The effect of glazing in the thermal environment of a fully-glazed office building: the case of the new CBE HQ office building

Netsanet Hailu

A Thesis Submitted to the Department of Architecture

College of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Masters in Environmental Architecture

Office of Graduate Studies

Adama Science and Technology University

Oct. 2024

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Declaration

I hereby declare that this Master Thesis entitled "**The Effect of Glazing in the Thermal Environment of a fully-glazed office building: The Case of the New CBE HQ Office Building**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

____Netsanet Hailu_________	_______________________	__09/04/2025___
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Recommendation of Advisor

I, the advisor of this thesis, hereby certify that I/we have read the revised version of the thesis entitled "**The Effect of Glazing in the Thermal Environment of a fully-glazed office building: The Case of the New CBE HQ Office Building**" prepared under my/our guidance by Netsanet Hailu submitted in partial fulfillment of the requirements for the degree of Masters of Science in Environmental Architecture. Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedures.

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Approval Page of M.Sc. Thesis

I/we, the advisors of the thesis entitled "**The Effect of Glazing in the Thermal Environment of a fully-glazed office building: The Case of the New CBE HQ Office Building**" and Developed by Netsanet Hailu, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Netsanet Hailu have read and evaluated the thesis entitled "**The Effect of Glazing in the Thermal Environment of High-rise Office Buildings: The Case of the New CBE HQ Office Building**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Environmental Architecture.

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Finally, approval and acceptance of the thesis is contingent upon the submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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Office of Postgraduate Studies, Dean	Signature	Date

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AA Addis Ababa

AAiT Addis Ababa Institute of Technology

ANSI Approved American National Standard

ASHARE American Society of Heating Refrigerating and Air-conditioning Engineers

CBE Commercial Bank of Ethiopia

CIBSE Chartered Institution of Building Services Engineers

Co Company

COP Coefficient of Performance

CPNI Customer Proprietary Network Information

CSCEC China State Construction Engineering Corporation

CSCOD China State Construction Overseas Development

E East

EER Energy efficiency ratio

EBCS Ethiopian Building Code Standard

EPW Energy Plus Weather

Eqn. Equation

ETB Ethiopian Birr

HAP Hourly Analysis Program

HQ Head Quarter

HVAC Heating Ventilation and Air Conditioning

IAQ Indoor Air Quality

IE Indoor Environment

IES Integrated Environmental Solutions

LEED Leadership in Energy and Environmental Design

Low-E Low-Emissivity

Ltd. Limited

N North

OA Outdoor Air

PC Personal Computer

PVC Poly Vinyl Chloride

SC Shading Coefficient

SHGC Solar Heat Gain Coefficient

USA United States of America

UV Ultraviolet

VE Virtual Environment

VMU Visual Mock-up Unit

VRF Variable Refrigerant Flow

VTV visible Transmittance

WHO World Health Organization

WWR Window-to-Wall Ratio

ABSTRACT

The growing prevalence of large glass facades in office buildings raises questions whether considerations regarding the thermal environment of office spaces and their impact on energy usage throughout the building's lifespan are factored in during the selection of glazing materials. This research aims to explore the impact of glazing on thermal comfort in high-rise office settings, with particular emphasis on the recently completed CBE building in Addis Ababa, Ethiopia. As the tallest high-rise structure in the nation with advanced features, a 100% wall-to-window ratio, and an advanced HVAC system makes this building ideal for this study. Data from weather sources, architectural details, and HVAC specifications were collected from the project management office and literature sources. Carrier's Hourly Analysis Program software was used to simulate the thermal load and energy consumption of different glazing structures based on the HVAC system of the building. The finding of this study shows that the Double-Glazed vision panel glass utilized in the CBE-HQ office building is one of the most effective glazing options, recording the lowest thermal loads and ranking third in energy savings among the alternatives. The cooling load was recorded 1727.1 kW indicating the energy required to keep the indoor environment comfortable in warmer seasons, while the heating load was recorded 567.7 kW showing the energy needed for colder seasons; showing a higher demand for cooling. It also achieves a notable 14.14% reduction in energy consumption compared to the least efficient option, highlighting the effectiveness of the Double-Glazed vision panel glass in enhancing the overall occupant comfort and energy efficiency and the importance of selecting appropriate glazing materials in building design. The subjective evaluation made using questionnaire implies that the thermal environment in the new CBE HQ building is largely acceptable to its occupants. In general, This research recommends the integration of multi-pane and reflective glazing within the combination of glazing systems in buildings, allowing professionals to design buildings that emphasize thermal comfort and energy efficiency.

Keywords; Energy consumption, office building, glazing structure, Thermal environment, Thermal Load,

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the study

People started making shelter-like- ‘environmental envelopes’ for themselves so that they can be protected from the harsh external environment. This ‘environmental envelope’ has started from caves to what we see and use in present days (high-rise buildings) and they are needed so that the human body maintains its heat balance; where heat exchange is conducted. (Gezer, 2003). In which it can be identified whether or not the thermal comfort of a person is maintained.

In recent years, reduction in energy consumption has become an environmental sustainability goal for many countries due to the risk of climate change and depletion of fossil fuels (Kini, 2017). In 2020, as a result of global warming, the average surface temperature has increased by 1.02^{o}C compared to 1951-1980 (Calama, 2021). This in return affects human comfort in many ways, one being thermal comfort both inside and outside of a building. And this increases occupants’’ total discomfort, where health is the most affected aspects by this factor (Alwetaishi, 2016).

Thermal comfort is a condition of mind that expresses satisfaction with the thermal environment (ANSI/ASHARE standard55, 2017). As ASHARE stated due to its subjectivity, thermal comfort is different for every individual. It is maintained when the heat generated by the human metabolism is allowed to dissipate at a rate that maintains thermal equilibrium in the body (Nobert Lechner, 2014). While designing a building these are one of the properties that must be taken into consideration as long as they are made to accommodate human beings.

New buildings should incorporate ways of reducing energy consumption. In which one will be energy that will be used to maintain occupants’ total comfort so that promoting their health. WHO defines good health as being ‘… a state of complete physical, mental and social well-being, not merely the absence of disease and infirmity’. Most people think of this as ideal not as reality, but it indicates that IE should be managed not merely to avoid illness but also to promote health. (CIBISE, 2014). The aim of design should be to minimize dissatisfaction as much as possible.

Indoor space's thermal comfort is an important factor to consider during design and construction. Mamodooh S. Alwetaishi in his review paper has stated that the thermal comfort in IE has to be highlighted because it is one of the comfort standards required for the users (Alwetaishi, 2016). This thermal comfort can be achieved by designing the building to suit the local climatic conditions. Therefore, knowledge of the climate in question is a start to achieve comfort in a building.

Designing strategies to control this climate will help in maintaining comfort by providing the right design approaches. Site selection, building orientation, choice of thermal insulation, selection of building materials, as well as vegetation are example of passive strategies that may help in maintaining comfort. One of the tangible objects that affect the IAQ and thermal comfort is building materials: it is because they are an important layer in the transfer of heat between the outside and the inside (Gezer, 2003). The reasons that may affect occupant's indoor thermal sensation within the same building could be the different room orientations, façade designs, or effects of buildings in the neighborhood (Nikolina and Sandro, 2017), the different floor height may also be one of the reasons.

High-rise buildings are being vastly constructed throughout the world with enormous facades using different curtain walls and/or glass facades. Large glass envelopes have become common in commercial and office buildings and this is because of their ability to make any building look more stunning, spacious, and modern with sufficient daylight. And because of its lightweight it decreases the dead load of a building allowing to build a higher building (skyscrapers).

100% coverage of glass for high-rise buildings has become a usual occurrence. This raises questions regarding the influence of extensive glass surfaces on the thermal environment of the buildings and whether considerations regarding the thermal conditions of office spaces play a role in the selection of glazing materials.

Figure 1-1: Example of the highest-glazed high-rise buildings in the world

From daily life observation in Addis Ababa construction of high-rise buildings is increasing. These high-rise buildings are mainly Apartments, Commercial buildings, office buildings, and mixed buildings. Also, large glass coverage is seen in many buildings. Going around the main business district of Addis Ababa mainly to the (road) one can note that many glazed high-rise buildings are under construction and also that have already finished and started operating. These buildings are mostly office or mixed buildings: most of them are constructed as headquarters of different banks. The headquarters of the commercial bank of Ethiopia is one and the longest of this building where its construction is finished and is assumed to start its operation phase very soon.

In Addis Ababa, Ethiopia, the Commercial Bank of Ethiopia Headquarters stands tall as a symbol of progress and achievement. Completed on 13 February 2022, this skyscraper has become the tallest building in the country. As the headquarters of the state-owned Commercial Bank of Ethiopia, it represents the strength and influence of the country's largest bank. Furthermore, it holds the prestigious title of being the tallest building in East Africa. This high-rise building will be used as a case study in this research.

Figure 1-2: The new headquarters of Commercial Bank of Ethiopia (Barnes, Robert, 2015)

This study seeks to assess the impact of glazing on thermal comfort within the office environments of the newly constructed CBE high-rise building. By analyzing the influence of different glazing configurations, including the one utilized in the CBE HQ tower, the research aims to identify the most effective glazing structure in terms of thermal load and energy consumption.

1.2 Statement of the problem

Workers in office buildings spend most of their time at their desks, and the indoor environment can greatly affect their productivity and well-being, especially in hot seasons. High temperatures can cause discomfort, excessive sweating, and a need for fresh air, leading to increased stress and decreased efficiency. Mechanical systems like HVAC and fans are commonly used to address these issues, but they often result in higher energy consumption and costs. Buildings with more glass are particularly prone to thermal discomfort.

The prevalence of large glass facades in commercial and office structures has become increasingly common. This trend prompts an examination of how expansive glass surfaces affect the thermal environment and energy consumptions of these buildings. Additionally, it raises the question of whether the thermal conditions of office spaces are taken into account when choosing glazing materials. Early design decisions are crucial for reducing energy usage and enabling passive design strategies. However, there is currently no guidance in Ethiopia for selecting efficient curtain walls.

Unfortunately, energy-efficient building materials are not given enough consideration during construction in Ethiopia. Many new buildings still use standard glass and aluminum cladding, leading to significant energy waste over time. These materials have low thermal resistance and mass, creating uncomfortable conditions. To ensure occupant comfort, an energy-optimized HVAC system is essential.

1.3 Objective

1.3.1. General Objective

The general objective of this research is to assess the impact of glazing on the thermal environment of office spaces in the new CBE high-rise building.

1.3.2. Specific Objective

- To evaluate the building’s glass façade’s effect on the indoor thermal environment and energy demand of the new CBE high-rise building.
- To compare the building's glazing systems against various alternatives to determine which structure offers the best efficiency in terms of thermal properties and energy consumption.
- To assess the building’s perceived thermal comfort through survey.

1.4 Research questions

The aim of this research is to answer the following questions

- Does the building’s glazing affect the indoor thermal environment and energy demand of the new CBE high-rise building?
- When it is compared with other types of glazing structures which one has a better thermal property and energy efficiency?

- What is the response of the office workers regarding the indoor thermal environment of their workspace?

1.5 Significance of the study

This study aims to fill the research gap in Ethiopia regarding the thermal comfort of high-rise buildings with 100% glazing. Existing research focuses on visual comfort, but lacks studies on the thermal effects of curtain wall glazing. The findings of this study will help identify energy-efficient curtain wall glazing. This study may also serve as a guide for future architects and engineers in selecting the appropriate glazing structure for specific building types and weather conditions.

1.6 Scope of the study

This thesis focuses solely on assessing the glazing structure used in the CBE Tower, specifically examining its effects on the thermal indoor environment and the energy consumption of the HVAC system. The goal is to perform a comparative analysis of this particular glazing structure against several alternatives. It is important to note that this evaluation is restricted to the combination of glazing structures and does not include any shading devices or sun-blocking elements associated with the building. Additionally, this evaluation does not address factors such as visual comfort, acquisition costs, and aesthetic considerations. general survey was done regarding the subjective survey.

1.7 Limitations of the Study

The procedure of obtaining and confirming permission from the CBE headquarters to access the necessary data proved to be quite intensive and took an unexpectedly long time, resulting in an extension of the overall timeline. Additionally, during this period, project management was in the process of transitioning control from the Chinese contractors, which led to some confusion regarding the provision of assistance and the willingness to share data for the research. Furthermore, access to certain floors was restricted, complicating the collection of hourly measurements. Given the significance of weather data for this study, the project relied on weather information sourced from EnergyPlus, formatted as an EPW file, which was subsequently integrated into the HAP software for simulation purposes.

1.8 Operational definition

Cooling load: refers to the amount of heat energy that needs to be removed from an area to maintain the temperature in an adequate range.

Design temperature: refers to the extreme hot or cold temperature that includes everything up to or below a certain percentage of hours in the year.

Energy consumption: refers to the amount of energy consumed by buildings for various purposes, such as heating, cooling, and lighting.

EnergyPlus: is a versatile software used by engineers, architects, and researchers to simulate energy usage in buildings. It accurately models heating, cooling, ventilation, lighting, plug loads, process loads, and water usage, making it valuable for analyzing and optimizing building designs.

Heating load: refers to the amount of heat energy required to be added to an area to maintain the temperature in an adequate range.

High-rise building: a tall structure, typically with multiple floors, specifically designed for residential or commercial/ office purposes. They are often defined as architectural structures that stand taller than average buildings, usually having more than 12 stories.

HVAC: refers to Heating, Ventilation, and Air Conditioning, the use of various technologies to control the temperature, humidity, and purity of the air in an enclosed space.

Glazing structure: are types of curtain wall systems consisting of glass that is bonded or anchored back to a structure without the use of continuously gasketed aluminum pressure plates or caps.

Thermal load: the amount of heat (sensible and latent) energy to be removed from an inner environment by the refrigeration equipment to maintain that environment at the design temperature when the worst-case external temperature is being experienced.

1.9 Organization of the paper

This research paper is structured into five distinct chapters, each of which thoroughly analyzes the study's content and data. The primary chapters of the thesis are outlined as follows. Chapter one, titled Introduction, provides an overview of the study's background, articulates the problem statement, outlines the objectives, poses the research questions, discusses the significance of the study, the scope, and limitations, presents operational definitions, and the organization of the paper. Chapter two focuses on the Literature Review, which addresses both theoretical and empirical issues pertinent to the conceptual framework of the study. This chapter aims to clarify key research themes, including thermal comfort, curtain walls, glazing structures, thermal load calculations, and associated studies. Chapter three, Methods and Materials, concisely. outlines the methodologies and techniques employed in the study, detailing the description of the study area, data sources, data collection methods, and data analysis techniques. Chapter four, Results and Discussion, presents the findings derived from simulations conducted using Carrier HAP software, focusing on heating and cooling loads as well as energy consumption for each glazing structure, while also engaging in a discussion and comparison of the quantitative data results. Finally, chapter five, Conclusion and Recommendations, serves as the concluding chapter of the research, summarizing the overall findings based on the results and discussions presented in chapter four, and offering recommendations informed by the conclusions drawn.

CHAPTER TWO

2. LITRATURE REVIEW

2.1. Introduction

In recent years, window and glazing systems have gained attention as essential elements of building facades due to their impact on functionality and aesthetics. Windows fulfill various roles, such as allowing natural light, providing ventilation, offering advantageous solar gain in colder climates during winter, enhancing aesthetic appeal, and contributing to positive psychological effects, there by rendering their inclusion in architectural designs unavoidable. (Moghaddam SA)

Glazing systems play an essential role in architectural design, facilitating the creation of visually impactful structures that address both environmental considerations and the requirements of occupants. The choice of glazing systems is equally important. Options range from traditional single-pane windows to advanced double glazed units, each offering varying levels of thermal insulation, soundproofing, and energy efficiency (Foroughian & Aiini, 2017). Glass treatments, such as tinted or reflective finishes, also influence a building's look (Chaiyapinunt et al., 2005). The size of glazing elements is important as well; large glass areas enhance natural light and views, while smaller windows create intimacy and privacy. Materials like aluminum, PVC, timber or Al-clad timber frames shape a building's architectural character (Asif et al., 2005).

Innovations such as low-emissivity coatings and smart glass improve design, energy efficiency, and occupant comfort. Research has demonstrated that indoor thermal comfort plays a crucial role, as it influences both the health and productivity of occupants, as well as the energy efficiency of buildings (Amini et al., 2021). During the preliminary design stage of new energy-efficient structures or while executing energy retrofitting initiatives, it is essential to integrate factors related to thermal comfort.

This chapter offers theorethical and empirical overview of the literature related to indoor thermal comfort, different types of curtain walls, the impact of building glazing on the indoor environment, and the principles of cooling and heating loads. It also covers calculation methods, software simulations, and related previous studies.

2.2. Curtain wall

'Curtain wall' is a term generally applied to a non-structural vertical, external element of a building that helps to keep the weather out and people in. Besides keeping out the wind and rain, it can also provide a multitude of different options related to appearance and functionality. Its external surface might be 100% glass or might include other cladding materials such as stone and aluminum panels. Also, it may contain specific architectural features designed to enhance the appearance of the building or elements intended to manage the effects of the environment. Such features may include brise soleil (a type of solar shading system) and external fins designed to provide shading or photo-voltaic panels capable of generating electricity (CPNI, 2019).

Curtain wall being non-structural can be made of light weight material which helps in reducing construction costs. Using glass as a curtain wall has long become a popular choice of construction; this in return helps natural lights to go deeper into the building, it can also act as a fire barrier; slowing down or preventing the spread of fire between floors of a building (Jacek K., 2016). Using glass as a curtain wall is known as a glazed wall system. Because of their beauty and exceptional benefits, glazed walls are being used in almost all high-rise buildings, also in commercial and residential buildings. They are easy to maintain, affordable, and have a wide range of applications.

2.2.1. Evolution of curtain wall system

Curtain wall has had long history of development which has evolved to today's very extensive applications all over the world. The changing history of curtain walls can be seen in three phases according to their period, exploration phase, development phase, promotion phase, and improvement phase (Summer T., 2020).

Exploration phase (1851-1950): this phase announced the beginning of the modern era of the curtain wall and is also called the first generation of a curtain wall. During this phase, the quality of the glazing and the profiles were continuously developed focusing on the solution of problems that happen over a period of time like leakage resistance, sound and thermal insulation, silicone structures, sealant material aging, and others. The first building to use glass curtain walls is The Crystal Palace, designed by Joseph Paxton and built to house the Great Industrial Exposition of 1851 in London, England (Summer T., 2020).

Figure 2-1: The Crystal Palace, London, England (Allison, 2020)

The development phase (1950-1980): this stage is also known as the second-generation curtain wall. This phase was characterized by the use of new technologies and new materials, to find a solution to the impact of the curtain wall. Development and promotion of ways and means for the development of solutions for various issues such as the development and promotion of hidden frame, silicone structural adhesive was used for semi-hidden frame glass curtain walls, with good adhesion, deformation properties, and aging resistance.

The Alcoa building in Pennsylvania, USA is the first curtain wall building to successfully solve the problem of leakage using the principle of pressure balance. It was designed by Harrison & Abramovitz (Summer T., 2020).

Figure 2-2: The Alcoa Building, Pittsburgh, Pennsylvania, USA

The promotion phase (1980-1996): since the promotion of the application of architectural curtain walls increasingly widened, the content of the building curtain wall and application of new technologies increased showing diversification, factory, and modernization characteristics; they tend to mature and become into the engineering practice. During this phase basic units of curtain walls are all manufactured in the factory and are mainly assembled and installed at the construction site; which improves the construction, the efficiency, and the quality of the curtain wall (Summer T., 2020).

The improvement stage (1990 – to the present): more and more new materials and new technologies are being introduced every day. Curtain wall became not only the pursuit of practical and comfortable but also environmentally friendly, such as photo the emergence of the eco-curtain wall concept, Aluminum non- combustible panel and photovoltaic curtain walls (Summer T., 2020).

The improved design and aesthetic appeal of glass curtain wall systems have had huge impact on commercial and residential properties. These have become so commonplace that it is rare to find a high-rise building in modern metro areas that does not incorporate them in some capacity.

2.2.2. Types of glass curtain wall

Due to fabrication and installation methods, glass curtain wall systems are classified into two general categories; stick systems and unitized or modular systems. 1. Stick systems consist of a framework made up of various components, such as glass or opaque panels. As shown in Figure 3, the vertical elements (mullions) and horizontal components (transoms) are usually assembled on-site, often spanning multiple floors and differing widths, with the glazing installed afterward (Orlowski et al., 2018). Unitized curtain walls are prefabricated panels that combine glazing and framing, classifying them as modular systems. Manufactured in a factory and transported for quick installation, they reduce installation time and labor costs. These systems are primarily used in mid to high-rise buildings for their economic advantages (Orlowski et al., 2018).

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Figure 2-3: Stick-built glass curtain wall system (Orlowski et al., 2018)

Figure 2-4: Unitized or modular built curtain wall system (Orlowski et al., 2018)

In curtain wall systems, the transparent glass installed is called the vision glass. It may be single, double or triple glazed and it may include Low-E coatings or reflective coatings.

Single and double-glazed

Single glazing: Single-glazed windows consist of a solitary pane of glass, serving as the sole barrier between the interior of a building and the external surroundings. Double-glazed windows consist of two panes that are divided by a gap. Traditionally, this gap measured between 12mm and 16mm in width (Ben J., 2023).

Single glazing is often more affordable compared to double glazing (Ben J., 2023). This affordability makes single glazing a popular choice for those on a tight budget or for projects where cost is a significant factor.

In terms of visual appeal, single glazing can offer a sleek and minimalist look, especially in modern architectural designs. The single pane of glass allows for uninterrupted views and a clean aesthetic. On the other hand, double glazing can also be visually appealing, with the added benefit of providing a more substantial and substantial appearance due to the presence of two panes of glass (Victoria L., 2023).

One of the most significant advantages of double glazing is its enhanced insulation properties. The air or gas trapped between the two panes acts as an insulating barrier, reducing heat transfer between the interior and exterior of a building. This insulation helps to keep the interior space warmer in winter and cooler in summer, resulting in reduced energy consumption for heating and cooling (Forughian & Aiini, 2017).

Double glazing also contributes to improved energy efficiency. The insulation provided by the double glazing reduces the need for artificial heating or cooling, resulting in lower energy bills and a reduced carbon footprint (Forughian & Aiini, 2017). This energy efficiency is particularly important in today's environmentally conscious world, where reducing energy consumption is a priority.

Another benefit of double glazing is its ability to reduce noise transmission. The additional layer of glass and the air or gas in between act as a sound barrier; reducing the amount of external noise that enters a building (Quirt, 1982). This can be particularly advantageous for properties located in noisy areas, such as near busy roads or airports, as it helps create a quieter and more peaceful indoor environment.

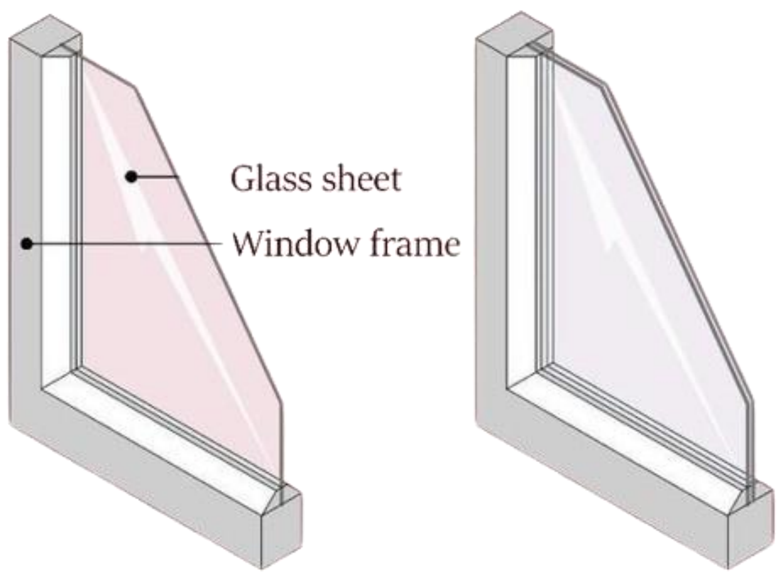


Figure 2-5: Simplified view of a single-glazed window and a double-glazed window (Geboes, 2020).

Overall, while single glazing may have its advantages in terms of affordability and visual appeal, double glazing offers numerous benefits in terms of insulation, energy efficiency, noise reduction, and overall comfort. Double glazing is a more comprehensive and effective glazing alternative that helps to maintain a consistent temperature, reduces drafts, and creates a quieter space, enhancing the overall comfort and well-being of occupants.

Low e-coating

Low-emissivity (low-e) coated products can be classified into two primary categories: hard coatings and soft coatings. The hard coatings are primarily composed of tin oxide and are commonly known as "online" coatings due to their production process being directly linked to the float line. On the other hand, soft coatings typically consist of a thin layer of silver surrounded by dielectric protective layers. In comparison to hard-tin oxide-based coatings, soft silver-based coatings exhibit higher infrared reflectance and lower solar transmittance. (Johnson, 1991).

To minimize energy consumption in both opaque and transparent areas of a building, the implementation of low-emissivity (low-e) materials is highly beneficial. The primary focus of these materials is to mitigate the transfer of heat through thermal radiation. Moreover, low-e materials also play a significant role in influencing the amount of daylight and total solar radiation energy that enters windows. This aspect is often quantified as the solar heat gain coefficient (SHGC) (Bjorn, 2015).

Tinted glazing

Tinted glazing is a type of glass created by adding metal oxides during production, resulting in permanent colors like bronze, green, blue, and gray. Its primary purpose is to reduce solar heat and glare, with light blue and green tints offering better visibility and thermal control (Tin-tai Chow, 2010). Despite the color change, tinted glazing maintains durability, transparency, and strength, primarily affecting solar energy management.

In hot climates, it helps keep buildings cooler, reducing air conditioning needs and energy consumption, while also filtering harmful UV rays. Additionally, it enhances privacy and adds aesthetic appeal to buildings (Tin-tai Chow, 2010). Tinted glazing is a popular choice in construction for its combination of functionality, beauty, and sustainability.

Reflective coating

A reflective coating is used to improve building glazing efficiency by reducing solar heat gain while allowing more natural light. Made of thin metallic or metal oxide layers, these coatings come in various colors like silver, gold, and blue, providing design flexibility without compromising heat reduction. Their effectiveness depends on thickness and reflectivity; thicker, more reflective coatings offer better heat reduction. While they may slightly affect the U-factor, the overall impact on energy performance is minimal. (Rathi, 2012).

They are an effective and attractive solution for enhancing daylight transmission and reducing solar heat gain, making them valuable for energy-efficient design. With various color choices and adjustable performance based on thickness and reflectivity, these coatings are a valuable resource for architects and designers looking to improve energy efficiency and aesthetics in glazing systems.

2.3. Indoor thermal comfort

Thermal comfort describes the human satisfactory perception of the thermal environment (ASHRAE 55). It refers to several conditions in which the majority of people feel comfortable. Thermal comfort is rated among the most important conditions for improving the comfort and satisfaction of occupants with their indoor environment. (M.Frontczak, 2011)

The heat exchange between the human body and its environment occurs mainly in three ways, namely through radiation, convection, and evaporation (S.P. Corgnati, 2011). The thermal indoor environment is affected by both internal and external sources.

- Common heat sources are electrical equipment (such as lighting and computers), sun radiation, and human presence
- Common sources of cold are window surfaces, poorly insulated walls, and thermal bridges (S.P. Corgnati, 2011).

In certain instances, achieving a thermal environment that caters to the preferences of all occupants in a building may prove to be unattainable due to their unique individual preferences. However, it is feasible to define conditions that are likely to be perceived as satisfactory by the majority. Moreover, when coupled with opportunities for individual control, such as adjusting clothing or opening windows, overall satisfaction with the environment is expected to significantly increase (CEN/TC, 2007). The thermal conditions within a building can impact the productivity and work performance of its occupants through various mechanisms. Thermal discomfort has the potential to lead to distractions, disrupt well-being, and diminish concentration (J. Varjo, 2015).

The concept of the comfort zone, widely utilized by ASHRAE, refers to the fundamental condition in which the majority of individuals experience comfort. This notion plays a crucial role in the design process of air conditioning systems. ASHRAE's ANSI/ASHRAE Standard 55, titled "Thermal Environmental Conditions for Human Occupancy," is an American National Standard that outlines the acceptable ranges of indoor environmental conditions necessary to achieve thermal comfort for building occupants. Initially published in 1966, this standard has undergone updates every three to six years since 2004. The most recent edition was released in 2020 (Cryer, 2021). Table 2-1 outlines the design criteria for an office building as specified by ASHRAE's Standard, emphasizing factors like indoor temperature, relative humidity, and air movement and circulation.

Table 2-1 Office Design Criteria (ASHRAE 55)

Category	Inside Design Conditions		Air Movement	Circulation, air changes per hour
	Winter	Summer		
Office Buildings	21 to 23°C 20 to 30% rh	23 to 26°C 50 to 60% rh	0.13 to 0.23 m/s 4 to 10 L/ (s ·m2)	4 to 10

2.3.1. Impacts of building’s Glazing system on the indoor thermal comfort

Glass curtain walls exposed to solar radiation and built-up zones with control temperature a very complex thermal system. The intensity of thermo physical processes directly in a glass and on boundary layers depends on weather conditions and indoor parameters determined by heating/cooling control system. Particularly, the following two weather parameters should be considered: solar radiation and air temperature. Solar radiation decides of the intensity of photo-thermal conversion in a construction of the facade and the adjacent zone. (Hein, 2013).

High intensity solar radiation is unfavorable, as it increases the temperature of internal surfaces, which then causes a rise of the mean radiant temperature. Air temperature determines the heat exchange with the human body and affects the internal surface temperature. Therefore, both parameters and thermo physical processes indirectly create thermal comfort in a building.

As architects like transparent building components because of the aesthetic and practical point of view. Office workers sitting behind uncovered glass facades are usually strongly exposed to solar radiation which has an effect of radiation asymmetry. (Arbab M., 2010)

2.3.2. Cooling load and heating load calculation

The cooling load for a space refers to the amount of heat that needs to be extracted from the space to keep the air temperature constant (EBCS-11, 2015). It is important to note that the total heat gains in the space at any given time may not always be equal to the cooling load for that specific time. This is because radiant energy needs to be absorbed by the surfaces surrounding the space, such as walls, floors, ceilings, and objects like furniture before it can contribute to the cooling load. (EBCS-11, 2015).

The cooling coil load refers to the amount of energy that is extracted from the cooling coil, which is responsible for cooling one or multiple conditioned spaces. This load is determined by adding up the instantaneous cooling loads of all the spaces served by the coil, assuming that the space temperature remains constant. Additionally, any external loads such as fan heat gain, duct heat gain, and the heat and moisture from outdoor air brought into the cooling equipment to meet ventilation requirements are also included in the cooling coil load (EBCS-11, 2015).

The calculation of the cooling load for common building construction is derived from the transfer function method, which is based on the following formula (EBCS-11, 2015).

$$Q = UA*(T_1 - T_2) \qquad \text{………………………. (Eqn. 2.1)}$$

Where; U = Overall heat transfer coefficient

A = Net Surface area

T_1 = Outside temperature

T_2 = Inside temperature

<u>Cooling load principles and components</u>

The air-conditioning system's workload can be categorized into:

- Sensible transmission through glass,
- Solar gain through the glass,

- Internal heat gains,
- Heat gain through walls,
- Heat gain through the roof, and
- Ventilation and/or infiltration gains.

The heat transfer that occurs through glass windows can be categorized into two components. The first category is due to the difference in temperature between the outside and inside, while the second category is caused by solar radiation passing through the windows. On the other hand, the heat gains through solid ground floors are negligible and can be disregarded.

<u>Sensible transmission through glass</u>

The concept of Sensible Transmission through Glass refers to the Solar Gain that happens due to temperature differences between the inside and outside environments. This gain is especially significant in areas with hot climates.

It is worth mentioning that this gain only applies to materials like glass that have low thermal capacity.

$$Q_g=A_gU_g(T_o-T_r) \qquad \text{.......... Eqn. (2.2)}$$

Where; Q_g = sensible heat gain through glass (W)

A_g= Surface area of glass (m^2)

U_g = 'U' values for glass ($W/m^{2\ OC}$)

T_o = Outside air temperature (^{OC})

T_r = Room air Temperature (^{O}C

<u>Solar gain through the glass</u>

Solar gain through windows occurs when sunlight passes through the windowpanes.

$$Q_{sg} = F_c.\ F_s.\ q_{sg}.\ A_g \qquad \text{.......... Eqn. (2.3)}$$

Where Q_{sg} = Actual cooling load (W)

q_{sg} = Tabulated cooling load from (W/m^2)

F_c = Air node correction factor from Table below.

F_s = Shading factor from Table below.

A_g = Area of glass (m^2)

The Air point control factors (Fc) and Shading factors (Fs) for different glass types, building weights, and the presence of open or closed blinds are provided in the table 2-2 and table 2-3 below.

Table 2-2: Air node correction factors (F_C) for single and double glazing with respect to different weight (CIBSE guide, 2014)

Air node correction factors (F_C)		
Building weight	Single glazing	Double glazing
	Horizontal blind	Horizontal blind
Light	0.91	0.91
Heavy	0.83	0.90

Table 2-3: Shading factors (F_s)for various types of glass, building weight, and open and closed blinds (CIBSE guide, 2014)

Shading factors (F_s)					
Types of glass	Building weight	Single glazing		Double glazing	
		Open horizontal blind	Closed horizontal blind	Open horizontal blind	Closed horizontal blind
Clear 6mm	Light	1.00	0.77	0.95	0.74
	Heavy	0.97	0.77	0.94	0.76
Bronze tinted 6mm	Light	0.86	0.77	0.66	0.55
	Heavy	0.85	0.77	0.66	0.57
Bronze tinted 10mm	Light	0.78	0.73	0.54	0.47
	Heavy	0.77	0.73	0.53	0.48
Reflecting	Light	0.64	0.57	0.48	0.41
	Heavy	0.62	0.57	0.47	0.41

Internal heat gains

Internal heat gains in a building are primarily generated by occupants, lighting fixtures, and various types of equipment and machinery. These heat gains can be attributed to the average power density emitted by light fixtures, as well as the operation of electrical equipment such as PCs, monitors, laser printers, photocopiers, electric motors, and lift motors. These sources contribute to the overall thermal load within the building, impacting its energy consumption and temperature regulation.

Table 2-4: Typical heat gain values for different scenarios (EBCS-11, 2015)

Conditions	Typical building	Sensible heat gain (Watts)	Latent heat gain (Watts)
Seated very light work	Offices, hotels, apartments	70	45
Moderate office work	Offices, hotels, apartments	70	55
Standing, light work; walking	Department store, retail store	75	55
Walking. Standing	Bank	75	70
Sedentary work	Restaurant	80	80
Light bench work	Factory	80	140
Athletics	Gymnasium	210	315

Therefore, the overall latent heat load is determined by calculating the sum of all latent heat contributions: as shown below:

Q_{int}= Heat from occupants +Heat from lighting + Heat from electrical lighting + heat from cooking …. …..…….. (Eqn.2.4)

Sol-Air Temperature

In the determination of heat flow, the concept of sol-air temperature is employed to calculate infiltration. Sol-air temperature refers to the outside air temperature that would result in an equivalent heat flow rate into the outer surface of the wall, considering only temperature difference and excluding radiation exchanges.

$T_{eo} = T_a + [(\alpha.I \cos a. \cos n + \alpha I_s)/ h_{so}]$ ………… (Eqn.2.5)

Where; T_{eo} = Sol-Air Temperature (0 c)

T_a = Outside air temperature (0 c)

α= absorption coefficient of surface

I = Intensity of direct solar radiation on a surface at right angles to the rays of the sun. (W/m2)

a = Solar attitude (degrees)

n = Wall-solar azimuth angles (degrees)

I_s = intensity of scattered radiation normal to a surface (W/m2)

h_{so} = External surface heat transfer coefficient (W/m2 0C)

Heat gain through walls and roofs

This refers to the process by which heat is transferred across a wall or a roof due to the varying levels of solar radiation that impact its exterior surface. This dynamic transfer of heat occurs as the wall or a roof absorbs and releases thermal energy in response to the changing intensity of sunlight.

Understanding and managing heat gain through walls is crucial for maintaining a comfortable indoor environment and optimizing energy efficiency in buildings. By considering factors such as solar radiation, wall properties, and insulation, it is possible to minimize heat gain and create more sustainable and comfortable living or working spaces.

$Q_{wall} = A.\ U\ (T_{wi} - T_r)$ ……………… (Eqn.2.6)

Where; Q_{wall} = Heat gain from the wall (W)

A= Area of the wall (m2)

U = U-value (W/m2 0C)

T_{wi} = Inside wall temperature (°C)

T_r = Room temperature (°C)

Heat gain through roof

$Q_{roof} = A.\ U.[\ (T_{em} - T_r) + f\ (T_{eo} - T_{em})]$ ………… (Eqn.2.7)

Where; Q_{roof} = Heat gain from the roof (W)

A= Area of the wall (m2)

U = U-value (W/m2 0C)

T_r = Room temperature (°C)

T_{eo} = Sol-Air Temperature (0 c)

T_a = Outside air temperature (0 c)

<u>Ventilation and/or Infiltration Gains Heat load</u>

Incorporating infiltration gains into the room's heat gains is essential. For most air-conditioning scenarios, it is advisable to consider infiltration rates of 1/2 air change per hour. When accounting for ventilation or fresh air supply loads, it is important to add them either to the room or central plant loads, but they should only be considered once.

$Q_{si} = n. v. (T_o - T_i) /3$ ……………… (Eqn. 2.8)

Where; Q_{si} = Sensible heat gain (W)

n = number of air changes per hour (h^{-1})

V = volume of room (m^3)

T_o = outside air temperature (°C)

T_i = room air temperature (°C)

Total Room Load From Heat Gains

$Q_{total} = Q_g + Q_{sg} + Q_{int} + Q_{wall} + Q_{roof} + Q_{si}$ ………… (Eqn. 2.9)

Where; Q_{total} = Total Room Load From Heat Gains

Q_g = sensible heat gain through glass (W)

Q_{sg} = Actual cooling load (W)

Q_{int} = Internal heat gains

Q_{wall} = Heat gain from the wall (W)

Q_{roof} = Heat gain from the roof (W)

Q_{si} = Sensible heat gain (W)

2.3.3. General cooling and heating load calculation procedures (EBCS 11)

Space cooling load

To accurately calculate the cooling load for a space, access to detailed building design information and specific weather data is necessary. The following procedures should be followed:

Reviewing building plans and specifications reveals important details about a structure's design, such as materials, sizes, colors, and shapes, which are crucial for understanding its construction and overall appearance.

To determine building location, orientation, and external shading, analyze plans and specifications. Assess nearby building shading using a site plan or visit. Evaluate shading permanence before including it in calculations. Consider high levels of ground-reflected solar radiation. Account for solar load from neighboring reflective buildings.

Obtain meteorological data and identify ideal outdoor conditions for design purposes using a Table shown in Appendix 2 which lists design conditions for various locations in Ethiopia.

Select indoor environmental parameters, like dry-bulb temperature, wet-bulb temperature, and ventilation rate, following ASHRAE handbook guidelines. Consider acceptable deviations and limits for control.

Obtain a proposed schedule for lighting, occupancy, internal equipment, appliances, and processes affecting thermal load. Determine if the cooling equipment will be consistently running or turned off during unoccupied periods like nights and weekends.

Designing and sizing central air-conditioning systems involves more than just calculating the cooling load. Factors like system type, fan energy, duct heat loss, and lighting systems all play a role in determining system load and component sizing. Analyzing system performance through psychometric processes is essential for proper design and sizing.

Space heating load

To determine the design heating load for a building, specific information about the building design and weather data is necessary. This includes selecting outdoor design weather conditions and determining the desired indoor air temperature for each space.

Heat transfer coefficients for various building components must be chosen or calculated. The net area of outside walls, glass, and roof next to heated spaces, as well as any cold walls, floors, or ceilings next to unheated spaces, should be determined.

Transmission heat losses for each type of wall, glass, floor, ceiling, and roof need to be computed. Heat losses from basement or grade-level slab floors must also be calculated. Unit values should be selected, and the energy associated with cold air infiltration needs to be computed. If positive ventilation using outdoor air is provided, the energy required to warm the outdoor air must be considered. The total heating load is the sum of coincidental transmission losses, energy associated with cold air infiltration, and ventilation air required to replace mechanical exhaust.

Ventilation zone parameters shall be determined by Breathing Zone Outdoor Airflow through Zone Outdoor Airflow for each ventilation zone served by the ventilation system. The outdoor airflow required in the breathing zone of the occupiable space or spaces in a ventilation zone, i.e., the breathing zone outdoor airflow (Vbz), cannot be less than the value determined by the following equation. (ANSI/ASHRAE Standard 62.1-2010)

$$Vbz = Rp \cdot Pz + Ra \cdot Az \qquad \text{… …… (Eqn. 2.9)}$$

Where; Az = Zone floor area: the net occupiable floor area of the ventilation zone ft2 (m2)

Pz = zone population: the number of people in the ventilation zone during typical usage

Rp = outdoor airflow rate required per person as determined from Table 6-1 Note: These values are based on adapted occupants.

Ra = outdoor airflow rate required per unit area as determined from Table 6-1

Equation accounts for people-related sources and area-related sources independently in the determination of the outdoor air rate required at the breathing zone.

Table 2-5: Minimum ventilation rates in breathing zone of an office buildings (ANSI/ASHRAE Standard 62.1-2010)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values			Air Class
						Occupant Density (see Note 4)	Combined Outdoor Air Rate (see Note 5)		
	cfm/person	L/s·person	cfm/ft^2	L/s·m^2		#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	
Office Buildings									
Breakrooms	5	2.5	0.12	0.6		50	7	3.5	1
Main entry lobbies	5	2.5	0.06	0.3		10	11	5.5	1
Occupiable storage rooms for dry materials	5	2.5	0.06	0.3		2	35	17.5	1
Office space	5	2.5	0.06	0.3		5	17	8.5	1
Reception areas	5	2.5	0.06	0.3		30	7	3.5	1
Telephone/data entry	5	2.5	0.06	0.3		60	6	3.0	1

The hand calculation method for determining the cooling and heating load, as mentioned in the above sections, is extremely demanding and requires significant effort. Therefore, to simplify and streamline the process, the calculation for both cooling and heating load in this study was carried out using the Hourly Analysis software simulation software.

2.4. Carrier’s Hourly Analysis Program (HAP) software

Carrier's Hourly Analysis Program (HAP) is a comprehensive software package that combines the power of system design and energy analysis tools. HAP is cutting-edge software that combines two powerful tools in one convenient package. With its versatile features, HAP enables engineers and designers to efficiently create and optimize HVAC systems for commercial buildings. HAP helps users make informed decisions and develop energy-efficient systems for each project by providing energy analysis and cost comparisons. This saves time and allows for easy utilization of input data and outcomes in energy studies, improving overall efficiency.

HAP's energy analysis capabilities are advantageous for green building design, and is recognized by the U.S. Green Building Council for its; LEED (Leadership in Energy and Environmental Design) Rating System (AHI Carrier SE Europe Air Conditioning). It caters to consulting engineers, contractors, and facility engineers, helping determine system sizes for various types of buildings. HAP supports multiple system controls and can be used for a wide range of buildings and projects. The software has been tested according to ANSI/ASHRAE Standard 140-2007 Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs (US departments of energy, 2009).

The HAP software employs a visually appealing "explorer" graphic style, enabling users to swiftly and effectively access project data. By employing a modular approach, the software defines building components and HVAC systems, allowing for utmost flexibility in configuring data to suit various applications.

Its feature offers a time-saving advantage in the data entry process for spatial information. It proves to be particularly beneficial for initial projects and screenings. The Wizard efficiently generates the required data for the designated spaces in a prompt manner.

It conducts an actual hourly energy analysis by utilizing climatic data gathered for each of the 8760 hours in a year, in order to determine the heat transfer of the structure, as well as the loads, functioning of the air system, and operation of the equipment plant.

The computation involves the determination of space and zone loads throughout each hour. Additionally, it evaluates the heating flow for various components within the room, including walls, windows, roofs, skylights, doors, lighting, occupants, electrical appliances, infiltration, floors, and partitions, considering both the time of day and the time of year.

2.5. Variable refrigerant flow (VRF) system

Variable refrigerant flow (VRF) is an innovative technology that efficiently circulates the precise quantity of refrigerant required for a singular heating or cooling cycle. It is a specific configuration of an air-conditioning system that consists of a single outdoor condensing unit and multiple indoor units.

VRF technology is utilized to partition a building into customized zones to enhance comfort and energy efficiency. By eliminating the requirement for fossil fuels, an all-electric VRF system operates by circulating refrigerant between an outdoor unit and the ductless or ducted indoor unit(s) within each zone. Up to 50 indoor units can be linked to a single outdoor unit. (Alahmer and Alsaqoor: 2017)

The term "variable refrigerant flow" describes the system's capability to regulate the amount of refrigerant that circulates to the various evaporators (indoor units). This allows for the utilization of multiple evaporators with different capacities and configurations, all connected to a single condensing unit. Moreover, this configuration enables zone control, allowing for individual temperature control in different areas or zones. (EBCS-11, 2015)

VRF multi-split systems represent an advanced iteration of the multi-split system, offering enhanced sophistication. These systems provide both heating and cooling functionalities and can be equipped with either a 2-pipe or a 3-pipe refrigerant pipework system. The latter enables the transfer of heat from a room in need of cooling to another room within the same building that requires heating (Youho, 2015). By incorporating a variable speed compressor, the system can effectively adjust its capacity to precisely align with the heating and cooling demands of the building (Alan Abela, 2014).

VRF systems offer the flexibility to adjust the refrigerant flow to indoor units according to the specific demand. This unique feature enables precise control over the amount of refrigerant supplied to fan coil units distributed across a building. Consequently, VRF technology proves to be highly advantageous in scenarios where there are fluctuating loads or a need for zoning capabilities. (Goetzler, 2007)

In a VRF system, it is possible to connect several indoor fan coil units to a single outdoor unit (Afify, 2008). The outdoor unit is equipped with one or multiple compressors that are driven by inverters, allowing for the adjustment of their speed by altering the frequency of the power supply. Each indoor fan coil unit is equipped with its own metering device, which is controlled either by the indoor unit itself or by the outdoor unit. As each indoor unit sends a request to the outdoor unit, the outdoor unit supplies the necessary amount of refrigerant to fulfill the specific needs of each indoor unit. (ASHRAE, 2004)

Various zones are assigned specific set points according to factors such as usage, occupancy, solar loads, and user preferences. By allowing occupants to personalize comfort levels within their zones, facility managers can still efficiently manage heating and cooling through centralized equipment control. VRF systems are designed to operate quietly and consume minimal energy in order to uphold the desired set points for each zone. Additionally, the constant operation of VRF fans aids in air distribution, eliminates temperature inconsistencies, and reduces the necessity for high-velocity air blowing.

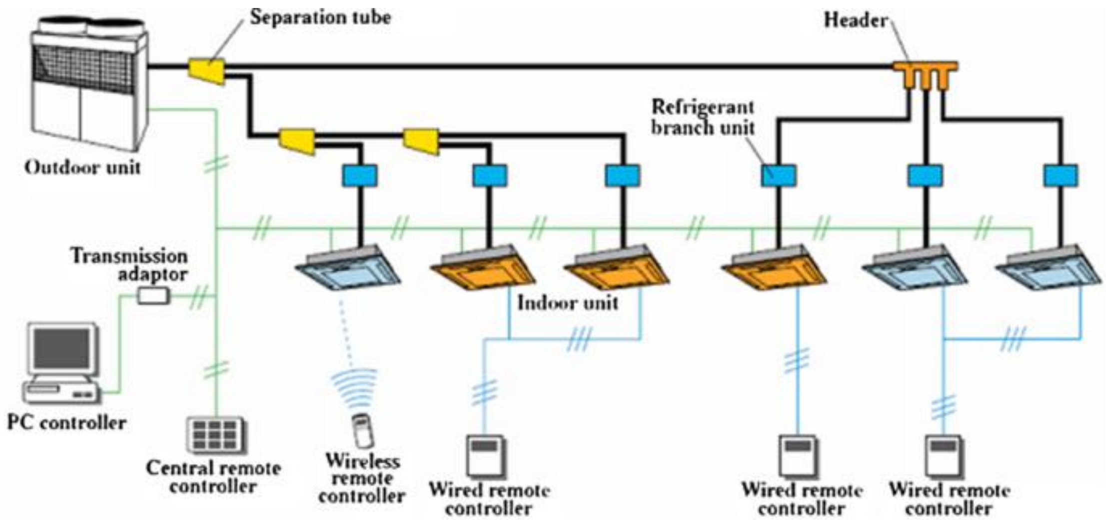


Figure 2-6: Components of a VRF system (Alahmer and Alsaqoor: 2017)

2.6. Empirical literature review

Selection of glass curtain walls based on their thermal performance

A study was made on the thermal performance of a three-bedroom residential house by analyzing the impact of windows glazing and frame in Abu Dhabi. The study utilized an existing house as a case study and aimed to assess the most effective windows glazing option in terms of solar heat gain, cooling loads, and energy consumption. The cooling set point for the design temperature was set at 23^{o}C, while no heating system was taken into consideration. To achieve this, computer simulations were carried out using IES VE software, considering various scenarios. These scenarios included double clear, triple clear, double low-e, and triple low-e glazing options, with the latter incorporating both clear and low-e glazing materials, namely Aluminum and PVC frames. The study concluded that the optimal scenario for energy consumption reduction, amounting to a 6% decrease in annual energy consumption, was triple glazing with low emissivity pane and PVC frame (Awadh Omair, 2014).

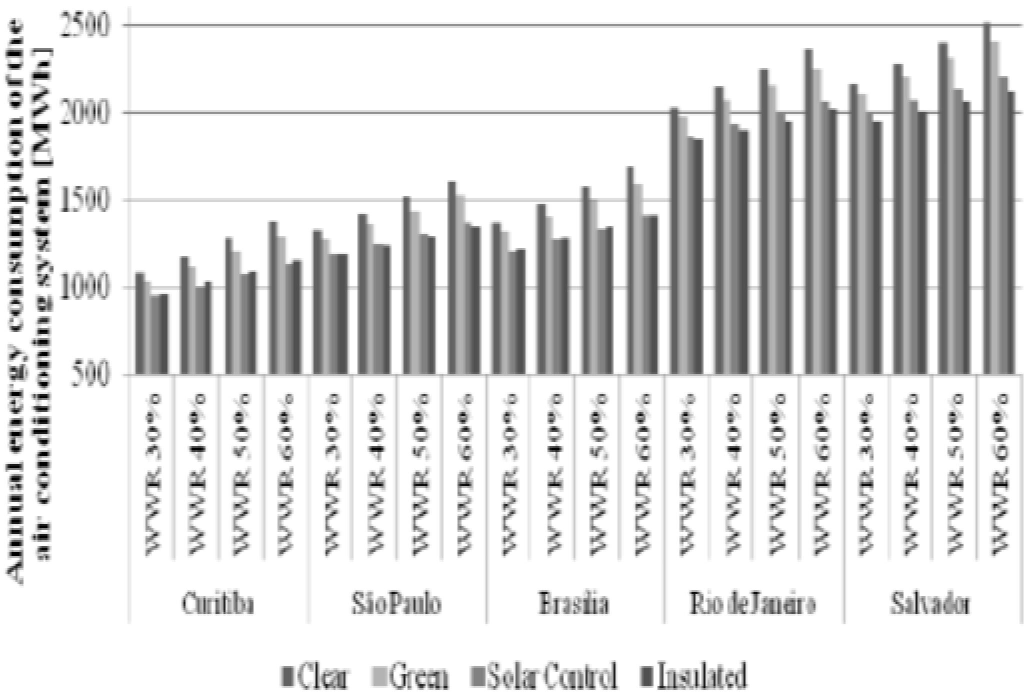
In another research the selection of suitable glazing for glass-curtain walls in tropical climates was investigated in three different climates in India: Composite (New Delhi), hot and dry (Jodhpur), and warm and humid (Chennai). A specific office building was chosen as a case study to analyze the appropriate glazing selection for glass-curtain walls in these tropical climates. The study examined five types of glazing, namely double-glazed clear glass, double-glazed low-e, and double-glazed solar control. Additionally, the study investigated the impact of glazed area, orientation, and climate on annual energy consumption. The findings revealed that energy consumption increases proportionally with the glazed area, with the minimum energy consumption observed for buildings with a north orientation. Among the different types of climates considered in the study, it was determined that a glass-curtain wall constructed with solar control glazing (reflective) consumes approximately 6-8% less energy compared to a standard window (Garg, 2011).

Impact of glazing façades on the energy consumption of buildings

A computer simulation was conducted by a researcher (Fernando Simon Westphal) to examine the impact of glazing façades on the energy consumption of the air conditioning system in an office building across five cities in Brazil (Fernando, 2016). The study analyzed various parameters including: the window-to-wall ratio (WWR), glass type, wall construction, façade configuration (fully glazed or not) and climate.

The research methodology used in this study involved the EnergyPlus simulation software. Two façade configurations were simulated: a conventional façade arrangement, where the wall is directly exposed to the outdoor environment, and a glazed skin façade, characterized by the application of white glass over the exterior walls.

The results were presented using graphs. The cooling energy consumption data for a set of 64 cases, simulated with a traditional façade configuration that lacks a glazed skin, was presented as below.



Annual energy consumption for cooling (MWh) of building models with conventional façade as function of WWR, type of glass and climate.

The relative rise in energy consumption was analyzed for each of the 64 scenarios featuring a glazed skin façade, in comparison to another set of 64 scenarios lacking this characteristic. Additionally, the analysis explored the variations in energy consumption between cases with a window-to-wall ratio (WWR) of 60% and those with a WWR of 30%. This assessment was conducted on building models both with and without a glazed skin façade, and the findings were illustrated through clear graphical representations.

The analysis revealed a linear relationship between energy consumption and window area. The use of selective glazing systems with a solar heat gain coefficient (SHGC) below 40% demonstrated better energy performance. Interestingly, for the coldest city among the five considered, the Insulated Glass Unit was found to be more energy-intensive, while the use of laminated (monolithic) glass was found to be energy-efficient for this particular area (Fernando, 2016).

The authors recommended the utilization of detailed computer simulations to determine the influence of architectural decisions on the energy performance of buildings, cautioning against generalizing the research findings as they are specific to the characteristics of the building model and the climate conditions considered (Fernando, 2016).

Selection of energy efficient glass curtain walls

An extensive investigation was conducted to explore the design considerations necessary for creating energy-efficient curtain walls in high-rise buildings across eleven major cities in the United States. This research highlighted the critical importance of performing a comprehensive assessment of glazing characteristics, as well as understanding the broader implications of glazing choices. These implications extend to essential aspects such as equipment sizing and the overall thermal comfort experienced within the building. The study specifically focused on various factors associated with the building envelope, placing particular emphasis on the curtain wall system. Among the key variables examined were the window-to-wall ratio, which refers to the proportion of windows to the total wall area; the U-value, which measures the thermal transmittance of both walls and windows; the solar heat gain coefficient (SHGC), which indicates how much solar radiation is admitted through the window; visible transmittance (VT), which measures the amount of visible light that passes through the glazing; and the dimensions of overhangs, which can influence shading and solar gain (DuMez, 2017)..

To conduct this analysis, the researchers utilized EnergyPlus, a sophisticated simulation tool specifically designed for evaluating energy loads, system performance, and overall energy efficiency in buildings. The particular curtain wall configuration analyzed in this study featured a substantial window-to-wall ratio of 70%, which is indicative of a design that maximizes natural light while still considering energy efficiency. The findings of the study were significant, with annual utility cost savings estimated to range between $61,505 and $303,389, depending on the specific glazing options selected. Notably, the glazing configurations that resulted in the most substantial savings were those with a solar heat gain coefficient (SHGC) of 0.6 and a visible transmittance (VT) of 50%. These results underscore the potential for well-considered glazing choices to not only enhance the aesthetic appeal of high-rise buildings but also to deliver considerable economic and environmental benefits (DuMez, 2017).

A thesis titled "Optimization of Energy Efficient Windows in Office Buildings for Various Climate Zones in the United States," aiming to identify deficiencies in fenestration standards and develop revised design guidelines using computer simulations was conducted. Utilizing the IES Virtual Environment (IESVE) tool, the study evaluated daylight availability and energy consumption in an office building with various window types, including Arctic Blue, Bronze, and several Low-E options, with clear glazing as the baseline. The optimization focused on improving daylight penetration and reducing electric lighting needs by selecting appropriate glazing and window-to-wall ratios (WWR). This effective use of daylight resulted in energy savings of approximately 10-15% in hot climates and 5-8% in temperate and cold climates (Rathi, 2014).

Summary

This chapter addresses both theoretical and empirical considerations relevant to the conceptual framework of the study. It provides an overview of window and glazing systems utilized in high-rise buildings, detailing various types and their characteristics, as well as their effects on the indoor thermal environment of buildings. The chapter also outlines the methodology for calculating thermal loads in accordance with the EBCS 11 procedure. Additionally, it discusses the theoretical aspects of simulation software and Variable Refrigerant Flow (VRF) systems. The empirical section reviews relevant research on the selection of appropriate glazing materials, specifically glass curtain walls, tailored to distinct climatic conditions. It evaluates the impact of window glazing and framing on the thermal performance of buildings, examines how glazing façades affect the energy consumption of air conditioning systems in office buildings, and considers energy-efficient design principles for curtain walls in high-rise structures. Furthermore, it explores the implementation of energy-efficient windows in office buildings across various climates, identifying shortcomings in existing standards and proposing revised guidelines through the application of computer simulation techniques. This body of literature significantly contributes to the study's development and analytical approach of the study.

CHAPTER THREE

3. MATERIAL AND METHODS

This section of the study offers a brief summary of the methods and techniques used to accomplish the objective of the study. Specifically, it includes information about the study area, data sources, data collection process, and the methods employed for data analysis.

3.1. Description of the study area

The headquarters of the Commercial Bank of Ethiopia is prominently located in Addis Ababa, Ethiopia, on Yohanis Street, adjacent to the Ethiopia Hotel. Its precise geographical coordinates are 9.0165513°N and 38.7543284°E.

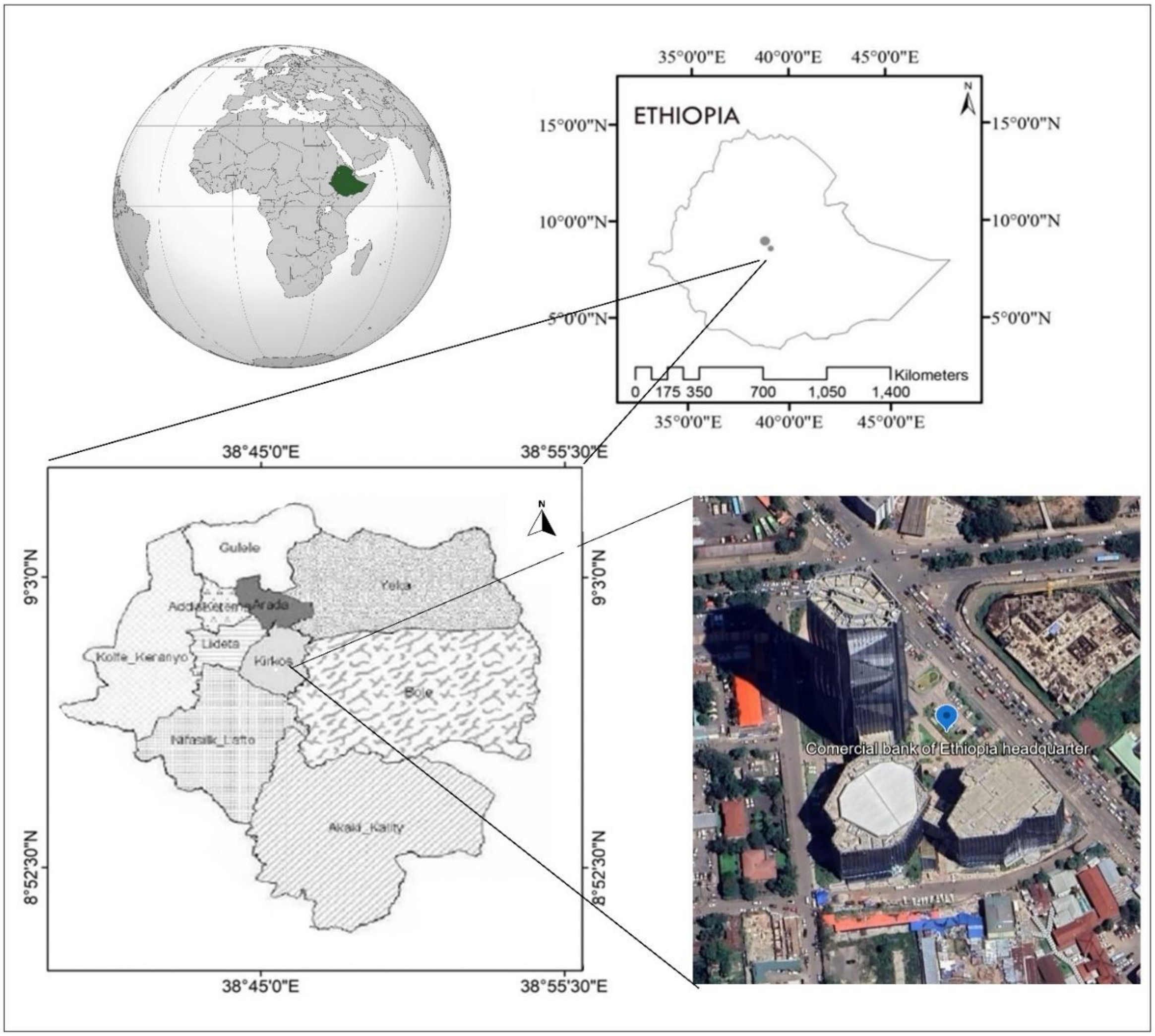


Figure 3-1: Location map of the study area; CBE HQ building

The CBE Tower in Addis Ababa, Ethiopia, has achieved its finished status. It was initiated in October 2015. The construction was completed on 13 February 2022, after being topped out on 11 November 2018. The project had a total cost of ETB 5.3 billion (US$303 million) and is currently owned by the Commercial Bank of Ethiopia. The architectural design was executed by Henn GmbH, while the China State Construction Engineering Corporation (CSCEC) served as the main contractor for its construction.

The Commercial Bank of Ethiopia's new headquarters showcases an impressive architectural design, with a height of 209 meters, and covers a floor area of 150,000 square meters. The tower consists of a total of 52 stories. Among these, 48 floors are situated above ground level, serving as commercial spaces up to the second floor, while the remaining floors are dedicated to office use. The building also has a mezzanine level, and a ground floor, and the underground part has 4 basement floors; mainly used for parking and equipment rooms with a total of 1422 parking bays.

Additionally, the building features two 5-story podiums that are bridged with each other and the tower. Notably, the design incorporates various functional spaces, including eight conference halls, an emergency waiting room dedicated to handling disasters, and two exquisite restaurants on the topmost floors. Furthermore, the building offers a sightseeing tower, providing visitors with a captivating panoramic view of the surrounding area.

This prominent location is surrounded by notable landmarks such as Ambassador Park, Filwoha, Ethiopian National Theatre, and various renowned private and governmental sectors

3.1.1. Case study selection

The headquarters of the Commercial Bank of Ethiopia is the principal facility for the state-owned Commercial Bank of Ethiopia, which is the largest financial institution in the nation, it is recognized as the tallest structure in both Ethiopia and the broader East African region. This characteristic renders the new CBE headquarters particularly suitable for this study, especially given that it represents the latest advancements in high-rise construction and HVAC technologies within the country, thereby encouraging research that aligns with contemporary developments.

3.2. Research design

This study aims to evaluate how glazing structure affects thermal comfort in indoor spaces. Consequently, the relationship between glazing structure and indoor thermal comfort serves as the foundation for this research, as these two variables are interrelated. Figure 3-2 outlines the comprehensive workflow associated with the research.

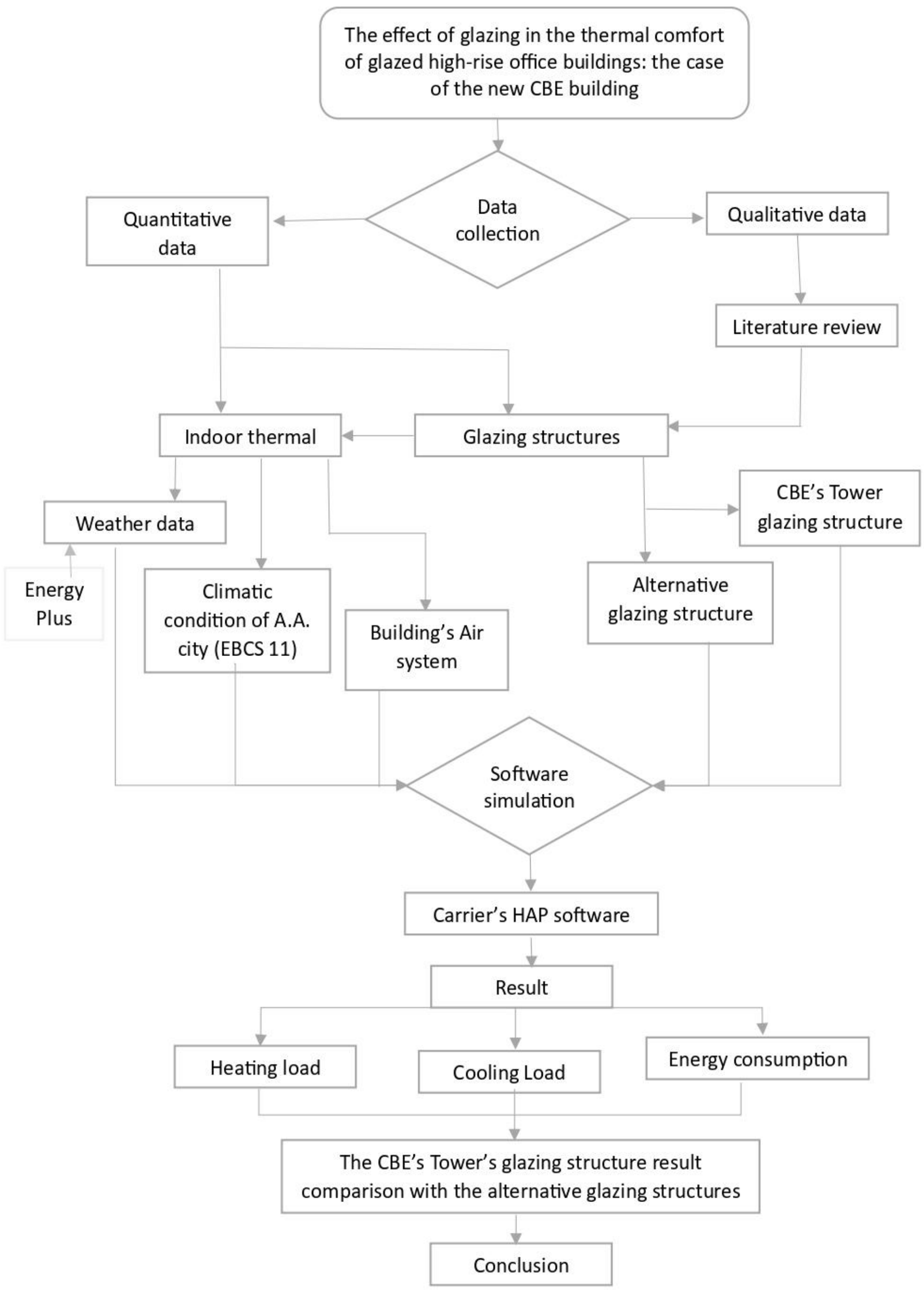


Figure 3-2 Research design diagram

3.3. Research Approaches

This study is based on a positivist approach, a philosophical theory that emphasizes the importance of observable phenomena and empirical evidence. Positivism promotes scientific methods to gather data, analyze it, and draw conclusions based on objective measurements rather than subjective interpretations; ensuring reliable and valid findings that can be generalized. The research design employs quantitative methods, which allow for the systematic collection and analysis of numerical data. Data regarding design parameters, weather data, performance metrics for various glazing configurations, and specific characteristics of the air system properties of the buildings were gathered and examined through the use of simulation software. This study's foundation in positivism reflects a commitment to empirical inquiry, rigorous methodology, and the pursuit of objective truths, ultimately aiming to contribute valuable insights to the existing body of knowledge; It Also, values replicability, enabling other researchers to reproduce the study and verify its findings.

3.4. Sources of data

The study utilized both primary and secondary data sources. The primary data sources included details of the glazing structure of the new CBE Tower, as well as architectural specifics like drawings and relevant information obtained through direct conversations with the responsible individuals. A subjective survey of the indoor thermal environment was carried out among the office workers of the building who expressed their willingness to participate.

The secondary data sources used were published and unpublished documents, journals, and articles. The building's Air system properties were taken from the building’s air conditioner machines supplier catalog. The climatic design conditions of Addis Ababa city are obtained from EBCS 11 (Ethiopian Buildings Codes and Standard). Weather data in the EPW (Energy Plus Weather) file format for simulation purposes was obtained from the EnergyPlus website. This helps to obtain energy consumption data of the building with specific glazing structure. EnergyPlus is compliant with ASHRAE Standard 140 for evaluation of building energy analysis computer programs and can be used for proving compliance with energy performance building standards and codes such as ASHRAE 90.1-2022, NECB 2020. This ensures its reliability and accuracy in building energy simulation.

3.5. Data collection

For this particular study, a combination of qualitative and quantitative data collection methods was employed. The qualitative aspect of the research primarily served the purpose of conducting a literature review and establishing a background understanding. On the other hand, the main focus of this study was to gather quantitative data to achieve its objectives.

The quantitative data collected played a crucial role in calculating the heating load, cooling load, and energy consumption of the glazing structure. To perform these calculations, Carrier's HAP software was utilized. By inputting the collected data into the software, reports were generated regarding the thermal loads and energy consumption of the glazing structures.

The quantitative data in this research consisted of weather data obtained from EBCS11 such as design parameters and Temperatures, as well as specific details on the building's glazing structure and its architectural form. These data elements were essential for the comprehensive analysis conducted in this study.

3.5.1. Weather data

The weather data of the building plays a crucial role in determining the overall comfort and energy efficiency of the space. By encompassing factors such as temperature, humidity, and solar radiation conditions, a building can be created so that it becomes well-suited to its specific climate.

In this case, the climatic design conditions for Addis Ababa were sourced from EBCS 11, a widely recognized standard for building energy performance for different cities in Ethiopia. These conditions were then inputted into Carrier HAP, simulation software that allows to model and analysis of the building's performance under various weather scenarios.

<u>Ethiopian Buildings Codes and Standards (EBCS)</u>

The EBCS 11, Code of Practice for Ventilation and Air-conditioning of Buildings, was first published in 1995. In response to the rapid modernization of the building construction industry post-2000, there has been a growing recognition of the importance of air conditioning in enhancing productivity in hot regions of Ethiopia. As a result, air-conditioning systems are now being installed in offices, social services, and residential buildings in extremely hot areas. Consequently, in 2014, the existing code was revised to encompass all facets of mechanical ventilation and air conditioning. (EBCS 11)

The design criteria outlined in this code are intended for areas where continuous hourly data has been recorded over an extended period and were calculated from the frequency distribution analyzed from data sets observed over several years. The design conditions for warm-season temperature and humidity are determined by annual percentile values of 0.4, 1.0, and 2.5. On the other hand, cold-season conditions are established using annual percentiles of 99.6, 99.0, and 97.5. By utilizing annual percentiles, the design conditions guarantee that they have an equal probability of occurring regardless of the seasonal distribution of extreme temperature and humidity.

The code's annual cumulative frequency distribution was created by combining the relative frequency distributions for each month. Only the data from months that satisfied the screening criteria for completeness and unbiased distribution of missing data were included. It is important to note that the minimum period of record chosen for this analysis was 10 years. For a station's design conditions to be included in the code, there needed to be data from at least 8 months that met the screening criteria for each month of the year. These design conditions in the code represent the same annual probability of occurrence regardless of the specific location or general climatic conditions. (EBCS 11)

The climatic design conditions for Addis Ababa weather properties used in Carrier HAP are presented in Table 3-1.

Table 3-1: Design condition of Addis Ababa

Design Parameter of Addis Ababa, Ethiopia			
Latitude	9.0Deg.	Atmospheric Clearness Number	1.00
Longitude	39.0 Deg.	Average Ground Reflectance	0.32
Elevation	2355.0 m	Soil Conductivity	1.385 W/(m-°K)
Summer Design Dry-Bulb	29.0 °C	Local Time Zone (GMT +/- N hours)	3.0 hours
Summer Coincident Wet-Bulb	23.1 °C	Consider Daylight Savings Time	No

Summer Daily Range	18.5 °K	Simulation Weather Data	ADDIS_ABABA/BOLE (EXT)
Winter Design Dry-Bulb	4.5 °C	Data source	User modified
Winter Design Wet-Bulb	0.7 °C	Design Cooling Months	January to December

Design Temperatures

The Design Temperatures are determined by obtaining dry and wet bulb temperature data from EBCS-11. In Table 3.2, the input parameters specifically for Addis Ababa city are provided, displaying the monthly dry bulb temperatures (representing the air temperature) and wet bulb temperatures (indicating the humidity level). These values are further classified as minimum and maximum temperature values.

The graphical representation in Figure 3-2 illustrates the hourly design temperature profile for the month of May, which serves as a sample for other months.

Table 3-2: Monthly maximum and minimum Temperature values of Addis Ababa

Month	Dry Bulb		Wet Bulb	
	Max	Min	Max	Min
Jan	26.7	4.9	18.6	0.6
Feb	28.1	6.3	19.8	1.8
Mar	28.6	7.5	20.2	2.8
Apr	28.4	9.5	220.0	4.4
May	28.5	10.0	20.1	4.9
Jun	27.1	9.6	18.9	4.5
Jul	24.4	9.5	16.7	4.4
Aug	23.6	9.5	16.1	4.4
Sep	24.2	8.9	16.5	4.0
Oct	25.8	6.9	17.9	2.3
Nov	25.2	4.3	17.4	0.1
Dec	25.7	5.4	17.8	1.1

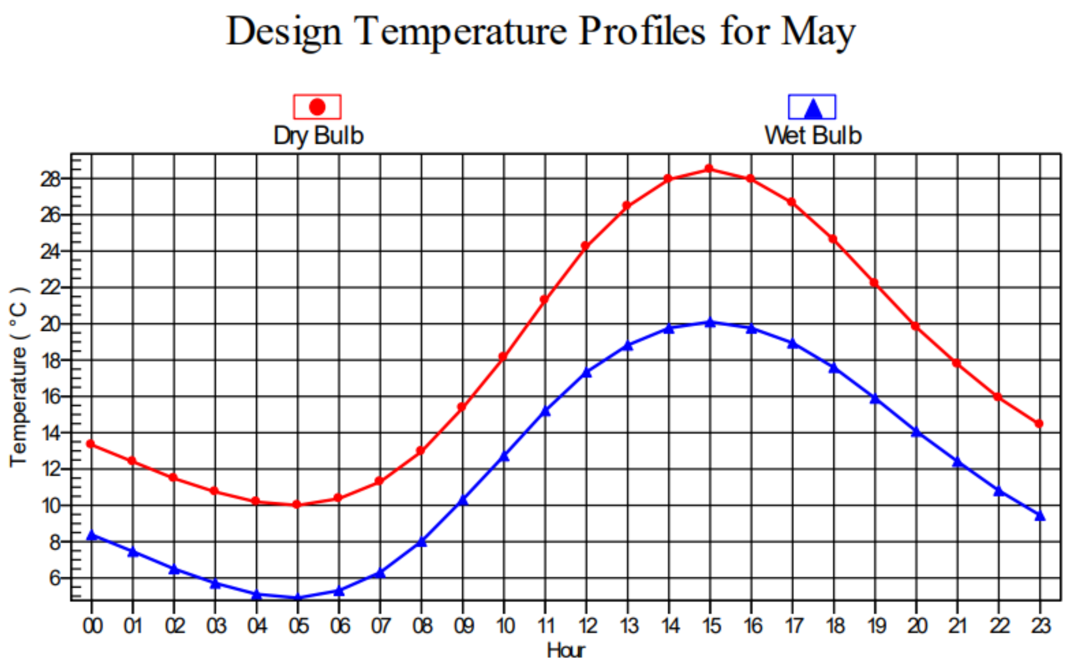


Figure 3-3: Design temperatures profile for May

Design Solar offers detailed information regarding solar heat gain profiles that are unique to Addis Ababa. These profiles specifically focus on solar conditions experienced on days with clear skies. Understanding this solar profile is essential for accurately determining the thermal load on various surfaces such as walls, roofs, and windows. The design day maximum Solar heat gain of Addis Ababa city can be referred on appendix 3, Table A3-1.

The solar heat gain patterns are influenced by the city's unique geographical location and climate. The city experiences high levels of solar radiation due to its proximity to the equator and high elevation. This results in intense sunlight and heat during clear sky days, which can have a significant impact on building design and energy consumption. A visual representation of the solar profile simulation for the month of May in Addis Ababa is depicted in Figure 3.3.

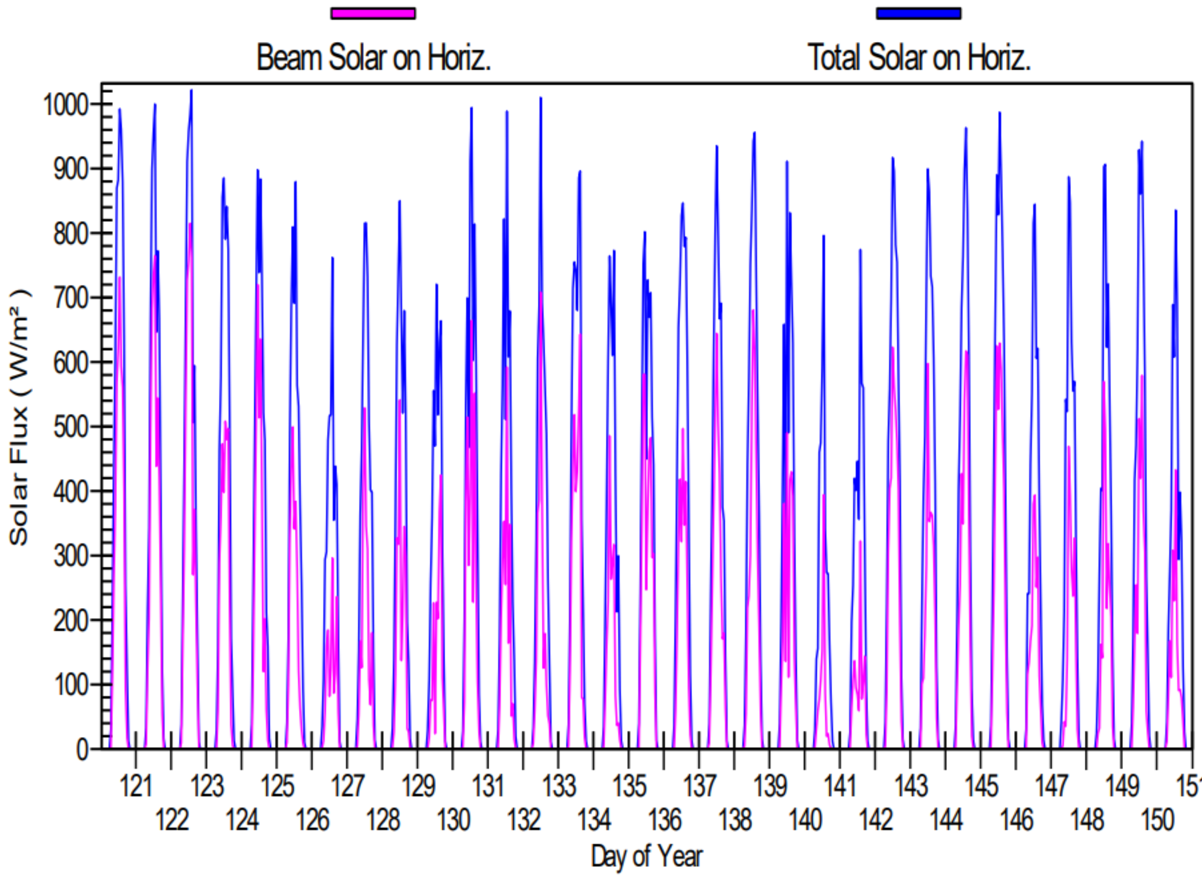


Figure 3-4: simulation weather solar profile for May of Addis Ababa

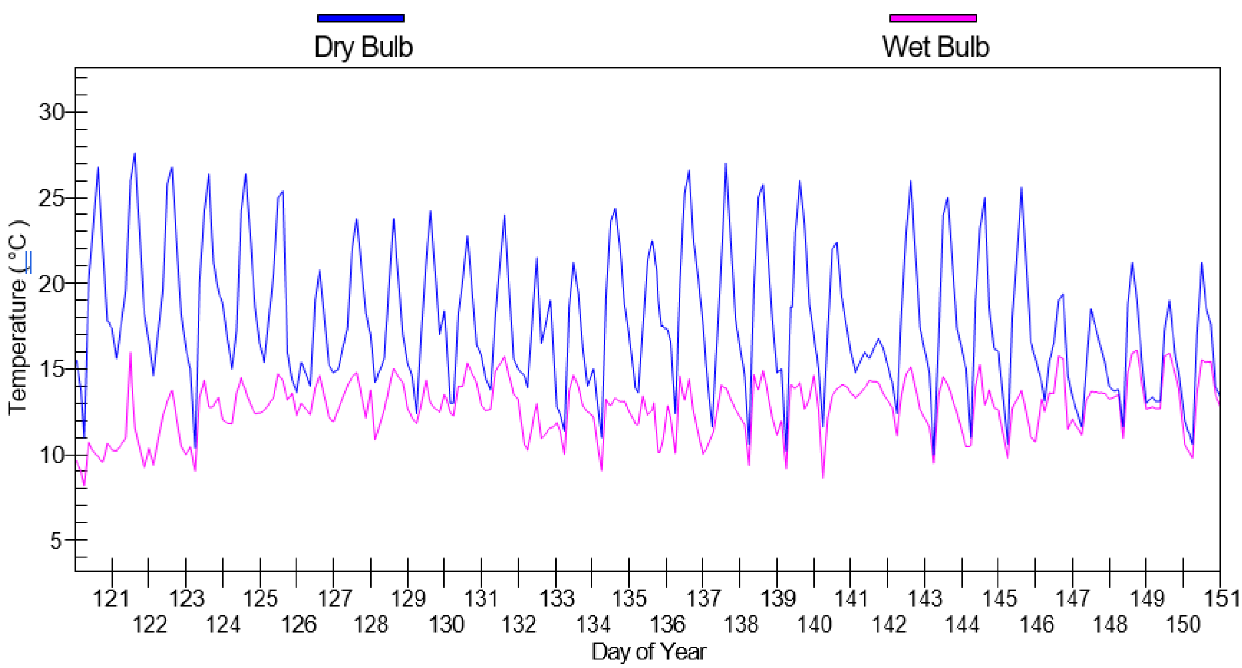


Figure 3-5: Temperature Profiles for May 1 and May 31 of Addis Ababa

3.1.1. Sample floor spaces

Space properties and their parameters were inserted in the software like floor area, average ceiling height. Also outdoor air (OA) requirements were taken from ASHRAE Std 62.1-2010 by default. The table shows the OA ventilation requirement for office space (ASHRAE Std 62.1-2010).

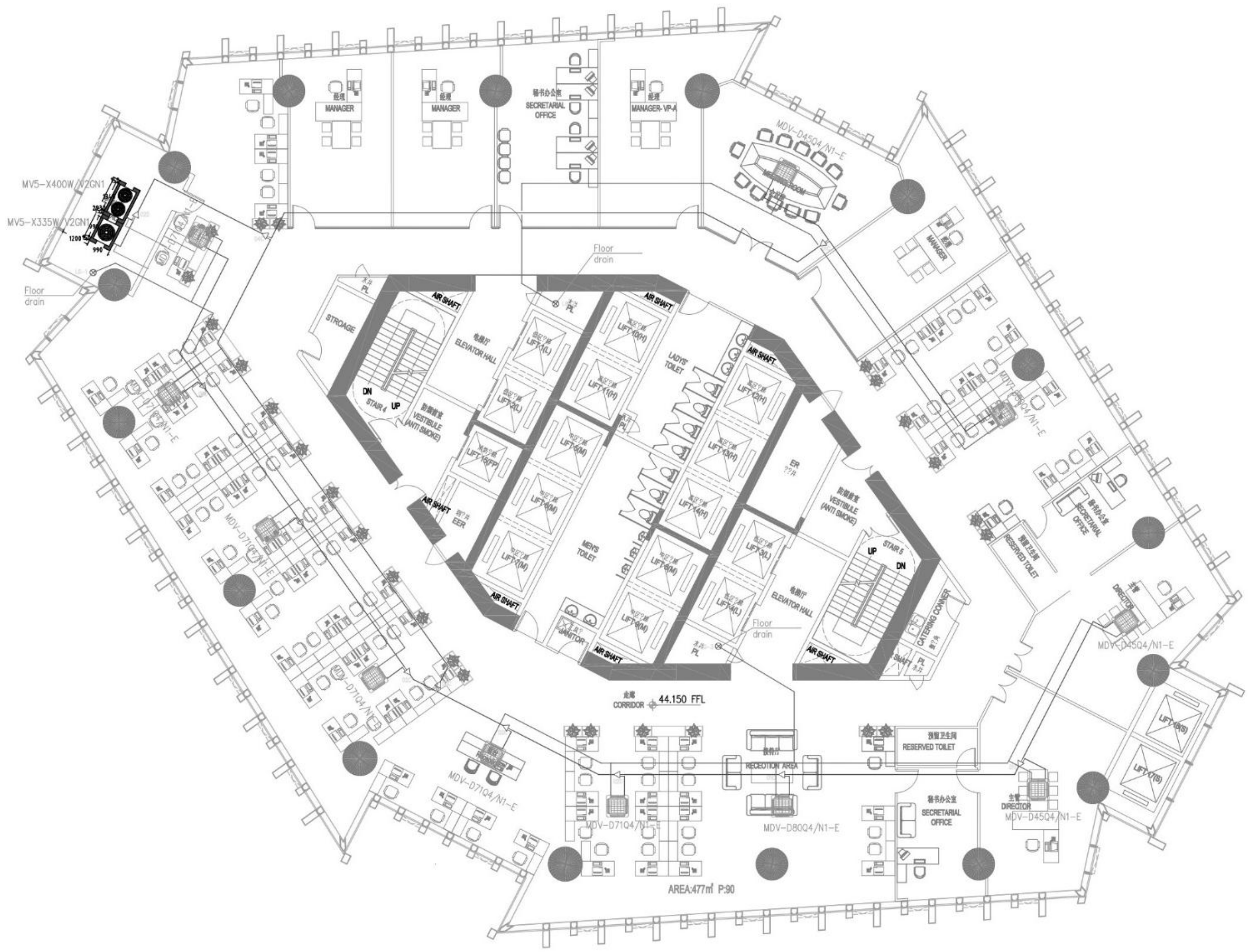
Table 3-3: Outdoor air ventilation requirements for an office space

Occupancy category	People Outdoor Air Rate (Rp)		Area Outdoor Air Rate (Rp)	
	cfm/person	L/S-person	Cfm/ft2	L/s-m2
Office space	5	2.5	0.6	0.3

The case study focuses on the Tower part of The new CBE HQ building which serves as an office building specifically and consists of a total of 48 floors. The building is divided into 45 zones, each serving a specific purpose or function. These zones consist of multiple spaces, such as offices, meeting rooms, and common areas.

The building's floor-to-ceiling height is 3 meters. The total floor area of each floor is 1447 m^2. There are a total of 169 individual spaces within the building, occupied by individuals or groups of people. Proper air distribution is necessary for comfort and ventilation in these spaces. To achieve this, each space is equipped with one or more air distribution terminals, determined by the size of the space and the number of occupants.

Figure 3.4 displays the floor plan of the tenth floor of the CBE Tower as a sample. This floor plan shows the arrangement of office spaces and the location of air distribution terminals.



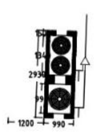
 Floor's Main Air distribution terminal  Air distribution terminals

Figure 3-6: Tenth-floor plan of new CBE HQ Tower

3.5.2. Curtain glazing structures

The main objective of this study is to analyze the thermal comfort of the building's glazing in relation to the IE, while also comparing it to different types of glazing structures and their energy consumption.

The various types of glazing structures that are being compared to the existing one include single glazed and double-glazed glazing structures. Single-glazed glazing structures consist of blue-green reflective glass, blue-green tint glass, clear Low-E glass, and double-glazed glazing structures consist of blue-green reflective glass with clear glass, blue-green tinted glass with clear glass, clear Low-E glass with clear glass and triple silver coated Low-E glass with clear glass. The gap between the outer and inner glazing is filled with air.

Furthermore, the analysis also takes into consideration the fact that the glass-to-wall ratio makes up 100% of the building envelope. The solar exposure of the glazing structures is considered and entered based on its orientation.

CBE Tower glazing structure

During the design phase of the new CBE HQ Tower, Koltay Facades, an engineering consultancy service based in Dubai, was responsible for providing their expertise for the façade of the building.

The selection of the curtain wall glass, on the other hand, was entrusted to AAiT (Addis Ababa Institute of Technology). To ensure the quality and performance of the curtain walls, a third-party testing agency conducted tests on the submitted samples. Additionally, a visual Mock-up Unit (VMU) was constructed on-site for the purpose of glass selection.

At the project site, AAiT's professionals who are supervising and participating in the project permanently thoroughly examined the vision panel and spandrel panel glass options of the VMU. After continuous and careful evaluation of the VMU samples and the performance parameters outlined in the third-party test report, they ultimately chose a Double-Glazed Vision Panel Glass (with specific glass type 6C HS(FSLE1-60B) #2+12A+8C TP HST). This glass type was manufactured by CSG Energy Conservation Glass Co., Ltd. The specific details of this selection can be found in the table 3.3. below.

Table 3-4: The performance value of the new CBE HQ building

Glazed Vision Panel Glass type	Visible light transmittance	Visible light reflectance		Heat transfer coefficient (U-value) $W/(m^2K)$	Shading coefficient (SC)	Gap type
		Outdoor	Indoor			
6C HS(FSLE1-60B) #2+12A+8C TP HST	50.0%	20.0%	10.0%	1.84	0.47	12mm Air space

Other Curtain walls' glazing glass detail

In this section an overview of the general and thermal properties of each glass type that are going to be used as an alternative will be provided with the details of each glazing structure.

Given that the building has a 100% glass-to-wall ratio, the dimensions for each glass type are set the same as the floor-to-ceiling height of the building's floor which is 3.00 meters in height and 0.90 meters in width.

Additionally, all glass types will have an Aluminum frame without thermal breaks, and the internal shade type will be Drapes with an open weave and medium density. The thermal property details of each glass type are presented in table 3.5. and Table 3.6. below for both single and double-glazing structures.

Table 3-5: Glass detail for single-glazing curtain wall types

Glass type	6mm blue-green reflective	6mm blue-green tint	6mm clear Low-E glass
Overall U-value ($W(m^2\text{-}^oK)$)	5.048	5.048	5.048
Overall shade coefficient	0.411	0.564	0.628
Transmittivity	0.282	0.488	0.639
Reflectivity	0.295	0.062	0.116
Absorptivity	0.423	0.450	0.245

Table 3-6: Glass detail for Double-glazing curtain wall types

Type	Blue-green reflective with clear glass		Blue-green tint with clear glass		Clear Low-E glass with clear glass	
Glazing	External	Internal	External	Internal	External	Internal
Glass type	6mm blue-green reflective glass	6mm clear glass	6mm blue-green tint glass	6mm clear glass	6mm clear Low-E glass	6mm clear glass
Transmittivity	0.282	0.792	0.488	0.792	0.639	0.792
Reflectivity	0.295	0.079	0,062	0.079	0.116	0.079
Absorptivity	0.423	0.129	0.450	0.129	0.245	0.129
Overall U-value (W(m^2-^{o}K))	3.356		3.356		3.356	
Overall shade coefficient	0.393		0.510		0.586	
Gap type	13mm air space		13mm air space		13mm air space	

3.5.3. CBE Tower Air system

The high-rise office building relies on the utilization of VRF outdoor and indoor units to effectively regulate indoor temperature and ensure a pleasant environment. The selection of the VRF outdoor unit, along with its COP and EER values, has been made by referring to the catalog provided by the air conditioner machines supplier, which provides detailed information on the capacity of the air conditioner machines required to meet the building’s load demands.

The software incorporates the following parameters: the cooling thermostat is set to 23.9°C during occupied hours and 26.7°C when unoccupied. For the heating system, the thermostat is adjusted to 21.1°C during occupancy and 18.3°C during unoccupied periods. The operational schedule is established for the CBE HQ office from Monday to Saturday, running from 8:00 AM to 7:00 PM, with the ventilation system being demand-controlled. To assess heat gains and appropriately size HVAC units, the HAP software, which adheres to ASHRAE guidelines, is utilized. Additionally, the air systems encompass various parameters essential for conducting energy analysis.

3.5.4. Questionnaire

A thermal comfort survey was administered to employees of the CBE Tower HQ office building on a random basis (see Appendix 4). The purpose of this survey was to evaluate the overall comfort levels of workers in relation to the thermal conditions of their work environment. The responses collected from the survey provided insights into the subjective thermal comfort experienced within the office spaces of the building. The findings illustrate the impact of the thermal environment on employees throughout their working hours.

The survey was divided into three sections

Section 1: location of the respondents' workspace

Section 2: thermal conditions at the Respondents' workspace

Section 3: what the respondents rather prefer related to thermal condition

3.6. Data analysis

To determine whether the glazing of the building influences the thermal comfort of the IE, it is essential to first assess the thermal load associated with each type of glazing configuration. This involves a comprehensive analysis of how different glazing materials and designs affect heat transfer and overall energy efficiency within the building.

The thermal load of the building, concerning the glazing configuration, is assessed by calculating both heating and cooling loads. The thermal performance of glazing can also be evaluated through simulations and modeling techniques that consider the building's design, occupancy patterns, and HVAC systems. By analyzing these variables, it becomes possible to quantify the impact of different glazing configurations on the indoor thermal environment.

Given that the manual calculations for heating and cooling loads, as outlined in the literature review, are extensive, this study employed Carrier's Hourly Analysis Program software as a simulation tool to conduct the necessary calculations. This software efficiently evaluates the thermal effects of each glazing configuration on the overall indoor climate.

The procedure for conducting this research involves the following steps: define the problem, gather data, enter data into HAP, use HAP to generate design reports, and select equipment. Moreover, to conduct energy simulation analysis, system sizing data as design airflow rates for zones, fans, and outdoor ventilation air must already be known. Hourly weather data and load information must also be available. For simulation purposes, the project relies on weather data in the EPW (Energy Plus Weather) file format provided by the EnergyPlus and was integrated into HAP software. The simulations are carried out to estimate the thermal load and annual energy consumption.

The evaluation of thermal conditions in the office environment of the CBE Tower was carried out using a questionnaire designed to gather subjective perceptions about the thermal environment in the new CBE headquarters' office areas. The findings were then illustrated through graphical charts and analyzed alongside the feedback from the participants.

To ensure the accuracy of the data collected, details regarding the glazing structure of the CBE Tower were obtained directly from the project site, complete with the official stamp and signature of the CBE new HQ Project director (see Appendix 1). The design parameters relevant to Addis Ababa were sourced directly from EBCS11.

To gauge the thermal perceptions of respondents about their workspace, the questionnaires were prepared in English (refer to Appendix 4). The distribution process included a polite request for employee participation, making it clear that they had the option to decline. To further accommodate some participants and minimize any potential inconvenience, the questionnaires were also administered through interviews conducted in the local language, Amharic.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

The thermal load for each glazing structure combination was determined, and an analysis of energy consumption was conducted using software simulation. This analysis was made on the glazing system of the CBE office building, as well as six additional alternative glazing structures for comparative evaluation.

The results are generated based on the HVAC system used in the CBE Tower as per the demand of the occupancy schedule and outside temperature; considering 100% window-to-wall ratio of the Tower.

For each type of curtain wall glass material, system cooling and heating load results that was found from Carrier's HAP software and the result from the energy simulation are presented and described in this chapter.

4.1. Effect of the new CBE HQ Tower's Glazing on Indoor Thermal Comfort

Evaluating how a building's glazing affects indoor thermal comfort requires its thermal load; thereby the system heating and cooling load for the building's glazing.

The system heating and cooling load for the new CBE HQ Tower's glazing structure glass combination, which is calculated using Carrier's HAP software is shown in the table below.

Table 4-1 Heating and cooling load of the CBE Tower HVAC system of its glazing structures.

Glass combination	Heating load (Kw)	Cooling load (Kw)
Double-glazed vision panel glass of the new CBE HQ Building	567.7	1727.1

From the table we can see that for the building's glazing, the system cooling load is 1727.1Kw and the system heating load is 567.7Kw. this table can be interpreted like this;

The cooling load of 1727.1 kW indicates the amount of energy required to maintain a comfortable indoor temperature during warmer months, specifically through the glazing components of the building. Conversely, the heating load of 567.7 kW represents the energy needed to heat the indoor environment during colder months. The significant difference between these two values suggests that the building experiences a greater demand for cooling than heating, likely due to the building's complete glass coverage. N.B. This evaluation doesn't consider any shading devices or sun-blocking elements.

4.2. Comparison of the new CBE HQ building's glazing thermal properties with other alternatives

The findings related to the cooling and heating load outcomes for each category of alternative glazing structure, as determined by Carrier's HAP software, are presented and described here.

Table 4-2 presents a summary of the heating and cooling load results for seven distinct glazing combinations including the CBE HQ building's glazing structure, highlighting the performance differences associated with each configuration. This table serves as a reference for understanding how varying glazing types can impact the thermal demands of a building. Each glazing combination is analyzed in terms of its efficiency in managing heat gain and loss, which is essential for optimizing HVAC system performance and energy consumption. the heating and cooling load of the CBE Tower HVAC system with these different glazing structures is illustrated graphically In Figures 4-1, 4-2, and 4-3.

Table 4-2 Heating and cooling load of the CBE Tower HVAC system with different glazing structures.

Glass combination	Heating load (Kw)	Cooling load (Kw)
Single 6mm clear/uncoated low-e	1283.3	3218.3
Single 6mm blue-green tint	1283.3	2978.8
Single 6mm blue-green reflective	1283.3	2409.3
6mm Clear/uncoated low-e + 13mm Air space + clear glass	930.4	3469.1
6mm Blue- green tint + 13mm Air space + clear glass	930.4	2787.3
6mm Blue-green reflective + 13mm Air space + clear glass	930.4	2349.4
Double-glazed vision panel glass at CBE	567.7	1727.1

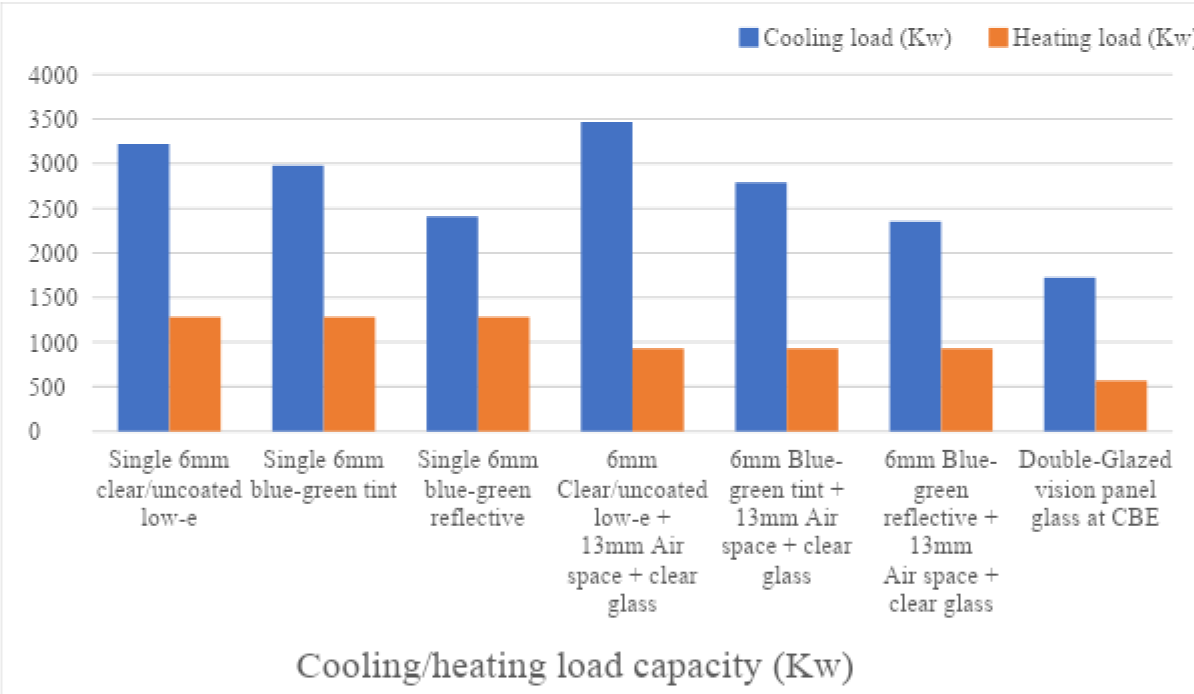


Figure 4-1 Heating and cooling load of the CBE Tower HVAC system with different glazing structures.

The thermal loads associated with different combinations of glazing structures were found to exhibit variability among one another. Although the heating loads for certain glazing types may appear comparable, the cooling loads for each glazing configuration are distinct.

Of the seven types of glazing types, the one with the least cooling as well as heating load is noted to be the Double-glazed vision panel glass of the CBE Tower with 1727.1Kw cooling load and 567.7Kw heating load. The glazing structure with the second least cooling load is 6mm Blue-green reflective +13mm air space + clear glass with 2349.4 Kw cooling load.

Vice versa the glazing structure with the largest cooling load is the 6mm Clear/uncoated low-e+13mm air space +clear glass with 3469.1Kw cooling load and the largest heating load was seen on all of the single glazed glasses (single 6mm clear/uncoated low-e, single 6mm blue-green tint and single 6mm blue-green reflective) with each 1283.3Kw heating load capacity.

4.3. Contribution of the glazing structure of the CBE HQ building in enhancing energy efficiency

To assess the impact of the glazing structure of the new CBE HQ building on its energy efficiency, the annual energy consumption attributed to the glazing was calculated using HAP software, in alignment with the heating and cooling loads of the HVAC system employed in the CBE Tower. Then, the annual energy consumption for the six alternative glazing combinations was also evaluated to facilitate a comparison with the CBE glazing, thereby determining whether the glazing of the building significantly influences its overall energy consumption relative to the alternatives.

Table 4-3 summarizes the annual energy consumption for each glazing combination determined using HAP software based on their heating and cooling properties. Figure 4-4 illustrates graphically the annual energy consumption of the building's HVAC system for each type of glazing structure combinations

Table 4-3 Annual energy consumption for each glazing structure from HAP software.

Glass combination	Annual Energy consumption (Kwh)
Single 6mm clear/uncoated low-e	2,657,870
Single 6mm blue-green tint	2,525,092
Single 6mm blue-green reflective	2,207,381
6mm Clear/uncoated low-e + 13mm Air space + clear glass	2,792,934
6mm Blue- green tint + 13mm Air space + clear glass	2,636,104
6mm Blue-green reflective + 13mm Air space + clear glass	2,336,977
Double-glazed vision panel glass at CBE	2,397,909

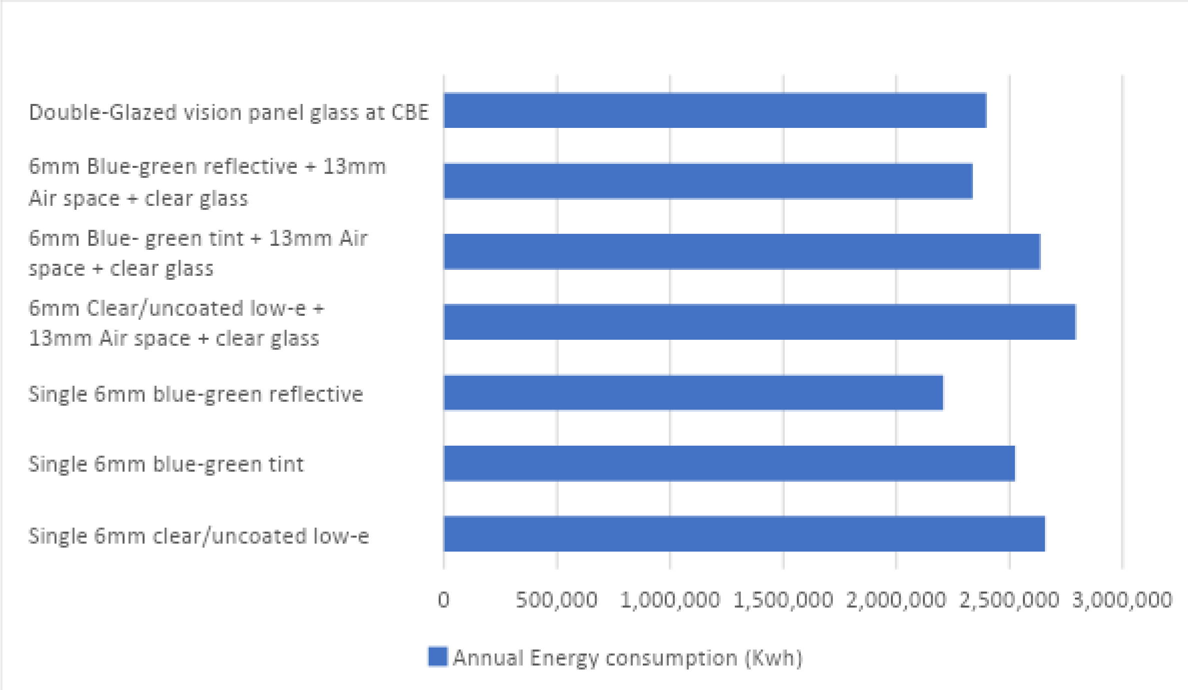


Figure 4-2 Annual energy consumption of the CBE Tower HVAC system with different glazing structure.

On the energy consumption simulation result, it is seen that the single 6mm Blue-green reflective glazing type with the least energy consumption from all glazing structures with 2,207,381KWh; whereas 6mm clear/uncoated low-e +13mm air space +clear glass to with the largest energy consumption which is 2,792,934KWh.

Using the 6mm clear/uncoated low-e +13mm air space +clear glass, which has the highest energy consumption, as the benchmark for the annual energy analysis; in comparison, the 6mm Blue-green reflective glazing saves 20.97% energy, making it the most energy-efficient option. Following closely is the 6mm Blue-green reflective + 13mm Air space + clear glass, which saves 16.33% energy.

The Double-Glazed vision panel glass at the CBE Tower ranks third in energy savings, with a reduction of 14.14%. The fourth option, a Single 6mm blue-green tint, consumes 9.59% less energy than the benchmark. The fifth option, 6mm Blue-green tint + 13mm Air space + clear glass, offers a 5.62% energy-saving ability compared to the benchmark. Lastly, the sixth option, Single 6mm clear/uncoated low-e, provides a 4.84% reduction in energy consumption.

4.4. Subjective thermal comfort survey

A total of 30 participants willingly engaged in completing the questionnaire, and the findings are illustrated graphically for clarity and ease of understanding. Among the respondents, a significant majority—70%—occupied workspaces located above the second floor, while the remaining 30% of participants were situated on the ground floor.

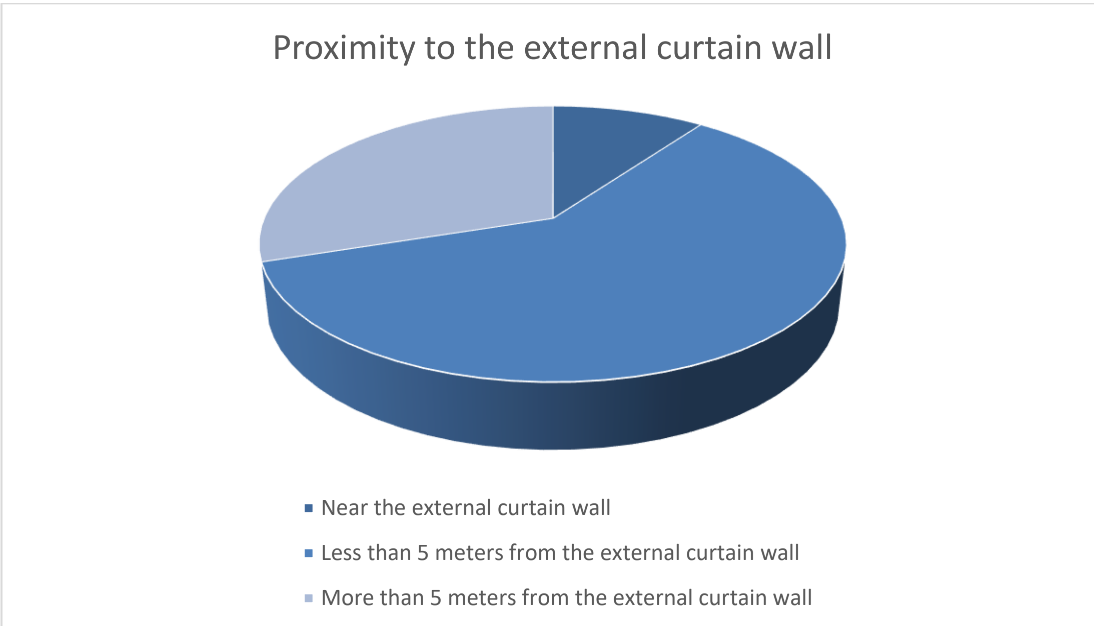


Figure 4-3 Proximity of the respondents to the external curtain wall

In terms of proximity to the external curtain wall, the data reveals that 60% of the respondents reported their workspaces were positioned less than 5 meters from the external curtain wall. This close proximity may have implications for natural light exposure and views, which can influence overall workplace satisfaction. Meanwhile, 30% of the respondents indicated that their workspaces were situated more than 5 meters away from the curtain and 10% of the participants were located in very close proximity to the external curtain wall, which could affect their thermal comfort and exposure to external environmental conditions.

The subsequent chart provides a visual representation of the responses regarding thermal comfort conditions within the building.

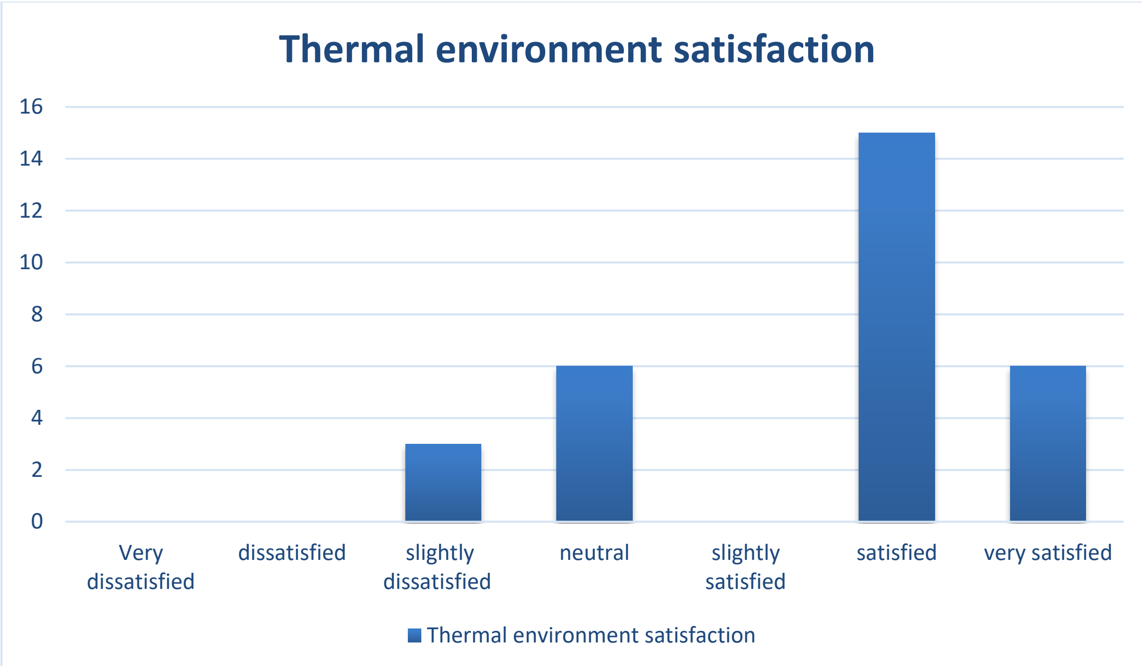


Figure 4-4 Respondents satisfaction to the thermal environment of their workspace

Notably, more than half of the respondents expressed satisfaction with the thermal comfort of their workspaces, indicating that they found the temperature and overall environment conducive to their work. Conversely, 20% of the participants remained neutral, suggesting that they neither felt particularly satisfied nor dissatisfied with their thermal conditions. A smaller segment, comprising 10% of the respondents, reported slight dissatisfaction with the thermal comfort in their workspaces. Those who expressed dissatisfaction attributed their discomfort to specific factors, such as the clothing policy enforced in the workplace or the inaccessibility of the thermostat, which may have hindered their ability to adjust the temperature to their personal preference.

4.5. Discussion

The evaluation of thermal loads and energy consumption associated with various glazing systems conducted using HAP (Hourly Analysis Program) software, particularly in the context of the HVAC configuration implemented in the CBE Tower provides insights into how different glazing materials and designs impact overall comfort and energy efficiency.

The analysis of thermal loads revealed significant variations among the various types, particularly in terms of cooling loads. While some glazing types showed similar heating loads, the differences in cooling loads were particularly pronounced.

Among the glazing options evaluated, the Double-glazed vision panel glass used in the CBE Tower stood out for its efficiency, recording the lowest thermal demands on the building's air conditioning system. Specifically, it registered a cooling load of 1727.1 kW, which indicates a relatively low requirement for cooling energy, and a heating load capacity of 567.7 kW, suggesting that it also performs well in retaining heat during colder months.

In contrast, the 6mm Clear/uncoated low-e + 13mm air space + clear glass glazing system exhibited the highest cooling load of all the options analyzed, reaching an impressive 3469.1 kW. This indicates a much greater demand for cooling energy, which could lead to increased operational costs and energy consumption. Furthermore, all single-glazed options tested in the study demonstrated the highest heating load, with a capacity of 1283.3 kW. This suggests that single-glazed systems may not be as effective in insulating against heat loss, thereby requiring more energy for heating purposes.

The energy consumption findings from the simulation reveal that the glazing configuration featuring 6mm clear/uncoated low-e glass paired with a 13mm air gap and additional clear glass results in the highest energy consumption among the options assessed. This indicates that this particular combination is less effective in minimizing energy loss, which can lead to increased operational costs for heating and cooling.

In contrast, the 6mm Blue-green reflective glazing emerges as the most energy-efficient option, demonstrating a significant reduction in energy consumption. Specifically, this glazing type achieves a remarkable 20.97% decrease in energy use when compared to the aforementioned structure with the highest energy consumption. This substantial reduction highlights the effectiveness of reflective glazing in enhancing energy performance, particularly in climates where solar heat gain can be a concern.

The second most efficient glazing structure identified in the study is the combination of 6mm Blue-green reflective glass with 13mm air space and clear glass. This configuration yields a commendable 16.33% reduction in energy consumption, further emphasizing the advantages of using reflective materials in conjunction with appropriate air gaps to enhance thermal performance.

Following closely, the Double-Glazed vision panel glass installed in the CBE Tower ranks third in terms of energy savings. This glazing option achieves a 14.14% decrease in energy consumption relative to the highest-consuming configuration, showcasing its ability to provide a balance between aesthetic appeal and energy efficiency.

The occupants' thermal environment survey results indicate that while a majority of respondents considered the thermal environment in their workspaces to be acceptable, there remains a notable portion of the population that experiences discomfort. This highlights the importance of addressing individual preferences and accessibility to temperature control in order to enhance overall workplace satisfaction and comfort.

In summary, the research highlights the efficiency of the Double-Glazed vision panel glass utilized in the CBE-HQ office building situated in Addis Ababa. This glazing option not only facilitates considerable energy savings for both cooling and heating within the HVAC system but also significantly contributes to lowering the overall operational expenses of the building. By refining glazing selections, the CBE Tower can enhance its energy efficiency, which is crucial for sustainable building practices and effective long-term cost management. Furthermore, the analysis of annual energy consumption indicates that a combination of glazing with reflective glass can also yield energy efficiency benefits.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The purpose of this study is to investigate the impact of glazing on the thermal comfort of office spaces in high-rise buildings, with a focus on the new CBE building as a case study. Situated on Yohanis Street in Addis Ababa, Ethiopia, adjacent to the Ethiopian hotel. The new CBE HQ office building was selected for this research due to its status as the most recent high-rise construction in the area, featuring a glazing system with a 100% wall-to-window ratio, as well as its advanced HVAC system and utilization of the latest construction technologies available in Ethiopia.

The study was conducted using; weather data obtained from EBCS 11 and EnergyPlus, along with architectural and mechanical specifics including floor area, floor-to-ceiling height, and HVAC details of the CBE office building sourced from the on-site project management office, primarily from AAiT professionals. Office space standards and specifications for 6 single- and double-glazing structures commonly found in glazed buildings were also collected from various literature sources. These data were inputted into Hourly Analysis simulation software; which is called Carrier's Hourly Analysis Program software, a simulation tool used to generate the thermal load of the building's HVAC system. The software was employed to analyze the cooling and heating load for each glazing structure, as well as their energy consumption.

The findings and discussion in chapter Four provide compelling evidence that the Double-Glazed vision panel glass utilized in the CBE-HQ office building in Addis Ababa performs exceptionally well. It records the lowest cooling load at 1727.1 kW, signifying effective heat transfer management and a comfortable indoor environment with minimal cooling energy requirements. The heating load is also low at 567.7 kW, indicating significant insulation and reduced heat loss.

In energy consumption simulations, this glazing ranks third in energy savings among various options, achieving a 14.14% reduction compared to the least efficient alternative. Additionally, the examination of yearly energy usage suggests that utilizing reflective glass in conjunction with glazing can provide advantages in energy efficiency. This underscores the Double-Glazed vision panel glass's contribution to enhancing the CBE Tower's energy efficiency, improving occupant comfort, minimizing environmental impact, and lowering energy costs making it an outstanding choice for architectural design. This substantial energy savings not only highlights the effectiveness of the Double-Glazed vision panel glass in enhancing the overall energy efficiency of the CBE Tower but also underscores the importance of selecting appropriate glazing materials in building design.

The subjective evaluation of the thermal conditions in the CBE Tower indicates that while many respondents found the thermal environment in their workspaces satisfactory, a notable portion still reported feelings of discomfort. This discomfort was linked not to the building's glazing but to differences in personal preferences and the accessibility of temperature control options. Therefore, it can be concluded that the thermal environment in the new CBE HQ building is largely acceptable to its occupants.

5.2. Recommendation

The simulation outcomes provide valuable insights for architects, builders, and developers aiming to enhance energy efficiency in construction. By applying these findings, professionals can improve building performance and support sustainability goals.

The research highlights that using a multi-pane glazing configuration with air gaps significantly boosts thermal insulation, reducing heat transfer and reliance on heating and cooling systems. Incorporating reflective glass further enhances energy efficiency by deflecting solar radiation, leading to lower energy costs and a more stable indoor climate for occupants.

In summary, adopting multi-pane and reflective glazing is an effective strategy for sustainable architecture, enabling professionals to meet the demand for energy-efficient buildings while promoting innovation and environmental responsibility.

Further study on advanced glazing systems can be done on their long-term durability and performance across various climates through longitudinal research. This should include life cycle assessments to evaluate environmental impacts like energy consumption and carbon footprint. Also integrating advanced glazing with smart building technologies could optimize energy efficiency and occupant comfort. Additionally, Economic feasibility analyses comparing initial investments, maintenance costs, and potential energy savings across different building types can also be done.

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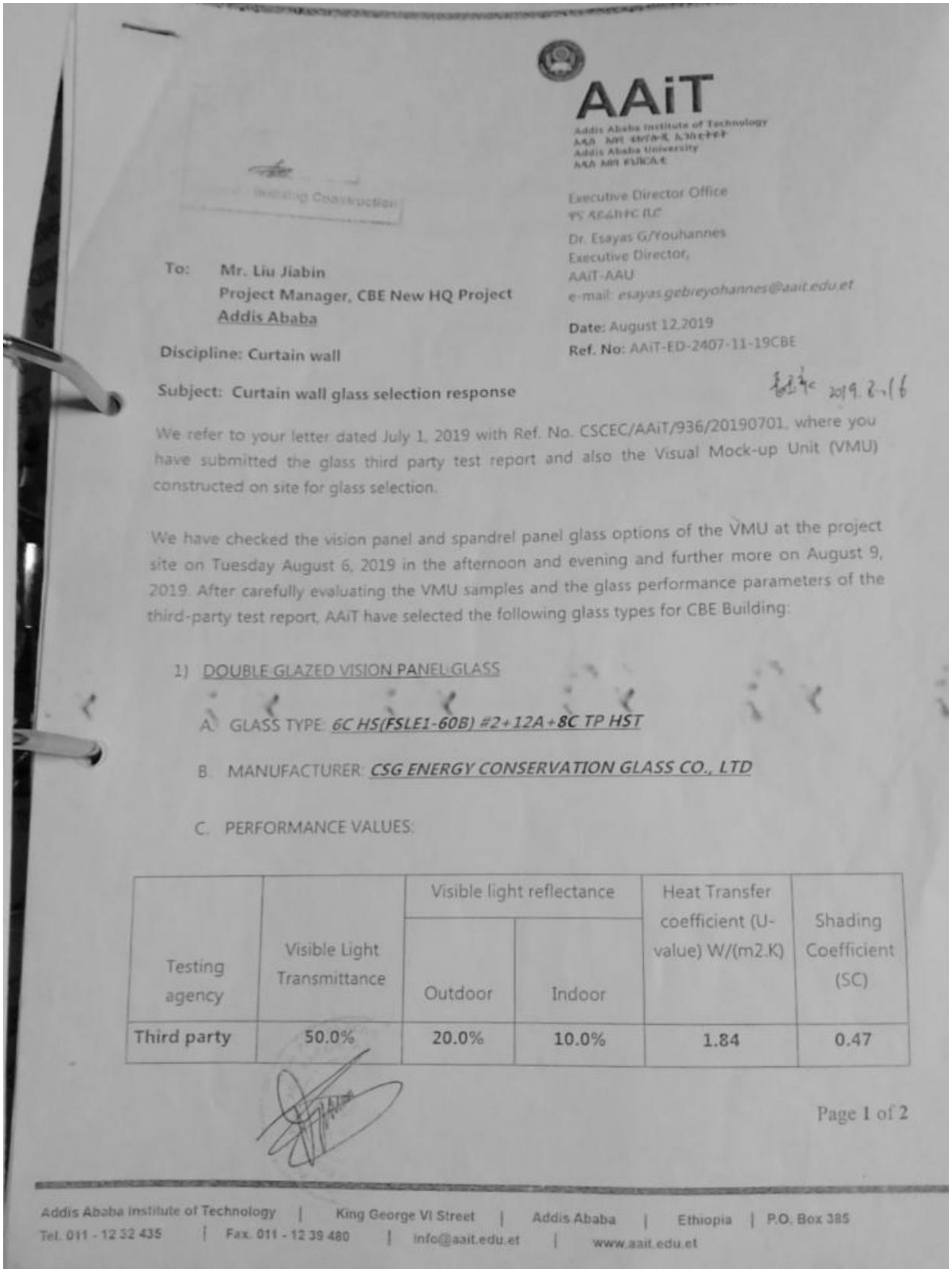
APPENDIX

APPENDIX 1: CBE Tower glazing structure Detail



AAiT

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To: Mr. Liu Jiabin
Project Manager, CBE New HQ Project
Addis Ababa

Date: August 12,2019
Ref. No: AAiT-ED-2407-11-19CBE

Discipline: Curtain wall

Subject: Curtain wall glass selection response

We refer to your letter dated July 1, 2019 with Ref. No. CSCEC/AAiT/936/20190701, where you have submitted the glass third party test report and also the Visual Mock-up Unit (VMU) constructed on site for glass selection.

We have checked the vision panel and spandrel panel glass options of the VMU at the project site on Tuesday August 6, 2019 in the afternoon and evening and further more on August 9, 2019. After carefully evaluating the VMU samples and the glass performance parameters of the third-party test report, AAiT have selected the following glass types for CBE Building:

1) DOUBLE GLAZED VISION PANEL GLASS

A. GLASS TYPE: *6C HS(FSLE1-60B) #2+12A+8C TP HST*

B. MANUFACTURER: *CSG ENERGY CONSERVATION GLASS CO., LTD*

C. PERFORMANCE VALUES:

Testing agency	Visible Light Transmittance	Visible light reflectance		Heat Transfer coefficient (U-value) W/(m2.K)	Shading Coefficient (SC)
		Outdoor	Indoor		
Third party	50.0%	20.0%	10.0%	1.84	0.47

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D.

2) SINGLE GLAZED SPANDREL PANEL GLASS

A. GLASS TYPE: ***6C HS(CNT 60B)#2 WITH BACK PANEL***

B. MANUFACTURER: ***CSG ENERGY CONSERVATION GLASS CO., LTD***

C. PERFORMANCE VALUES:

Testing agency	Visible Light Transmittance	Visible light reflectance		Heat Transfer coefficient (U-value) W/(m2.K)	Shading Coefficient (SC)
		Outdoor	Indoor		
Third party	**51.0%**	**18.0%**	**13.0%**	**4.83**	**0.62**

D.

Best regards,

Dr. Esayas Gebreyouhannes
Project Director, CBE New HQ Project

CC:

- Mrs. Tesfaye Gutema, Director, CBE Building Construction Management
- Dr-Ing. Girma Zerayouhannes; Design Team Lead, CBE New HQ Project, AAiT
- Dr. Abraham Assefa; Resident Engineer, CBE New HQ Project, AAiT

APPENDIX 2: Climatic design Condition of cities of Ethiopia from EBCS 11

Table A2.1. Design Condition for Cooling (Maximum Temperature)

Location				**Annual cumulative frequency of occurrence (%)**											
				0.4				**1**				**2.5**[1]			
City/Town	**Latitude**	**Longitude**	**Elevation**	**DBT (^{0}C)**	**CWB (^{0}C)**	**DPT (^{0}C)**	**MDR**	**DBT (^{0}C)**	**CWB**	**DPT (^{0}C)**	**MDR**	**DBT (^{0}C)**	**CWB**	**DPT (^{0}C)**	**MDR**
Adama	08^{0}55'N	38^{0}55'E	2485m	33.9	28.03	21.25	19.71	33.5	23.43	18.25	19.71	32.6	24.54	20.82	19.71
Addis Ababa	09^{0}02'N	39^{0}42'E	2355m	29	23.07	20.35	18.46	28.5	22.59	19.81	18.46	28	21.19	17.73	18.46
Assosa	10^{0}04'N	34^{0}32'E	1570m	35	22.86	14.56	22.84	34.5	21.7	14.16	22.84	34	22.94	17.02	22.84
Bahirdar	11^{0}37'N	37^{0}10'E	1800m	33	21.48	14.72	23.59	32.6	19.73	11.3	23.59	32.2	21.09	14.52	23.59
Dire Dawa	09^{0}35'N	41^{0}45'E	1200m	38.5	25.88	19.8	20.31	38	27.4	22.75	20.31	37.6	25.99	20.53	20.31
Gambella	08^{0}15'N	34^{0}34'E	514m	42.5	29.92	24.92	23.50	42	30.08	25.38	23.50	41.5	29.78	25.11	23.50
Gode	05^{0}57'N	43^{0}27'E	254m	39.6	34.78	33.13	17.89	39.2	33.94	32.1	17.89	38.7	33.33	31.44	17.89
Jijiga	09^{0}20'N	42^{0} 50'E	1609m	32.5	24.12	20.1	26.72	32.2	22.53	17.45	26.72	31.7	23.64	19.72	26.72

For this standard, a 2.5 % Maximum temperature occurrence shall be taken.

Mekelle	13^{0}33'N	39^{0}30'E	2084m	30	27.97	27.18	18.95	29.8	27.48	26.57	18.95	29.4	27.28	26.44	18.95
Semera	11^{0}30'N	41^0 12'E	633m	44.5	28.71	21.81	25.85	44	28.62	21.99	25.85	43.8	31.65	27.1	25.85

Table A2.2. Outdoor Design Condition for Heating

Location				Annual cumulative frequency of occurrence (%)					
				99.6		99		97.5	
City/Town	**Latitude**	**Longitude**	**Elevation**	**DBT (^{0}C)**	**CWB (^{0}C)**	**DBT (^{0}C)**	**CWB (^{0}C)**	**DBT (^{0}C)**	**CWB (^{0}C)**
Adama	08055'N	38055'E	2485m	6	2.52	7.7	5.19	9.4	6.7
Addis Ababa	09002'N	39042'E	2355m	4.5	0.66	5	1.57	5.6	2.09
Assosa	10004'N	34032'E	1570m	8.4	4.92	9	5.62	10	5.4
Bahirdar	11037'N	37010'E	1800m	3.5	0.54	4.1	1.33	5	2.77
Dire Dawa	09035'N	41045'E	1200m	11.1	8.14	12	9.32	12.8	9.9
Gambella	08015'N	34034'E	514m	17	14.99	17.5	15.51	18.5	16.3
Gode	05057'N	43027'E	254m	17.3	14.11	18.5	14.5	19.6	16.29
Jijiga	09020'N	420 50'E	1609m	1	-0.16	2	0.2	3.5	1.84
Mekelle	13033'N	39030'E	2084m	5	2.9	6	3.9	7.3	5.3
Semera	11030'N	410 12'E	633m	13.5	11.82	14.5	11.16	15.3	13.38

DBT= Dry Bulb Temperature
CWB = Coincident Wet Bulb Temperature

Table A2.3. Monthly Maximum and Minimum Temperature Values for Different Locations

		Location									
Month		**Adama**	**Addis Ababa**	**Assosa**	**Bahirdar**	**Dire Dawa**	**Gambella**	**Gode**	**Jijiga**	**Mekelle**	**Semera**
January	Max. DBT (^{0}C)	30.1	26.67	33.28	29.53	31.91	40.90	37.70	30.25	26.16	34.62
	Min. DBT (^{0}C)	7.61	4.87	9.60	4.55	11.71	17.50	18.12	2.91	5.44	14.66
	MDR (^{0}C)	22.45	21.8	23.68	24.98	20.20	23.40	19.58	27.34	20.72	19.96
February	Max. DBT (^{0}C)	32.09	28.13	34.07	30.92	34.71	42.20	38.53	31.95	27.91	37.13
	Min. DBT (^{0}C)	10.11	6.27	10.93	6.26	12.17	18.60	19.32	3.85	6.99	15.86
	MDR (^{0}C)	21.98	21.86	23.14	24.66	22.54	23.60	19.21	28.11	20.92	21.27
March	Max. DBT (^{0}C)	32.71	28.62	34.53	32.16	36.65	43.00	39.29	32.44	28.42	40.30
	Min. DBT (^{0}C)	10.92	7.54	11.69	7.66	14.07	19.50	21.40	5.72	8.11	16.73

	MDR (⁰C)	21.79	21.08	22.84	24.49	22.58	23.50	17.89	26.72	20.31	23.57
April	Max. DBT (⁰C)	32.5	28.39	33.85	32.39	37.12	42.20	39.34	32.14	28.73	41.90
	Min. DBT (⁰C)	12.42	9.55	13.17	8.80	16.42	21.20	21.64	8.60	9.65	18.30
	MDR (⁰C)	20.08	18.84	20.68	23.59	20.70	21.00	17.70	23.54	19.08	23.60
May	Max. DBT (⁰C)	33.38	28.46	32.29	31.89	38.17	39.50	36.97	31.74	29.66	43.84
	Min. DBT (⁰C)	13.67	10.00	13.22	11.45	17.86	20.90	21.70	10.03	11.26	23.60
	MDR (⁰C)	19.71	18.46	19.07	20.44	20.31	18.60	15.27	21.71	18.40	20.24
June	Max. DBT (⁰C)	32.68	27.11	28.21	29.99	38.05	38.02	36.48	30.93	29.97	45.25
	Min. DBT (⁰C)	12.99	9.60	14.15	12.06	17.60	19.90	22.67	11.98	11.02	22.35
	MDR (⁰C)	19.69	17.51	14.06	17.93	20.45	18.12	13.81	18.95	18.95	22.90
July	Max. DBT (⁰C)	29.54	24.36	26.59	26.67	36.85	36.50	35.56	30.36	27.06	45.55
	Min.	13.81	9.49	13.80	11.87	16.89	20.10	22.11	13.56	10.96	19.70

	DBT (⁰C)										
	MDR (⁰C)	15.73	14.87	12.79	14.80	19.96	16.40	13.44	16.80	16.10	25.85
August	Max. DBT (⁰C)	28.47	23.61	27.25	26.48	35.84	35.43	36.09	30.02	25.52	42.68
	Min. DBT (⁰C)	13.61	9.54	13.70	12.01	16.92	19.30	22.04	12.78	11.10	18.48
	MDR (⁰C)	14.86	14.07	13.55	14.46	18.92	16.13	14.04	17.24	14.42	24.20
September	Max. DBT (⁰C)	29.46	24.2444	27.74	26.92	35.69	36.07	37.16	30.58	26.36	42.93
	Min. DBT (⁰C)	12.29	8.92	13.70	11.07	16.64	20.30	22.46	11.03	9.20	19.80
	MDR (⁰C)	17.17	15.3222	14.04	15.85	19.04	15.77	14.70	19.55	17.16	23.13
October	Max. DBT (⁰C)	29.7	25.8	28.77	27.95	35.53	37.67	37.36	30.09	26.19	40.25
	Min. DBT (⁰C)	9.83	6.92	11.80	9.85	14.63	20.30	21.18	5.83	7.02	18.20
	MDR (⁰C)	19.87	18.8778	16.97	18.10	20.90	17.37	16.18	24.26	19.17	22.05
November	Max. DBT (⁰C)	29.22	25.19	30.03	28.53	33.84	38.33	36.51	29.88	25.40	37.65

	Min. DBT (^0C)	9.31	4.26	9.98	5.27	12.44	18.17	18.60	3.11	6.99	17.20
	MDR (^0C)	19.91	20.93	20.05	23.26	21.40	20.17	17.91	26.76	18.41	20.45
December	Max. DBT (^0C)	28.7	25.7	31.25	28.59	31.78	38.73	36.78	30.26	25.23	35.20
	Min. DBT (^0C)	8.02	5.37	9.26	4.44	12.21	17.63	18.40	2.84	5.76	17.20
	MDR (^0C)	20.68	20.3333	21.99	24.14	19.56	21.10	18.38	27.42	19.46	18.00
Annual	Max. DBT (^0C)	33.38	28.5	34.53	32.39	38.17	43.00	39.29	32.44	29.97	45.55
	Min. DBT (^0C)	13.67	10.00	11.69	8.80	17.86	19.50	21.40	5.72	11.02	19.70
	MDR (^0C)	19.71	18.46	22.84	23.59	20.31	23.50	17.89	26.72	18.95	25.85

Table A3-1 Design Day Maximum Solar Heat Gains

The MSHG values are expressed in W/m²																	
Month	**N**	**NNE**	**NE**	**ENE**	**E**	**ESE**	**SE**	**SSE**	**S**	**SSW**	**SW**	**WSW**	**W**	**WNW**	**NW**	**NNW**	**HOR**	**Mult**
January	148.7	148.7	242.0	518.0	707.3	815.3	801.9	683.8	574.7	685.3	790.2	819.6	725.2	521.6	228.7	148.7	855.7	1.00
February	158.1	158.1	376.8	613.7	754.9	804.6	735.6	561.0	415.4	566.2	732.8	813.6	772.6	617.1	360.6	158.1	917.8	1.00
March	151.1	207.8	456.8	623.1	696.1	664.5	553.0	352.6	214.6	352.2	555.1	680.4	705.6	626.1	453.4	201.8	848.6	0.90
April	164.9	347.0	538.3	646.6	659.7	575.3	405.9	188.8	157.5	188.9	410.6	579.8	663.3	649.3	540.7	348.0	821.1	0.90
May	267.6	477.3	643.1	716.4	684.8	554.2	336.3	172.9	172.3	172.6	337.8	556.3	687.0	718.8	645.7	479.8	875.8	1.00
June	237.6	384.3	485.7	526.2	489.7	383.0	214.1	127.1	127.1	127.3	216.7	387.5	495.2	532.7	492.9	383.2	639.3	0.75
July	110.6	191.9	251.4	276.9	263.6	212.1	127.6	69.8	68.4	69.4	130.8	216.9	268.9	282.7	255.8	192.6	343.6	0.40
August	86.3	171.9	260.8	310.6	315.0	273.2	192.8	91.4	80.6	91.9	196.5	278.4	319.7	314.7	264.4	174.0	399.8	0.45
September	119.4	157.0	341.7	467.1	523.9	503.0	409.3	268.9	168.0	268.8	411.2	500.8	522.3	466.2	341.7	157.4	639.8	0.70
October	159.8	159.8	362.2	605.8	750.5	783.6	699.5	549.9	406.4	544.9	710.5	772.0	737.5	601.4	369.3	159.8	901.4	1.00
November	149.6	149.6	231.8	520.3	713.7	799.4	783.0	672.6	567.8	671.2	788.9	796.2	702.1	518.1	239.5	149.6	851.0	1.00
December	143.9	143.9	187.6	481.4	685.5	799.6	815.3	716.8	626.3	715.4	811.9	799.0	693.8	482.2	182.4	143.9	823.7	1.00

Mult. = User-defined solar multiplier factor.

APPENDIX 3: **Air System**

General Details:

Air System Name	VRF
Equipment Type	Terminal Units
Air System Type	Variable Refrigerant Flow (VRF)
Number of zones	45
Ventilation	Common Ventilation System

Ventilation System Components:

Ventilation Air Data:	
Airflow Control	Demand Controlled Ventilation
Ventilation Sizing Method	Sum of Space OA Airflows
Minimum Airflow	25 %
Damper Leak Rate	5 %
Minimum CO_2 Differential	100 ppm
Maximum CO_2 Differential	700 ppm
Outdoor Air CO_2 Level	400 ppm

Cooling Coil and Heating Coil Data:

Cooling Coil Data:		Heating Coil Data:	
Setpoint	23.9 °C	Setpoint	21.1 °C
Coil Bypass Factor	0.100		
Cooling Source	Air-Cooled DX	Heating Source	Electric Resistance
Schedule	JFMAMJJASOND	Schedule	JFMAMJJASOND

Thermostats and Zone Data:

Zone	All
Cooling T-stat: Occ.	23.9 °C
Cooling T-stat: Unocc.	26.7 °C
Heating T-stat: Occ.	21.1 °C
Heating T-stat: Unocc.	18.3 °C
T-stat Throttling Range	0.83 °K
Thermostat Schedule	T
Unoccupied Cooling is	Available

Common Terminal Unit Data:

Cooling Coil:	Heating Coil:

Design Supply Temperature	14.4 °C	Design Supply Temperature	35.0 °C
Coil Bypass Factor	0.100	Fan Control	Fan On
Cooling Source	Air-Cooled DX	Heating Source	Air Source Heat Pump
Schedule	JFMAMJJASOND		JFMAMJJASOND

Terminal Units Data:

Zone	All
Terminal Type	Fan Coil
Minimum Airflow	5.50 L/s/person
Fan Performance	30 Pa
Fan Overall Efficiency	50 %

Sizing Data (Computer-Generated):		Safety Factors:		
Cooling Supply Temperature	Heating Supply Temperature	Cooling Sensible	Cooling Latent	Heating
14.4 °C	35.0 °C	10 %	10 %	20 %

Equipment Data

Vent. Cooling Unit - Air-Cooled DX		VRF Outdoor Unit - Heat Pump							
Design OAT	35.0 °C	Performance Data - Cooling		Performance Data - Heating		System Data:		Heat Pump Data:	
Equipment Sizing	(Auto-Sized) 731.2 kW	Equipment Sizing	(Auto-Sized) 3502.0 kW	Equipment Sizing	(Auto-Sized) 403.4 kW	Compressor Type	Variable Speed Scroll	Heat Recovery Used	No
Capacity Oversizing Factor	0 %	Design OADB	35.0 °C	Design OADB	8.3 °C	Minimum Load	10 %	Heat Pump Cutoff OADB	-20.0 °C
ARI Performance Rating	3.320 EER	AHRI Performance Rating	3.320 EER	AHRI Performance Rating	4.02 COP	Refrigerant Piping Equivalent Length	100.0 m	Auxiliary Heating Type	Electric Resistance
Conventional Cutoff OAT	12.8 °C					Refrigerant Piping Vertical Rise	2.0 m	Auxiliary Heating Upper Cutoff	21.1 °C
Low Temperature Operation	Used								
Low Temperature Cutoff OAT	-17.8 °C								