling....if any
- ○ Adjustable floor air vent (diffuser).....if any
- ○ Others: ______________________

2. How satisfied are you with the thermal comfort in your workspace?

Very Satisfied ○ ○ ○ ○ ○ Very Dissatisfied

3. Overall, does your thermal comfort in your workspace enhance or interfere with your ability to get your job done?

Enhances ○ ○ ○ ○ ○ Interferes

4. To what extent your room thermal comfort affects your normal level of productivity

- ○ No effect
- ○ Positive effect
- ○ Normal effect
- ○ Quite good effect
- ○ Bad effect

5. Which time of the day do you often feel thermal discomfort?

- ○ 9:00am – 11:00am - Morning
- ○ 11:00am – 1:00pm - Morning
- ○ 1:00pm – 3:00pm - Afternoon
- ○ 3:00pm – 5:00pm - Afternoon

6. Which month of the year do you feel thermal discomfort?

○ January	○ February	March	○ April	○ May	○ June
○ July	○ August	September	○ October	○ November	○ December

7. Please describe any other issues related to thermal comfort that are important to you.

____

____

Section 4: **Visual Comfort/Natural Lighting/ Sunlight**

1. How satisfied are you with the amount of sun light in your workspace?

Very Satisfied ○ ○ ○ ○ ○ Very Dissatisfied

2. How satisfied are you with the visual comfort of the lighting (e.g., glare, reflections, contrast)?

Very Satisfied ○ ○ ○ ○ ○ Very Dissatisfied

3. Does the lighting quality enhance or interfere with your ability to get your job done?

Enhances ○ ○ ○ ○ ○ Interferes

4. Manual Control over the level of natural lighting in your office

Possible ○ ○ ○ ○ ○ Impossible

5. Which of the following devices do you use to control direct sun light penetration/glare?

- ○ Internal movable shading device
- ○ Internal fixed shading device
- ○ External fixed shading device
- ○ External movable shading device

6. Are you satisfied with the shading technology in your office building?

○ Yes ○ No

7. Please describe any other issues related to thermal comfort that are important to you.

____
____

PART TWO - STUDYING THE EFFECT OF FACADE CHOICES ON STREETS AND DRIVERS

The questionnaire is formulated to investigate the effect of facade systems on adjacent buildings and street users/drivers.

Section 1: The effect of nearby building facade over your office space

1. Does nearby building facade interfere your normal work ((e.g., glare, reflections, and contrast)?

- ○ Yes
- ○ No

2. Does nearby building facade interfere your view to the outside?

- ○ Yes
- ○ No

3. Does nearby building block natural light entry into your office space?

- ○ Yes
- ○ No

Section 2: The impact of windows on drivers

1. How often do you spend driving in the city?

Frequently ○ ○ ○ ○ ○ Occasionally

2. To what extent window glare affects your driving?

- ○ No effect
- ○ Positive effect
- ○ Normal effect
- ○ Bad effect

3. Which time of the day is the glare mostly occur?

- ○ 1-4 o'clock (local time)
- ○ 5-8 o'clock
- ○ 9-11 o'clock

4. Have you ever made any trouble or accident because of glare?

- ○ Yes
- ○ No

5. **Any additional comments or recommendations about the building facade/windows**

____