COMPUTATIONAL MULTIVARIABLE OPTIMIZATION OF INDOOR DAYLIGHTING AND GLARE IN ARCHITECTURAL DESIGN

By

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A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfilment of the Requirements for the Degree of Master of Science in

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CERTIFICATE

Addis Ababa University

School of Graduate Studies

This is to certify that the thesis submitted by Dagmawi Habtamu Zeleke, entitled: "Computational Multivariable Optimization of Indoor Daylighting and Glare in Architectural Design" in partial fulfilment of the requirements for the degree of Master of Science in Advanced Architectural Design complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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CONFIRMATION

The research completed by Dagmawi Habtamu Zeleke, titled "Computational Multivariable Optimization of Indoor Daylighting and Glare in Architectural Design", is conducted under my supervision, and it is submitted to school of graduate studies of Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science in Advanced Architectural Design.

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ABSTRACT

Buildings with daylighting problems may lead to compromised psychological and physiological wellbeing, and decreased productivity of occupants. Although there exists some research on design optimization for enhanced daylight and glare performance of buildings, most studies considered single design variable in the optimization. In this study, a computational multivariable optimization framework is developed for enhanced interior daylighting and glare performance of buildings. The proposed framework is derived considering the influence of (a) building orientation and (b) facade opening. The suitability of the proposed optimization framework is assessed through implementation on a sample office space and a selected case study building. To ensure the accuracy of the computational results, the illuminance level obtained from the simulations are compared with that of on-site measurements taken using Lux meter. The performance of the proposed framework is evaluated in terms of the acceptable values of annual sunlight exposure (ASE) and spatial daylight autonomy (sDA). For the sample office space, multiple optimized design solutions that satisfy the criteria specified by Illuminating Engineering Society (IES) and Leadership in Energy and Environmental Design (LEED) are obtained using the proposed framework. The application of the framework on case study building, based on the existing facade design, has provided several optimized solutions. The solutions have resulted in a significant reduction of glare/ASE (i.e., up to 12% reduction) without significant compromise in the daylighting/sDA (i.e., 0.8% reduction). Therefore, it is concluded that the proposed framework has the potential to provide multiple design options that could achieve optimized daylight and glare performance.

Keywords: Parametric Design, Genetic Algorism, Daylight Metrics, Building Orientation, Facade Opening, Multivariable Optimization, Architectural Design

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Dagmawi Habtamu

EiABC, Addis Ababa.

June, 2021.

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ABBREVIATIONS

ASE	Annual Sunlight Exposure
BIM	Building Information Modelling
CD	Computational Design
cDA	Continuous Daylight Autonomy
CIE	Commission International del'eclairage
DA	Daylight Autonomy
DF	Daylight Factor
DGP	Daylight Glare Probability
EBCS	Ethiopian Building Code Standard
GD	Generative Design
HSA	Horizontal Shadow Angle
IES	Illuminating Engineering Society
LEED	Leadership in Energy and Environmental Design
NOC	National Oil Company
PD	Parametric Design
sDA	Spatial Daylight Autonomy
SLL	Society of Light and Lighting
SWERA	Solar and Wind Energy Resource Assessment
UDI	Useful Daylight Illuminance
VSA	Vertical Shadow Angle
WWR	Opening or Window to Wall Ratio

CHAPTER ONE
INTRODUCTION

1.1 Background

There are several challenges associated with the development of different infrastructure projects, such as buildings and other habitable spaces. Some of the paramount challenges include ensuring sustainability, efficient energy usage, water efficiency, indoor environmental quality, and efficient use of materials/resources. The advancements in various design strategies, computer aided design, two-dimensional (2D) design, three-dimensional (3D) design, and building information modelling (BIM) are providing significant contribution to tackle these challenges. One of the prominent challenges in building design is ensuring superior indoor environmental quality. The planned and optimized use of daylight with a controlled level of glare is an essential part of ensuring enhanced indoor environmental quality. Such implementation of innovative, advanced daylighting strategies and systems also contributes to energy efficiency of buildings (Bahdad *et al.*, 2020).

The lack of appropriate, low-cost, high-performance daylight systems and simple tools to predict the building performance has led to weak daylight strategies and systems in the past. Also, different architectural studies have also shown the need for further experiments and computational methods of analysis to provide the best and optimized solution for daylight and building performance (Brooks, 2011; Soliman *et al.*, 2019). This has given birth to the application of new techniques, such as generative modeling, genetic algorithm, daylight simulation, and parametric design in architecture. Various computational software/tools, such as DIVA, Radiance, Ladybug+Honeybee, and Ecotect, have also been developed to assess daylighting in buildings. Moreover, in recent years, research in three broad areas: (1) assessment of the performance of systems and lighting control strategies, (2) development of integrated design tools, and (3) case studies to provide evidence of daylight and glare performance in actual buildings have contributed in providing better solutions for daylighting design of buildings (Ruck *et al.,* 2000). However, there is still a need for further research to enhance the daylight and glare performance of buildings, especially in the consideration of various design variables/parameters to arrive at optimized output.

1.2 Problem Statement

One of the design strategies to enhance indoor environmental quality is the utilization of natural light to provide the required illuminance for habitable spaces. This is an important factor, especially for buildings located in areas with limited or excessive sunlight. Buildings designed in an area with sufficient sunlight may also fail to make optimum use of the daylight or end up with excessive glare in the interior space. For example, various high-rise office buildings located in Addis Ababa that are designed with curtain wall facade have been observed to have internal spaces exposed to excessive direct glare. In these buildings users are forced to resort to the use of various do-it-yourself (DIY) interventions, that potentially completely block the much-needed adequate light. On the other hand, there are several buildings located in Addis Ababa with internal spaces that do not get sufficient daylight due to their design and construction. The lack of sufficient daylight in the interior spaces forces occupants to use artificial light, which increases the energy consumption of the buildings.

Various design strategies and processes could be implemented to tackle the challenge of ensuring adequate interior space daylight without presence of excessive glare. Various research has been conducted and different optimization strategies have been proposed and implemented regarding daylighting. However, most of the available literature considers single-variable optimization techniques, whereas there is lack of strategies that consider multivariable optimization.

1.3 Research Objectives

Main objective:

To develop and evaluate a suitable computational multivariable optimization framework, that is useful to ensure optimized daylighting and minimized glare in architectural design of buildings.

Specific objectives:

1. To take on-site daylight illuminance measurements on a case study building, and to validate the results of daylight simulation tools by comparing the simulation results with that of the on-site measurements,

2. To theoretically compare various optimization algorithms and identify a suitable algorithm with potential for application in multivariable optimization of buildings for enhanced daylighting.

1.4 Research Questions

Main Question:

Does the proposed framework for design provide good daylight and glare performance for buildings?

Specific Questions:

1. Do the results of the lighting simulation with DIVA 4 and the onsite illuminance measurements taken by Lux meter (for various locations and time of day) show reasonable matching?
2. Which optimization algorithm is suitable for a potential application of multivariable optimization of buildings for enhanced daylighting?

1.5 Significance of the Study

The ultimate aim of the study is to give architects and designers a multivariable optimization framework for the optimization of daylight and glare in architectural design of buildings. Since the framework is tested on a small-scale sample office space and a large case study building, it can be used by designers on different scale projects. On the other hand, the study gives awareness of significant of daylight for occupants in a building.

In addition, this kind of study creates awareness about daylight performance of buildings so that people can have a space with sufficient daylight distribution and low level of glare in their space. As an academic input the significance of this paper is to create a bridge for more research regarding multivariable optimization, daylight and glare in buildings in terms of providing better indoor environmental quality for users. So, this study contributes in providing new technique in architectural design development for the construction industry of Ethiopia.

1.6 Scope of the Study

The study mainly focuses on the computational multivariable optimization of daylighting and glare. Numerous variables could impact daylighting and glare. The scope of the study is concentrated on the optimization of the two main design variables: (a) Building Orientation and (b) Facade Opening (WWR) for the development of the multivariable optimization framework for daylight.

1.7 Limitations of the Study

Concerning the limitations of this research, there were difficulty to get access to information as well as physical access to various sites at a desirable time due to the COVID-19 pandemic. The other most significant limitation in this research has been the limitation of available computer computational power for simulation and optimization. More design variables and cases study buildings could have been assessed and integrated if the time and computational power limit was ideal for the research. The limitation of having only one lux meter, has led to selection of limited number of area and points in a space from case study building for on-site daylight illuminance measurement.

1.8 Organization of the Thesis

The thesis is organized into six chapters.

Chapter 1 discusses background knowledge on daylight and glare performance of building. It also discusses the problem statement, objectives, research questions, significance of the study, research outline, scope of the study and the limitations of the study.

Chapter 2 covers the review of literature on building and daylight, glare, variables influencing daylight performance, computational design, simulation and optimization. It also contained the foundations of the study that were directed in giving information required in answering the research questions.

Chapter 3 presents the materials and methods used in the study. It also presents the validation of simulation tools done to assure the accuracy of the study and developed framework.

Chapter 4 presents the results and discussions. It also presents analysis of the data collected from the field, the daylight condition of case study building, and the evaluation of the developed framework for computational multivariable design optimization of buildings to achieve optimized daylighting with a suitable limit to glare on sample office building as well as case study building.

Chapter 5 presents conclusions and recommendations drawn based on findings from the previous chapters.

Finally, the summary of questionnaire, detailed on-site measurements taken and simulation illuminance results from NOC building, site picture from NOC building, and Lux Meter specifications and calibration report are given in the Appendices A to H.

CHAPTER TWO

LITERATURE REVIEW

2.1 Theoretical Review

2.1.1 Building and daylight

Natural light is the light generated naturally. The most common source of natural light is the sun. Daylight is the most impactful source of natural light among the various natural light source. Daylight is the combination of all direct and indirect sunlight during the daytime in an area. It consists of direct sunlight, diffused sunlight, and both of these reflected by Earth, landforms, and buildings. When dealing with daylight study it is important to identify the characteristics, type, and frequency of skies to carry out a study focused on realistic lighting conditions. From numerous researches done over several years, CIE (Commission International del'eclairage) has developed a reliable luminance distribution of real sky. There are mainly 15 general sky types stated by CIE standard that represent different sky conditions up to date. They can be categorized into three sky conditions for daylight performance study, namely clear sky, partly cloudy sky, and overcast sky (See Figure 1).

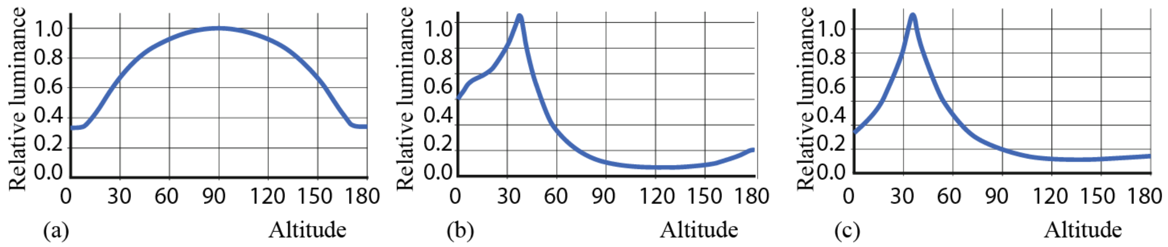


Figure 1: Relative sky luminance of 3 sky conditions: (a) overcast, (b) clear, and (c) partly cloudy. Source: ISO (2004) and CIE (2014)

In a world concerned with global warming and depletion of the resource, the role of daylight in buildings has become an important strategy to improve the energy efficiency of buildings. The introduction of innovative, advanced daylighting design, strategies, and systems can significantly reduce a building's electricity consumption and improve the quality of light in the working space.

The utilization of daylight when designing buildings has been one of the major design aspects of architecture. A study conducted by Borisuit and Linhart (2015) shows that poor lighting conditions in workplaces contribute to a lack of work satisfaction, productivity, and well-being.

They found a higher acceptance score under daylight than electrical lighting. This shows that qualitative daylighting design is not only the aesthetic aspects of design rather includes the impact of daylight on human health and work performance.

A well-daylit building space requires both adequate lighting levels and distribution. In recent years, the building industry considers daylighting as a building performance measure in green building certification programs such as Illuminating Engineering Society (IES), the society of Light and Lighting (SLL), and Leadership in Energy and Environmental Design (LEED). The contribution of daylight to the recommended lighting level determines the daylighting performance of a building. Illuminating Engineering Society (IES) and LEED 4 have approved two metrics for evaluation of daylighting performance: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for daylight and glare respectively.

2.1.1.1 Benefit of daylight

Evidence of the benefit of daylight can be found in numerous researches as well as in observations of human behavior and the arrangement of space. Daylight is vital for its quality, color composition, and variability. A research done by Boyce (1998) shows that daylight is desired in indoor space to be able to see both a task and the space well and to experience some environmental stimulation. Openings are the primary techniques designers use to admit daylight in buildings. In addition, they are also vital for the view and connection they provide with the environment.

Humans are affected both psychologically and physiologically by daylight:

i) Physiological benefit of daylight

According to John Ott (1997), the body uses light as a nutrient for metabolic processes similar to water or food. Other researchers also state various benefits of daylight. For example, Liberman (1994) also converse that light plays a role in maintaining health: Also, Boubekri M (2008) states that daylight is responsible for preventing rickets, production of vitamin D in the body, reducing blood pressure, stimulating energetic activity, reduce fatigue and even increase work output.

ii) Psychological benefit of daylight

Findings of Dr. Ott from the research Ergo Biolight Report shows that daylight excites vital biological functions in the brain. Because of poor lighting condition created during cloudy day, the human eye may be unable to distinguish or perceive color from light. This mostly promotes to mood swings and minimized energy level.

In a built space, direct light from the sun and view are the major psychological benefits that humans have. Although direct sunlight may negatively affect work, a designed and properly located direct sunlight is stimulating and desirable. View to the exterior environment plays a vital role in the psychological health of occupants. Abkar *et al.,* (2010) finding shows that improvement in concentration, recovery from stress, high productivity, and improvement in the psychological state are all positively associated with viewing nature.

2.1.1.2 Property of daylight

Light is electromagnetic radiation within the electromagnetic spectrum. It is the visible portion of the spectrum. Like all other electromagnetic radiation visible light has a wave property. Light has different type property. The most significant one being wavelength. The Hight of a wavelength is its amplitude. Ever though light have several bands when considering wavelength, visible light covers small portion of the wave length from 380 nm and 730 nm (See Figure 2).

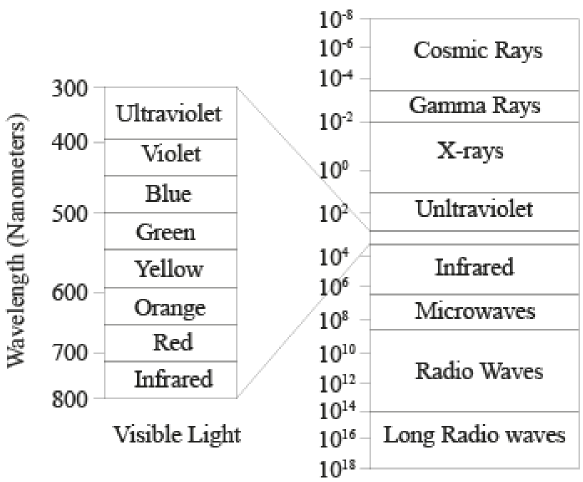


Figure 2: The electromagnetic spectrum and visible light.

Daylight has the capability to precisely distinguish colors of visible electromagnetic radiation spectrum of 380 to 780 nm wavelength. Furthermore, the luminous spectrum of daylight provides a greater feeling of well-being and comfort for the occupants, positively affecting production and concentration, thus being preferable over artificial lighting.

2.1.1.3 Daylighting metrics

Various daylight metrics were defined by various researchers to evaluate the quality and quantity of daylight in the interior space of buildings. The most significant ones are discussed below:

i) Illuminance (E)

Illuminance is the measure of the amount of light on a surface per unit area, and it is measured in lux. Illuminance is mainly used to evaluate the brightness of the indoor environment. according to Illuminating Engineering Society (IES) and LEED4, the recommended level of the illuminance of an interior space depends on the space type, the type of visual tasks, the age of occupants, etc. Table 1 shows the general recommended illuminance for the specific building spaces.

Table 1: Spaces, building type and recommended illuminance values (Source: DiLaura *et al.*, 2011)

Spaces	Task	Recommended Illuminance values (lux)
Bedroom	General	200-300
Cafeteria	General	200-300
Classroom	General	300-500
Conference Room	General	300-500
Lobby	General	200-300
Exhibit Space	General	300-500
Mechanical / Electrical Room	General	200-500
Parking-Interior	General	50-100
Workshop	General	300-750
Residences	General lighting	50-100
Residences	Noncritical kitchen duties	200-500
Restaurants	Kitchen	500-1000
Restaurants	Dining	150-200
Stores	Merchandising areas	500-1000
Stores	Feature displays	1000-2000
Stores	Stockroom	200-500
Hospitals	Patient rooms	50-100
Hospitals	Emergency rooms	500-1000
Hospitals	Operating rooms	1000-2000
Offices	Lobbies	100-200
Offices	Working and reading	300-1000 or 500-1000 or 1000-2000 depending on the work and reading material types

ii) Daylight factor (DF)

Daylight factor (DF) is the ratio of the horizontal indoor illuminance to the outdoor illuminance under continuously overcast sky conditions. DF is easy to measure and calculate. Thus, used in various building regulations to provide a minimum daylight standard (Reinhart *et al.*, 2006).

iii) Useful daylight illuminance (UDI)

Useful daylight illuminance (UDI) is a daylight availability metric that corresponds to the ratio of the number of hours within the year when illuminance provided by daylight is sufficient, to the total occupied hours in a year (Nabil and Mardaljevic, 2005). UDI is usually presented by three metrics: UDI<100 lux (too dark), UDI 100-2000 lux (intermediate), and UDI > 2000lux (too bright). The Illuminance level between 100-2000 lux is considered to be useful.

iv) Daylight autonomy (DA)

Daylight autonomy (DA) is the percentage of the number of hours in the year when the illuminance provided by daylighting is above the minimum illuminance requirement (Reinhart and Walkenhorst, 2001). DA is a dynamic daylight metric. It is based on annual solar radiation data of the building location (Reinhart *et al.*, 2006).

v) Continuous daylight autonomy (cDA)

Continuous Daylight Autonomy (cDA) is similar to that of daylight autonomy in measuring when the illuminance at a point is greater than or equal to a target threshold value. But Continuous Daylight Autonomy (cDA) would give partial credit to hours where the illuminance is less than the minimum requirement (Rogers, 2006).

vi) Spatial daylight autonomy (sDA)

Spatial Daylight Autonomy (sDA) is the percentage of area that meets the minimum daylight illuminance during analysis hours (Heschong *et al.*, 2012). It evaluates the spatial and temporal characteristics of daylight performance. As a result, it is used to know how much of the space receives sufficient daylight. Based on the standard set by Illuminating Engineering Society (IES) and LEED4 a minimum of 55% of space must achieve the identified sDA in order to have sufficient daylight for occupants. A value of $sDA_{300/50\%}$ is taken as a minimum requirement for simulation in this research.

vii) Annual sunlight exposure (ASE)

Annual Sunlight Exposure (ASE) is the percentage of the area where the illuminance of space exceeds the required level for more than a specific occupied hour in a year. This causes visual discomfort or increases cooling loads (Heschong *et al.*, 2012). A value of $ASE_{1000,250}$ is taken as a minimum requirement for simulation in this research.

2.1.2 Visual comfort

Visual comfort refers the condition where there is suitable amount of light for human eye without any distress or pain for the visual task on hand. DiLaura *et al*., (2011) showed that visual comfort is strongly related to illumination levels inside the working space either from natural or artificial light sources.

According to Carlucci *et al.*, (2015) daylight visual comfort indexes can be established in regards to the amount and distribution of light, and the risk of glare for building occupants in specific space. The indexes that are used to describe visual comfort can be point in Time and annual based daylight metrics. Table 2 below shows a simplified selected metrics currently used in daylight visual comfort analysis by various scholars and practitioners for amount and distribution of light as well as glare.

Table 2: Point-in time and annual-based metrics (Source: Gabriela, 2017)

Type of metric	Metric	Descriptions
Point-in-Time Metrics (P)	Illuminance (Ep)	Amount and distribution of light
	Luminance (L)	Surface 'brightness'
	Daylight Factor (DF)	Amount and distribution of light
	CIE Glare Index (CGI)	Glare
Annual-Based Metrics (A)	Daylight Autonomy (DA)	Annual amount and distribution of light
	Discomfort Glare Probability (DGP)	Glare from point of view
	Continuous Daylight Autonomy (DAcon)	Annual amount and distribution of light
	Useful Daylight Illuminance (UDI)	Annual amount and distribution of light
	Spatial Daylight Autonomy (sDA)	Annual amount and distribution of light
	Annual Sunlight Exposure (ASE)	Glare proxy: direct sun in space

2.1.3 Visual discomfort

Visual discomfort refers the condition where the human eye is distress or in pain due to unfavorable lighting condition. Visual discomfort can be cause by various underling conditions. Some are: poor visibility, overstimulation, distraction and glare. Among the source of visual discomfort, glare is the most significant and major cause of visual discomfort in the case of office building in Addis Ababa (Melaku, 2016).

Glare is caused by extremely bright light source or by high brightness contrast in the field of view. It is a visual discomfort caused by light directly from luminous source (Direct glare) or reflected on surface (Indirect glare). Glare source can be windows, smooth and glossy surfaces, computer screen or, incorrectly designed and installed light source.

Direct and indirect glare has both various impact on the ability to see (Lechner, 2015). Direct glare caused by light source may have sufficient brightness to result annoyance, disability and discomfort to the eye. While indirect glare may affect the ability to view object or work area when light reflect on a surface and reaches the eye.

For working space such us office the quality of light directly affects the visual comfort. when daylight is sufficient for specific climatic zone, it is usually used as a light source for building design but the use of large opening in building facade causes serious glare. Majority of the glare caused in office buildings is by direct light through openings from light source.

Illuminating Engineering Society (LM-83-12) introduced ASE metric as a measure for visual discomfort and glare by measuring the percentage of floor area that exceeds a specified direct sunlight illuminance level for a specified number of hours. The ASE metric as a prediction of probability of glare was adapted later by LEED in 2014. Although there is no clear threshold for these metrics in IES the LEED 2014 recommends the annual sunlight exposure ($ASE_{1000,250}$) to be no more than 10%. In addition, Heschong *et al.,* (2012) also stated a threshold of 10% or more to be unsatisfactory, 7% as neutral, and 3% as an acceptable level of glare in a space. The Illuminating Engineering Society LM-83-12 document states that the main limitation of ASE is its consideration of only direct sunlight which causes only direct glare.

In addition to ASE, Daylight Glare Probability (DGP) is another way scholars and practitioners used to analyze glare in a space. it uses vertical eye illuminance (Ev), luminance of the light source (Ls), the solid angle of the source seen by an observer (ωs), and a position index relative to azimuth and elevation (P) to predict the probability of glare from point of view. One of the significant limitations of this metric is that it is only valid and effective for vertical illuminance. In addition, it is limited to an illuminance level above 380lux and DGP between 0.2 and 0.8. values above 380 lux and DGP between 0.2 and 0.8 (Wienold, 2009) (See Table 3).

Table 3: Glare performance category based on DGP (Source: Wienold, 2009).

Glare Category	Daylight Glare Probability
Imperceptible Glare	$DGP \leq 0.35$
Perceptible Glare	$DGP \leq 0.35$
Disturbing Glare	$0.40 > DGP \leq 0.45$
Intolerable Glare	$DGP > 0.45$

Even though DGP provides strong correlation with glare perception from occupant's surrey taken by Carlucci *et al*., (2015) its limitation in perceiving only the vertical illuminance makes it limiting in analyzing horizontal glare condition in working space. Because of this limitation, this research proposes ASE as a measure for visual discomfort and glare.

2.1.4 Variables influencing daylight performance of building

2.1.4.1 Contextual variables

Contextual variables that impact daylight are the nature of the surrounding conditions, nature and built elements. The most significant contextual variables are: Climate, latitude and obstructions and reflections on site.

i) Climate

The overall preconditions for the daylighting design in terms of sunlight availability, visual comfort, thermal comfort, and energy performance in a building site is dependent on prevailing climatic condition.

ii) Latitude

Latitude is the measurement of distance north or south of the equator. It is imaginary lines parallel to the equator that form circles around the Earth east-west. In daylight design, the latitude determines the solar altitude for a given time of day and year. latitude will also determine the length of daytime and solar availability at different seasons of the year.

The movement of sun as well as solar altitude for a given time of day and year is represented by sun path diagram. The most widely utilized sun path diagram is the stereographic chart developed by Phillips (1948). Figure 3 shows the stereographic sun-path diagram for Latitude 9^0N Addis Ababa on April 2^{nd}, 2021 at 2:00pm.

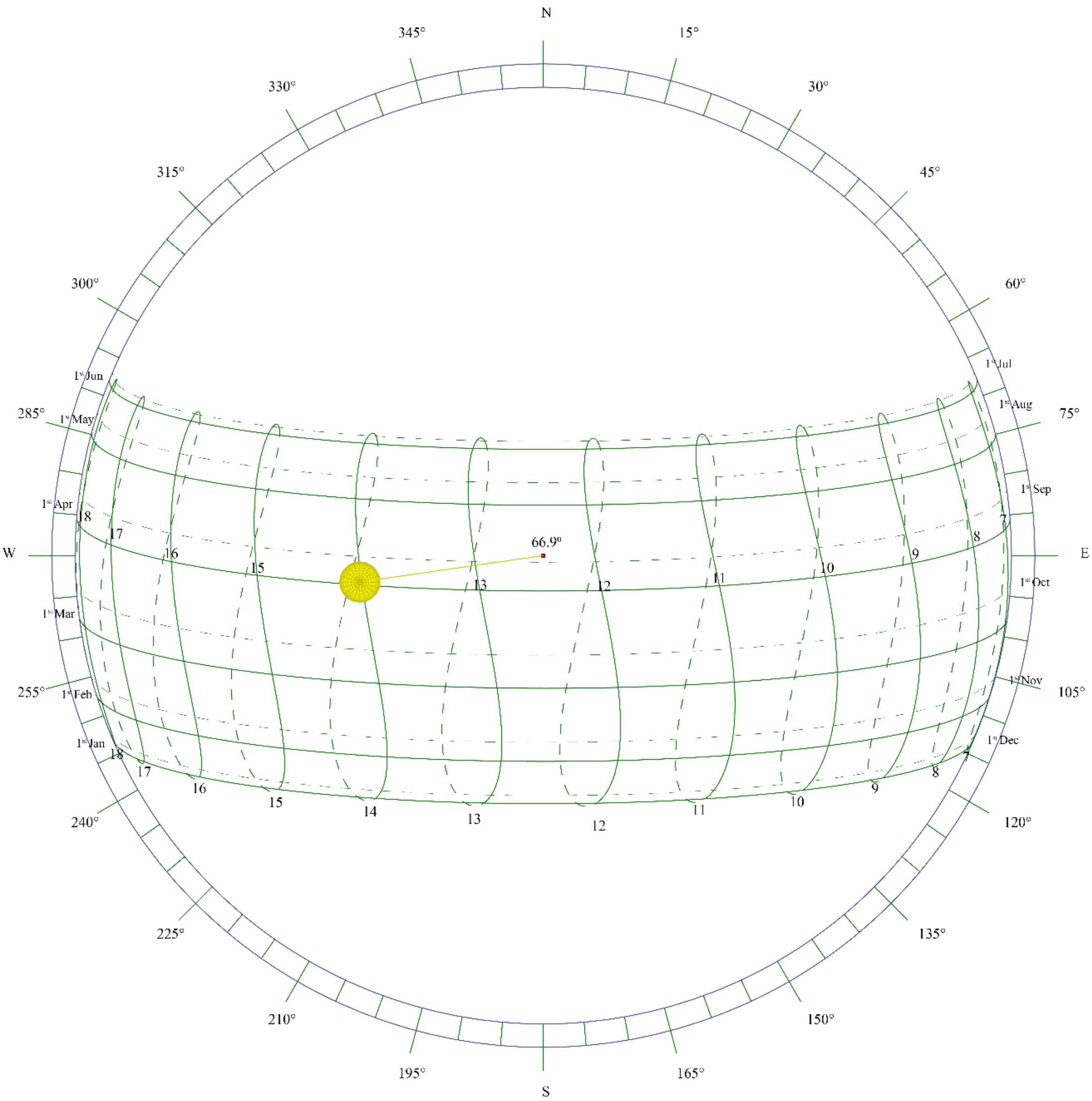


Figure 3: A stereographic sun-path diagram for latitude 9^0 N on April 2nd ,2021 at 2:00 pm, Addis Ababa (Ladybug Tools)

iii) Obstructions and reflections on site

Surrounding elements (buildings, vegetation, ground surface etc.) in and around building site have a significant impact in building design. The impact of external reflections and obstructions from the surrounding elements will influence the amount of light reaching the interior space of a building.

2.1.4.2 Design Variables

In Architectural design, there are various design variables to consider to accomplish the required design output. Design variables are the parameters or units which are kept constant in one case and varied at different to achieve the required design output. Among the various design variables, building plan shape, size of building, average story height, number of stories, building envelope, circulation space, grouping of buildings (obstruction and reflections), floor span constructability, material and orientation are some of them. For this list, building orientation, and building facade are the major determinant variables for consideration in daylight performance.

The research explored various variables that could impact the illuminance of the interior space of buildings. The key variables that are proposed to be studied in this research are: (a) the building orientation and (b) Facade openings (WWR).

i) Building Orientation

Building orientation is one of the most significant decision architects make to achieve efficient daylighting as well as energy saving. Optimum building orientation is used in various climatic condition as a strategy by designers to orient buildings to attain a specific result (Hyde, 2000). In addition, various researchers have also identified and verified a well-oriented building maximize daylighting through building facades and reduce the need for artificial lighting (IEA, 2000; Ibrahim and Zain-Ahmed, 2007; and Ko *et al*., 2008).

ii) Building Facade

Building facade is the exterior boundary between interior space and the outside environment. It functions as a protective cover and allows regulation and exchange of energy, light, and air. Because of its significant, envelop requires efficiency by complementing environmental condition. Facade design is impacted by different factor. Among them Abdel-Aziz and Shuqair (2014) stated that responsive environmental parameters such us orientations, voids and openings, vertical and horizontal shading devices, building material and surface texture and colors.

Some of the envelop design parameters complement the design strategies for providing visual comfort of the users such us opening and material parameter which allows light to enter a space, building orientation which determine the building surface which faces the light source, shading device which limits direct light entering the space while surface texture and color determine how much of the light will be reflected from a surface. This parameter impacts the amount of direct and indirect glare in a space. While opening, material and orientation affect direct glare, surface texture and color affect indirect glare significantly.

Openings perform various functions including permitting daylight to enter a room, ventilation, creating a view, and connection with the surrounding environment. Daylight level will differ depending on the time of day, time of year, and location. Light enters a building in a number of ways including direct sunlight, skylight, and diffused light, reflected external and internal light from surfaces (See Figure 4).

There are various variables that could impact the illuminance of the interior space of buildings. The key variables that are proposed to be studied in this research are: (a) the building orientation and (b) facade openings (WWR).

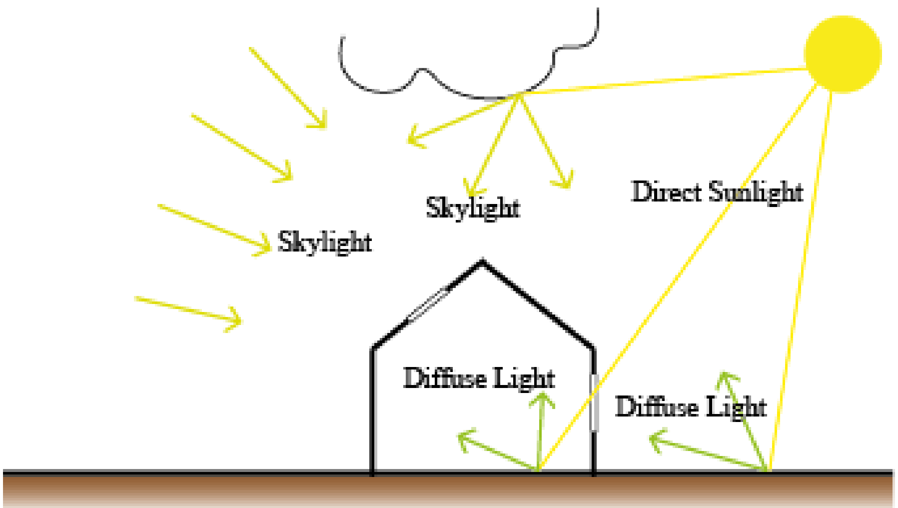


Figure 4: Direct sunlight, skylight and diffused light.

Light is inseparably connected with material in building design. They visibility of material and light to the human eye is dependent on each other. So, in building design direct sunlight, and skylight (diffused sunlight) are the most significant to allow a comfortable visual environment by natural light for occupants in interior space of buildings.

2.1.4.3 Identification of Constant and Changing Variables/Parameters

Identifying constant and changing variables/parameters that can impact daylighting and glare is significant to find optimal daylighting in buildings.

i) Constant variables/parameters

Material: property of materials was identified and kept constant throughout the simulation process (See Table 4).

Table 4: Material information for DIVA 4-Radiance daylight simulations (Source: Building materials report of case study building).

Building Component	Reflectivity	Visual Transmissivity
Walls and Partitions	0.4	-
Ceiling	0.8	-
Floor	0.4	-
External ground	0.2	-
Glass Partition	-	0.88
Glazing	-	0.80

Office Furniture: the furniture of the model is based on the real office. material properties and color will remain constant.

Space Dimensions: the majority of office space in Addis Ababa are pool offices. Pool office space will be taken as the design is very critical in terms of large space and how the daylight is distributed in the working space. The length, width, and height of the selected space will remain constant.

Building Form: the building form will not be changed since the cases taken are built and the major parameter that impacts daylight and glare are Building orientation and openings on facade.

Weather Data and Location: The selected weather data which define the sun position (solar altitude and azimuth angles) and the sky conditions. From Addis Ababa, Ethiopia, weather data gathered by Solar and Wind Energy Resource Assessment (SWERA) from bole (weather data 634500) is the nearest whether data in close proximity to study area that can be utilized for simulation, optimization and analysis.

ii) Changing variables/parameters

Time of Simulation: The simulation to be undertaken will be in two ways point in time, where simulation would be done at selected day of the year, and annually.

Building Orientation: The analysis and optimization of building orientation is done in all direction to investigate and identify optimal interior daylight of space and minimized glare.

Facade Opening: Opening plays a significant role in permitting daylighting to enter a space. The analysis and optimization of window to wall ratio and opening distribution will be done to get to an optimal daylight sufficiency and distribution with minimized glare.

2.2 Contextual Review

2.2.1 Daylight condition of Addis Ababa

According to weather data shown in Table 6, there is about 2hour and 48-minute sunshine hours in July and about 9 hour and 42-minute per day in December. Overall, there are around 2439 hours of sunlight hours per year of the possible 4383. This accounts for 55.6% of daylight hours with an average of 6 hours and 40-minute of sunlight per day. The 44% remaining daylight hours are most likely cloudy, shaded, haze or low sun intensity. So, the sufficient daylight availability in Addis Ababa, Ethiopia, will give architects and designers the potential to utilize daylight as a source of natural light for buildings.

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

Table 5: Sunshine and daylight hours in Addis Ababa, Ethiopia (Source: https://www.addis-ababa.climatemps.com/).

2.2.2 Ethiopian building code of standard

According to Ethiopian Building Code Standard (EBCS) revised in 2014, lighting in buildings is considered as services in Building Spatial Design - EBCS-12. This are standard and guideline regarding lighting stated on EBCS-12:

i) Every space intended for human occupancy shall be provided with natural light by means of exterior glazed openings.

ii) The minimum net glazed area of a space intended for human occupancy shall not be less than 15 percent of the floor area of the room served.

iii) Exterior glazed openings shall open directly onto a public way or onto a yard or court in accordance with section 6, except:

   a. Required exterior openings are permitted to open in to a roofed porch where the porch:
      - Abuts a public way, yard or court.
      - Has a ceiling height of not less than 2100 mm.
      - Has a longer side at least 65 percent open and unobstructed.

   b. Skylights are not required to open directly onto a public way, yard or court.

iv) Glazed wall openings and skylights shall be free of obstructions and provided with means for cleaning in order to maintain adequate supply of natural light and prevent the use of artificial light.

v) All occupancies other than dwelling occupancy shall be provided with means to generate at least 5% of their energy consumption themselves.

vi) For the purpose of natural lighting, any room may be considered as a portion of an adjoining room where one-half of the area of the common wall is open and unobstructed and provides an opening of not less than $1/10^{th}$ of the floor area of the interior room or 2.5 m^2, whichever is greater.

vii) All building spaces shall be provided with artificial light of an average illumination complying with relevant standards and EBCS 10.

EBCS 10 states the recommended lighting requirement for different types of interiors, tasks and workspaces. Table 6 shows the recommended minimum illuminance level for office space. In addition, EBCS 10 lighting requirements states:

i) For indoor workplaces that are manned full-time, a minimum rated illuminance of 200.0lx shall be provided unless other factors (such as nature of operation, physiological reasons) require different values.

ii) In interior designed for permanent human occupation, a minimum rated illuminance of 100.0 lx is required.

iii) If tasks are performed at fixed-location workplaces outdoor that correspond to tasks performed indoors (e.g., operation of wood-work machines), then a rated illuminance specified for such tasks in EBCS 10 for indoor workplaces shall be provided.

iv) At no stages in the useful life of the lighting installation shall the mean illuminance, E, obtained at the workplaces be less than 0.8 times the value of the rated illuminance; at no single workplace shall illuminance ever fall to less than 0.6 times the rated illuminance.

The Ethiopian Building Code Standard (EBCS) focuses mainly on consideration of artificial light. There is only limited consideration of natural lighting in buildings. The required level of illuminance as well as limit to glare caused by natural light are not clearly specified in EBCS.

Table 6: Indoor office recommended illuminance for artificial light. (Source: EBCS 10)

Type of Interior Task	Rated Illuminance, Em, in lx
1. Office and similar rooms	
1.1. Office with daylight-oriented workplaces, all in immediate vicinity of windows	300
1.2. Offices	500
1.3. Open-plan office with average reflectance with high reflectance	1000
1.4. Technical drawing office	750
1.5. Conference and consultation rooms	300
1.6. Reception rooms	100
1.7. Rooms open to the public	200
1.8. Data processing rooms	500

2.2.3 Review of building performance optimization studies in Ethiopia.

There are limited number of studies related to building performance in Ethiopia (Taeka 2015, Melaku 2016, Merdekiyos 2020, Getachew 2020, etc.). Among the review studies even small number of them are focused on daylight performance and indoor environmental quality. The following are the notable literature in the subject matter.

Taeka (2015) assesses the performance of selected building in Addis Ababa, Ethiopia. The research proposes a way to adapt green building theories and concepts to selected sample building to achieve better building performance. The study finding showed that the sampled buildings have inadequate indoor environment quality, excessive energy use, and disorganized waste management as compared to green building.

Melaku (2016) assessed the impact of glass facade on thermal and visual comfort performance of buildings indoor environmental comfort and nearby open spaces in the emerging central business district area of Addis Ababa.

Merdekiyos (2020) assessed and evaluated selected high-rise building in Addis Ababa based of green building criteria. The finding of the research gave direction for future buildings to incorporate the green building features in their design for better building performance including daylight performance and energy efficiency.

From the reviewed studies in area of indoor environmental quality, there are no studies which proposed a method or technique to improve daylight performance of buildings in architectural design. Rather, the studies analyze the existing condition of building in Addis Ababa, Ethiopia.

2.3 Empirical Review

2.3.1 Computational design (CD)

Computational design in architecture refers to the application of computational strategies to the design process to solve design problems. In architectural design practice and research, the computational design approach is becoming popular over the years. In the last two decades, the computational design techniques applied in architectural design surpassed the automation of drafting tasks (Terzidis, 2004). But the use of computational design often requires specialized expertise, thereby forcing designers to acquire new knowledge. This combination has given birth to new terms like parametric design, generative design, and algorithmic design.

Currently, emerging design approaches in the field of architecture have been integrating diverse computation-based techniques, such as building simulation and optimization, thereby originating new design approaches and terms (Oxman, 2017). Figure 5 and Figure 6 shows that parametric design (PD) is the most popular and used term, followed by generative design (GD). Parametric design accounts for 46.6 % of the total occurrence of CD-related research and practical used term. From the study done by Caetano *et al.*, (2020) one can see the application of parametric design significantly increased in the previous years than other computational design terms (Caetano et al. 2020).

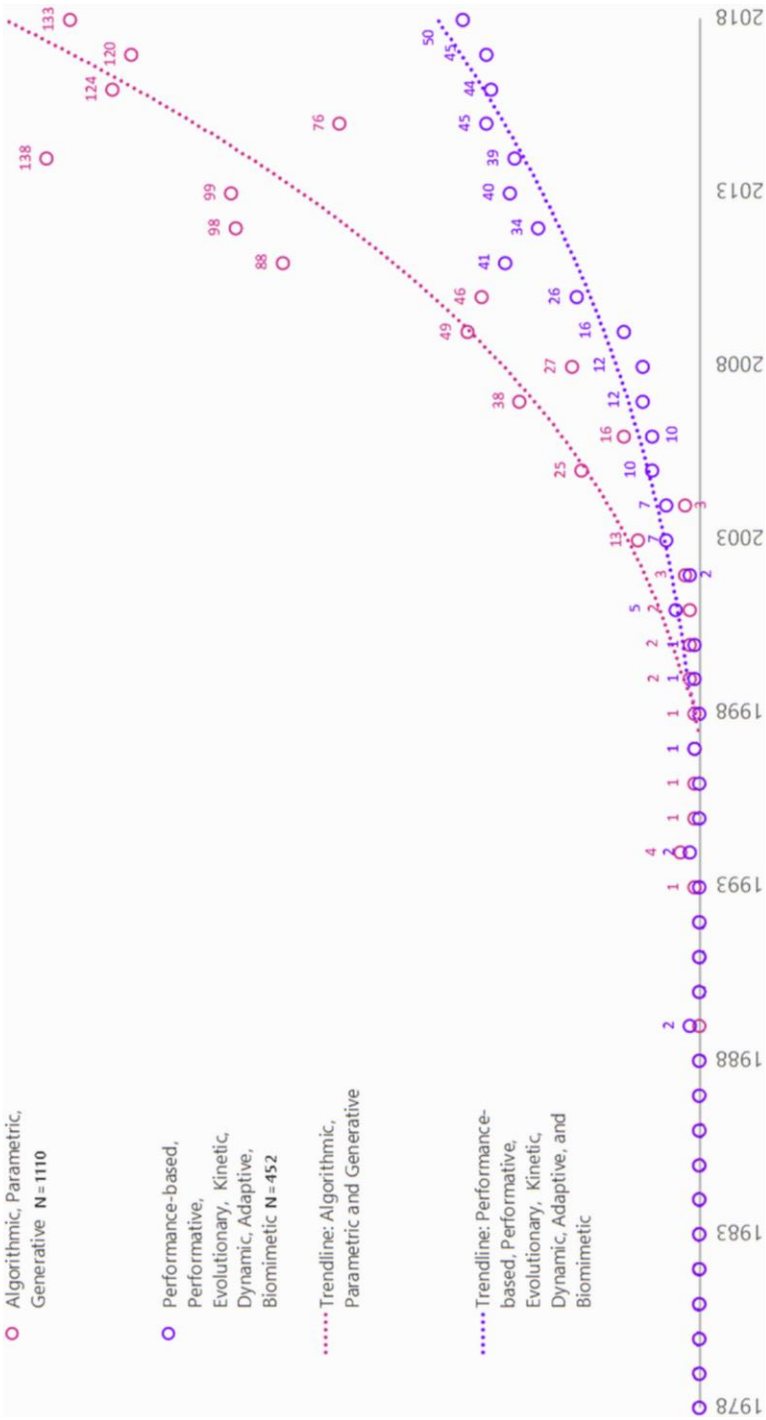


Figure 5: Frequency of use of selected and non-selected CD-related keywords between 1978

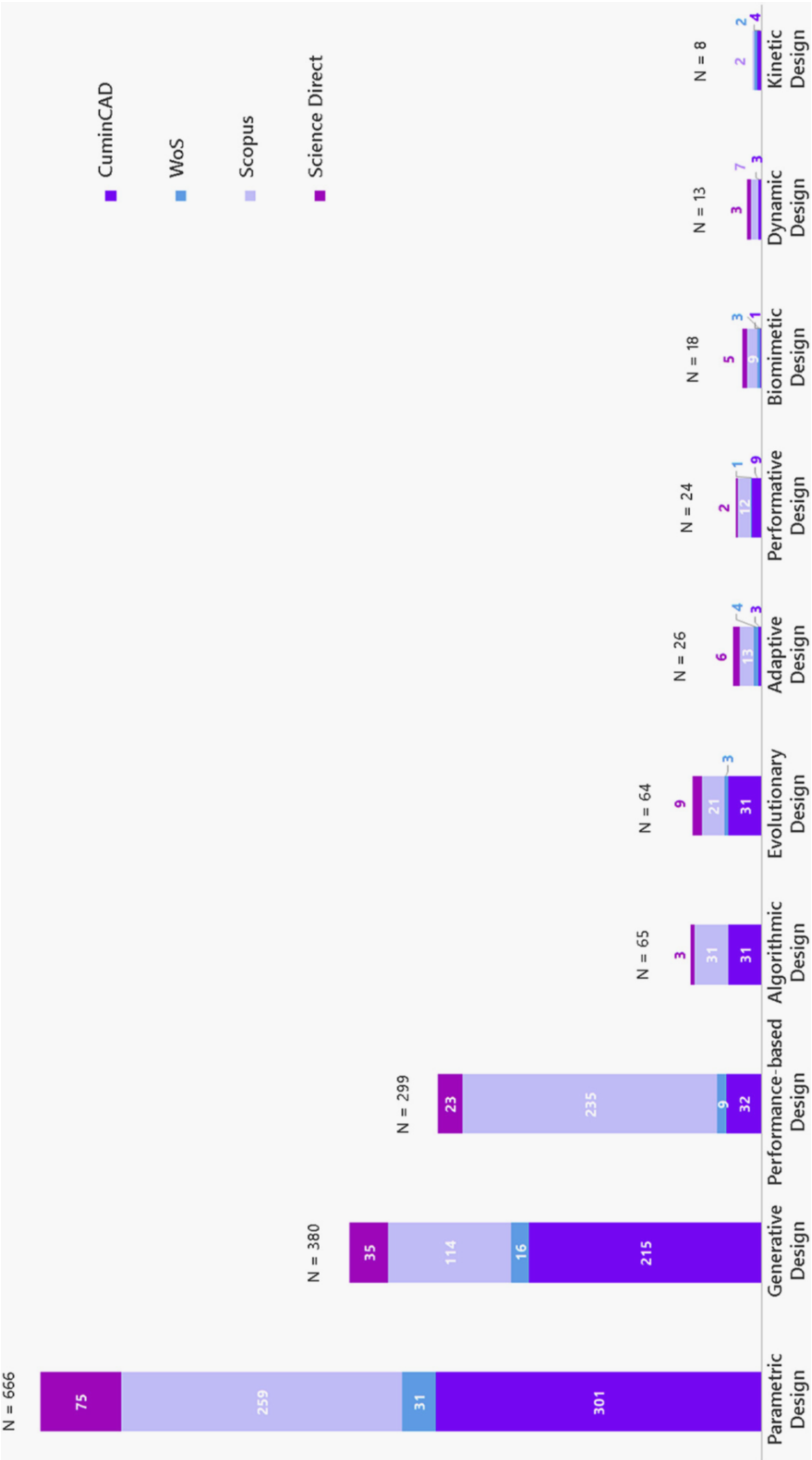


Figure 6: Number of times each CD Term appeared in literature between 1978 and 2018

2.3.1.1 Parametric design

The term parametric originates from mathematics. It is defined as the use of parameters or variables that can be manipulated and altered to produce the results of an equation or system. The first usage of the word by designers has been debated by many authors. Robert Stiles (2006) argues that the real provenance of parametric was a few decades earlier, in the 1940s' writings of architect Luigi Moretti (Bucci and Marco, 2000). Moretti (1971) defined parametric architecture as the study of "relationships between the dimensions" of a design based on parameters. Kalay (1989) extended Moretti's definition by considering parametric modeling as a computational representation of geometric relationships that are "automatically updated and visualized on the screen" upon parameter change. while Monedero (2000), focuses on the relations between form parameters. From the various parametric design definition, one can see that parametric design used by architects has helped navigate multiple options by varying selected parameters. This gives parametric design potential and ability to generate design alternatives faster than the conventional methods of design. This has made the application of parametric design in the development of architectural design significantly high.

2.3.2 Simulation, optimization and daylighting

2.3.2.1 Daylight simulation

Daylight simulation is a computer-based analysis of the amount of daylight available inside or outside of a building under one or several sky conditions. Simulation outputs could be illuminance or luminance for selected sensor points in a space. Wong (2017) finding related to daylight simulation show that, of the various methods used to evaluate the daylight performance of a building, computer simulation is the most commonly used in the building design stage because of its capability of involving design variants and its accurate result. The research also identified and review computer daylighting simulation tools, and the most frequently used tools used by researchers and practitioners are Radiance, Adeline, Ecotect, DOE, Daysim, and EnergyPlus.

Yu and Su, (2015) identified two mostly utilized illumination algorithms in daylighting simulation programs: ray-tracing (view-dependent algorithm) and radiosity (scene-dependent algorithm), which can be represented by Radiance and Relux respectively. From the two, Radiance is widely used in daylighting simulation-related research topics, and it has extensively validation by researchers (Mardaljevic, 1995; and Reinhart and Walkenhorst, 2001). One of the major drawbacks of the program is the lack of user interface. But it is usually incorporated within other tools. Because of its validation and availability Radiance is used as a simulation tool for this research. The following radiance parameters have been used by Truesdell (2018) for daylight simulation (See Table 7):

Table 7: Selected radiance parameter (Source: Truesdell, 2018)

Radiance Parameter	**Value**
Ambient accuracy (aa)	0.15
Ambient bounces (ab)	2
Ambient divisions (ad)	512
Ambient resolution (ar)	256
Ambient super-samples (as)	128
Direct relays (dr)	2
Source substructuring (ds)	0.2
Limit reflection (lr)	6
Limit weight (lw)	0.004
Source jitter (dj)	0
Specular jitter (sj)	1
Specular threshold (st)	0.01

2.3.2.2 Optimization

One of the most common approaches that designers and engineers use to find the best design solution to a problem is to consider different variables to establish multiple design alternatives. The ideal design solution is found through a comparison of the performances of the design alternatives. This approach is used widely in research and practice. For example, Ho *et al.,* (2008) explored 4 types of shading design with different height and width combinations to find the optimal design with maximum uniform illumination level and distribution. However, this type of approach is limited to certain options.

Optimization is an act, process, or methodology of making something (such as a design, system, or decision) as fully perfect, functional, or effective as possible (Merriam Webster Online, 2020). The development of parametric design, building simulation, and optimization technologies in recent years has enabled the possibility of optimization of building performance. The application of optimization has been used since the 1980s and 1990s but the application in building performance flourished in the late 2000s (Nguyen *et al.*, 2014).

The optimization process requires variables and objectives functions as input. In building performance optimization, variables are values controlling the design while objectives are the building performance metrics usually calculated by simulation tools (Machairas *et al.*, 2014). Numerous design variables are considered in building design. Some of the design variables include orientation of building, form of building, materials and openings (Fang, 2017).

2.3.2.3 Multivariable optimization

In solving building design problems, designers usually tackle various variables to reach to a solution. Multivariable optimization is much more difficult than the simpler problem-solving techniques used by various designers of using a single variable. In a multivariate optimization problem, multiple variables act together for making decision in the optimization problem-solving process. Mathematical representation of multiple variable optimizations can simply be represented as $z = f\left(x_1, x_2, x_3, ...x_n\right)$, Where "$x_1, x_2, x_3, ...x_n$" represents the various variable while "z" represents the objective.

The daylight performance of a building is affected by various design parameters or variables. These parameters or variables affect daylighting in a different manner. Some of the design variables are building plan shape, size of building, average story height, number of stories, building envelope, circulation space, material and orientation. In optimization of daylight, because of its multivariable nature, multivariable optimization has a higher potential in producing a more optimal solution to a problem of lighting than a single-variable optimization.

2.3.2.4 Optimization algorithms

Different optimization problem requires different optimization algorithms. In recent years, numerous optimization algorithms have been developed and used for building performance optimization. A review conducted on different optimization algorithms by Nguyen *et al.*, (2014) classified the algorithms into local or global methods, heuristic or meta-heuristic methods, deterministic or stochastic methods, derivative-based or derivative-free methods, trajectory or population-based methods, bio-inspired or non-bio-inspired methods, single-objective or multi-objective algorithms. Each family's' strengths and weaknesses were also reviewed with their typical algorisms. Evins (2013), and Machairas *et al.*, (2014) also conducted a similar review regarding computational optimization methods and algorithms for optimization of building design respectively.

Based on the review of the previous studies, stochastic population-based algorithms, such as Genetic algorithms, Particle swarm optimization, and Hybrid algorithms, were the most used in building performance optimization (Nguyen *et al.*, 2014). Out of the various stochastic population-based algorithms, Genetic algorithm is the most popular and used optimization algorithm in building performance studies. The algorithm randomly selects solutions of good performance from the current population and uses them as parents to produce the next generation, and the population "evolves" toward an optimal solution (MathWorks, 2016). In the application of genetic algorithm in building daylight optimization, the candidate solutions (Phenotypes) to an optimization of daylight are evolved towards better solutions (See Figure 7 and Figure 8).

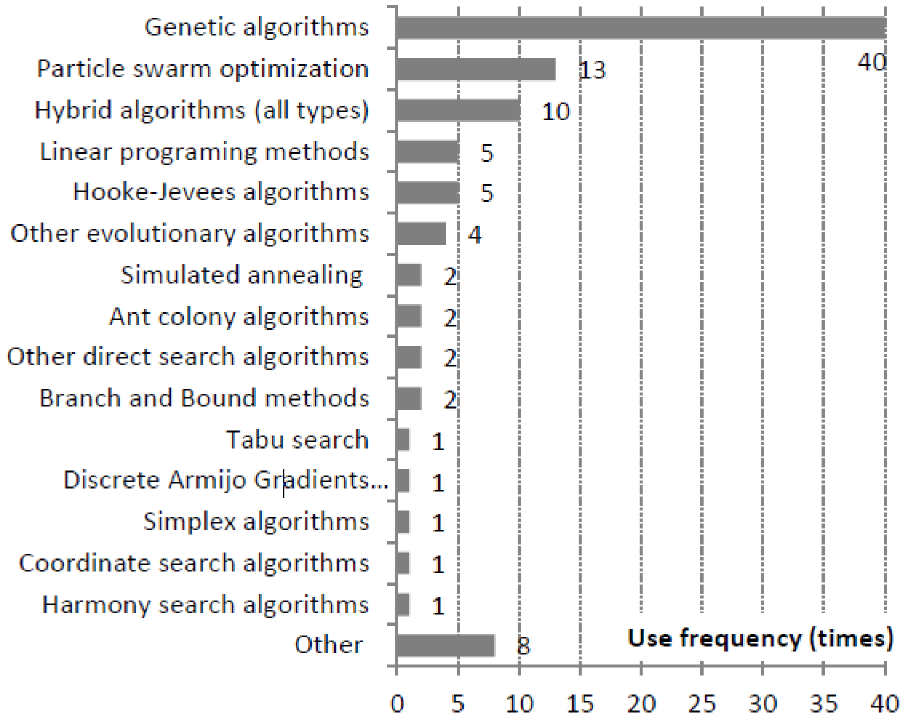


Figure 7: Use frequency of different optimization algorithms, the result was derived from more than 200 building optimization studies given by SciVerse scopus of Elsevier (Source: Nguyen *et al.*, 2014).

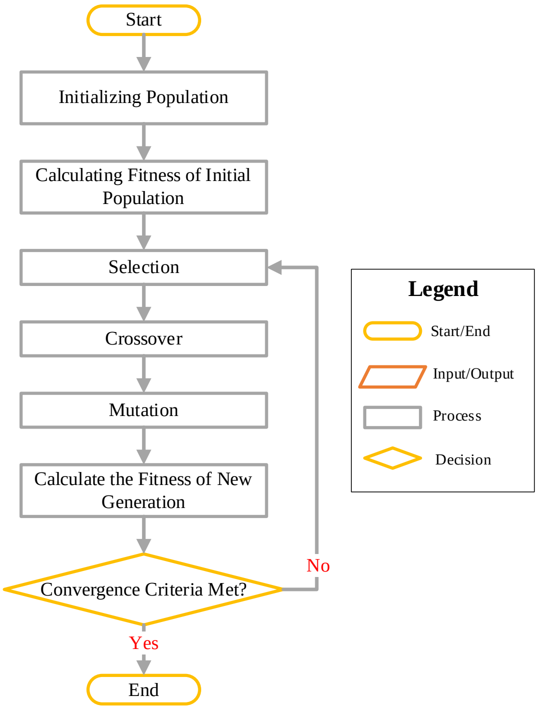


Figure 8: Flowchart outlining details of Generic algorithm

Generic algorithm's ability to handle continuous and discrete variables, allow parallel simulation on multi-processor computers, and be robust to high simulation failure rates to solve single or multiple objectives and variables in optimization problems makes it ideal for daylight performance optimization (Nguyen *et al*., 2014).

2.3.3 Review of building performance optimization studies

In recent years, there has been a significant increase in number of building performance optimization related research. From the various building performance related research, a limited number of research has been explored in area of daylight performance and lighting system. According to Evins (2013) findings, about 92 percent of the reviewed work focused on optimization of building envelop, building form, HVAC systems and renewable energy generation while the other 8 percent focused on control strategies and lighting systems.

In this review, precedent building daylight performance optimization studies related to building envelope and building geometry are presented below.

2.3.3.1 Optimization of building envelope

Building envelop is the barrier between the interior space of a building with the surrounding environment, which has significant influence on building daylight performance. Building envelope optimization studies explored are mostly concern with the selection of building materials, shading devices, fenestration options, and opening orientation. The most optimization objectives tackled in building studies are energy performance, thermal comfort, and environmental impact. From the limited studies which considers daylight or glare as the optimization objectives some of them are:

Lartigue, Lasternas, and Loftness (2013) has explored and provided a methodology for optimization of building envelope to minimize heating and cooling load while maximizing daylight. The variable explored to optimize the objectives are the window to wall ratio and window material. Pareto approach was used to identify the tradeoff solutions between objectives.

Bahdad *et al.,* (2020) explored the optimization of daylight performance by controlling light-shelf parameters. The utilization of parametric design, simulation modelling, and genetic algorithms in the research was used as a methodology approach. The result shows that the optimized result shows a significant potential for illuminance improvement.

Le *et al.,* (2021) implemented a concept of Origami-inspired shading device based on dynamic daylight for achieving optimum daylight performance with the implementation of automatic simulation optimization procedure by combining daylight simulation tool called DIVA and an optimization method called balancing composite motion optimization. The finding shows that the proposed kinetic device has outstanding performance in achieving optimum daylight in four orientations, including North, North-East, South and North-West.

2.3.3.2 Optimization of building geometry

The building form and orientation are the most significant design decisions made in early design stage of architectural design. Building form greatly influences a building’s energy daylighting performance. The main design variable impacting daylight performance are building shape, orientation, facade design, building shape, etc.

Futrell *et al.,* (2015) investigated building design for minimum energy demand and maximum daylight. A class room design is optimized for north, south, east, and west orientations. The result of the research showed that for south, east and west orientations, the objectives are not in strong conflict while there was a strong conflict for the north orientation.

Fang and Cho (2019) proposed a building performance optimization process for optimization of building geometry and facade fenestration to generate optimized design option with suitable daylight and energy performance. The application of parametric design building modeling and genetic algorisms have been utilized as a method. The finding shows an increase in daylight performance and a decrease in energy performance.

The reviewed studies in area of building daylight performance optimization, there are no studies which tries to optimization daylight and glare for interior space with consideration of multiple design variables: (a) Building Orientation (b) facade opening (WWR). So, this study aims to propose a frame work for multivariable optimization of indoor daylighting and glare in architectural design.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the Study Area.

This research was conducted in area located in Addis Ababa, Ethiopia, as shown in Figure 9 below. It is geographically found between 38.75º E longitude and 8.98º N latitude. Because of its location in respect to angle of sunlight coming from the sun Addis Ababa has an average of 12 hours of daylight per day. The 55.6% of daylight hours is with an average of 6 hours and 40-minute of sunlight per day while the remaining 44% daylight hours are most likely cloudy, shaded, haze or low sun intensity. The research is mainly focused on daylight performance of selected case study building located in the study area.

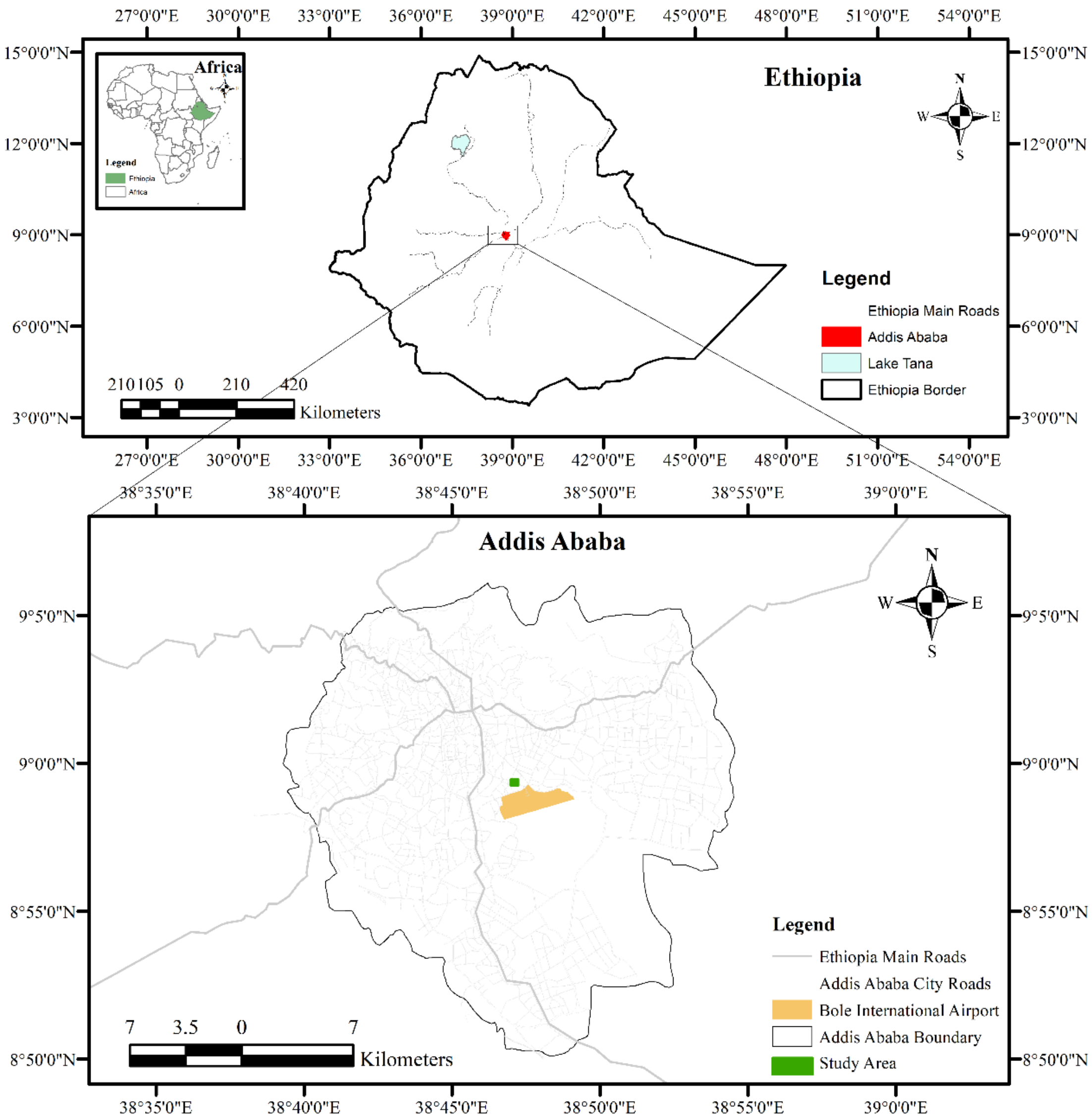


Figure 9: Location of Study Area

3.1.1 Case study selection criteria

The selection criteria for case study are based on four primary considerations. The First is the building must be high rise office building built in the past decades. The second is the location in relation to the weather data used for simulation for accurate comparison between simulation and field measurement. The third is consideration of the type of facade system, and orientation. The fourth is the availability of resource for case study as well as access to the building.

The selection of floor space from the case study building will be based on the following criteria:

1. The floor space must be occupied for 6 month or more.
2. Must be on a higher floor level to minimize impact of other parameters like context and focus on the most significant variables.
3. Facade openings of the selected floor must be similar to that of facade of the buildings.
4. Must have access to the floor.

The selected case study based on the above criteria is National Oil Company (NOC) of Ethiopia Headquarters Building due to availability of sufficient data, built time, type of facade, building orientation and access. The existing building have been used as a case for measuring and analysis of existing condition as well as in the development of the framework.

Questionnaire is used to find occupants feedback about the daylight condition of the case study building. Overall, 40 respondents were taken from occupants from NOC building with 6 months to 1 year stay in the building. This limited the study floor to 10th floor to 14th Floor because the floor levels below 10th floor rental office space which haven’t been occupied for more than 3 months. The selected floor for investigation based on the criteria is the 10th floor space.

3.1.2 National Oil Company (NOC) of Ethiopia Headquarter Building Project

Figure 10: Picture of National Oil Company (NOC) of Ethiopia headquarter building.

National Oil Company (NOC) is one of the key players in Ethiopia's oil industry. The company announced the completion of the construction of their new headquarters building on July 8, 2017. The new building is one of the tallest buildings in Ethiopia.

The building is 15 floor building which is designed for office function. the building is currently occupied by workers from the National Oil Company and rented space tenants. The building was designed with the shape of an ancient barrel, meant to reflect rich historical heritage and modern development ambitions of the East African country (Source: Xinhua (xinhuanet.com)).

3.2 Research Method

3.2.1 Data sources and data type

In this study, both qualitative and quantitative data have been utilized to achieve the objectives of this research. The qualitative and quantitative data used in this study, which are presented subsequently, are grouped into primary data and secondary data.

i) Primary data

There are two important primary data collected in this study. The first primary data collected during the study is the on-site daylight illuminance measurements taken at different location from the inside of a case study building. This quantitative data is later used to validate the accuracy and reliability of the daylight simulation conducted using software. The second primary data is qualitative information regarding the daylight and glare perception of occupants of the case study building, which is collected by means of questionnaire.

ii) Secondary data

The secondary data used in this study include the radiance parameters and weather data for Addis Ababa, Ethiopia. The radiance parameters are obtained from standard literature, whereas the weather data is obtained from the Solar and Wind Energy Resource Assessment (SWERA) global data set. Also, additional construction documents such as plan, elevation and material property for the case study building are obtained from the owners of the building, i.e., National Oil Company (NOC) of Ethiopia. In addition, acceptable values of the annual sunlight exposure (ASE) and spatial daylight autonomy (sDA) are taken based on international standards.

3.2.2 Sample size and sampling technique

Accessible population technique has been implemented for questionary distribution. It was accomplished by distributing the questionary to all population (40 occupants) throughout the case study building were the researcher has access too.

3.3 Instrument and Computation Power used in the Research

3.3.1 Instruments

Lux meter is used for measuring the daylight availability as well as amount of light in a space. The unit used for measuring the illuminance level as a specific point and time in a space is Lux (See Figure 11).

Figure 11: Lux meter

3.3.2 Computational power used

The simulation and optimization in the research are accomplished with a laptop with 24GB ram, Intel(R) Core (TM) i7-9750H CPU @ 2.6GH (12CPUs) and GPU of NVIDIA GeForce GTX 1660Ti running for multiple days at a time.

3.4 Computational Simulation Tool and Validation.

Computational simulations have the power to analyze the daylighting condition of building space much faster and detailed than calculations or model testing. It predicts the possible daylighting condition of a design before it is constructed with the effects of climate with hourly weather data from a typical meteorological year.

Ladybug tools 1.2.0 and DIVA 4 plugin for Rhinoceros 6 have been used for conducting point in time and grid-based analysis. Radiance is used as a calculation and simulation engine for lighting in this program. Ladybug tools 1.2.0 and DIVA 4 act as interfaces that facilitate conducting simulations with Radiance. Radiance has been validated by various research as well as International Commission on Illumination (CIE test cases 171:2006) (Reinhart and Walkenhorst 2001). While Rhino version 6 with grasshopper is used for modeling as well as a parametric design tool.

Further analysis is done to compare the variation between illuminance measurements taken by Lux meter from the case study building and simulation tools results for the case study building.

The illuminance level at the working plane is measured using lux-meter at different point and time of the day in selected spaces from the case study building. For office buildings, the study considered the European assumption of 0.85m as a working plane level for analysis and simulation of daylighting of the study model as well as case study building (Source: https://www.schorsch.com/en/kbase/glossary/workplane.html. Retrieved: April,10 2021). The result of the illuminance level measurement taken by one Lux meter from March 25th 2021 to April 25th 2021from points shown Figure 12 on the 10th floor of the case study building is compared with the illuminance level result from simulation to identify the variation between the simulation tools results and real measurements. The effect of sky condition (i.e., clear sky condition) as well as occupants' intervention were considered in selecting measurements for variation analysis.

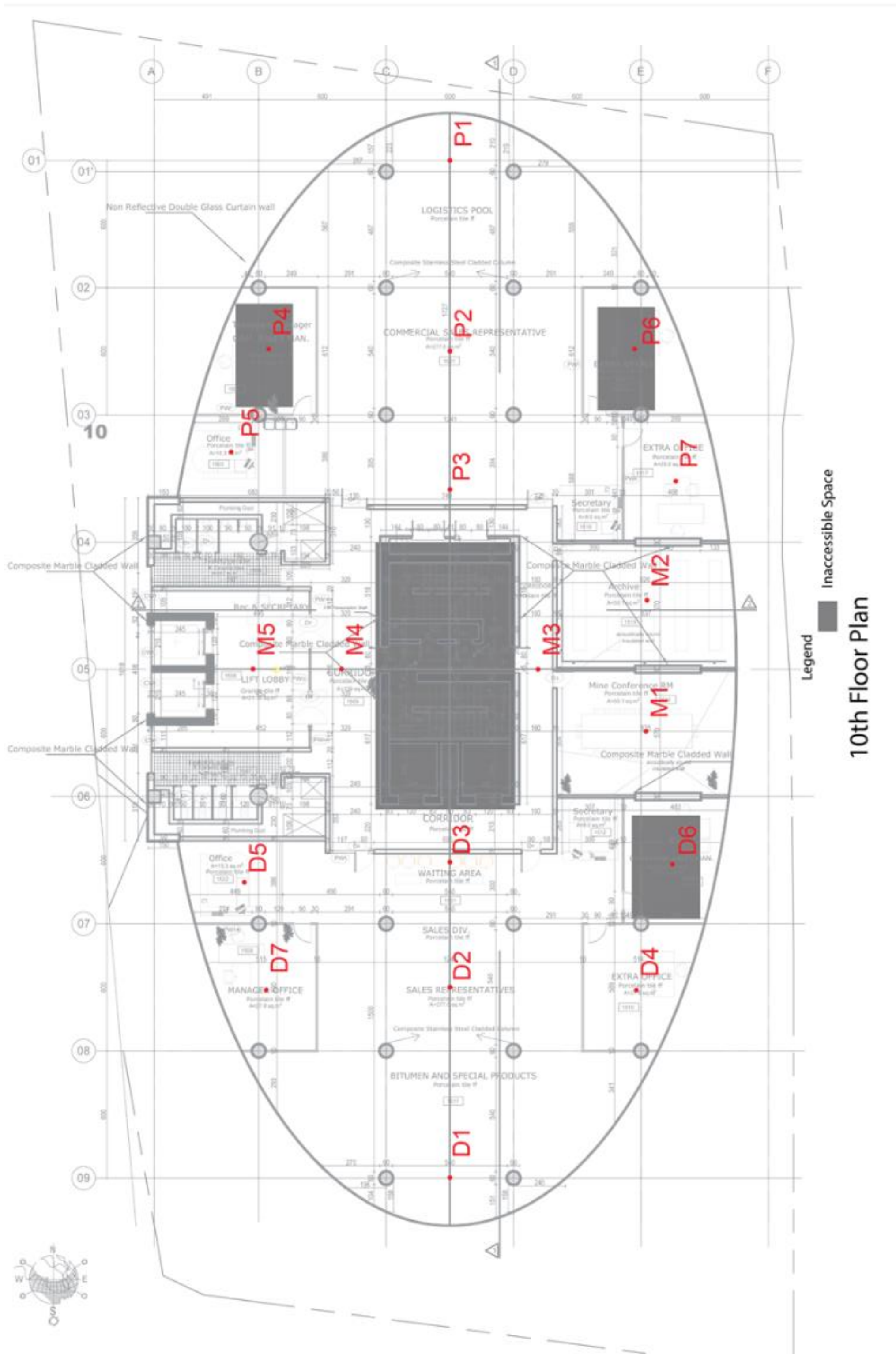


Figure 12: Point of measurement at 10th floor of the NOC building.

3.5 Research process

The general research process that is taken to accomplish and answer the research objectives and questions are shown in Figure 13.

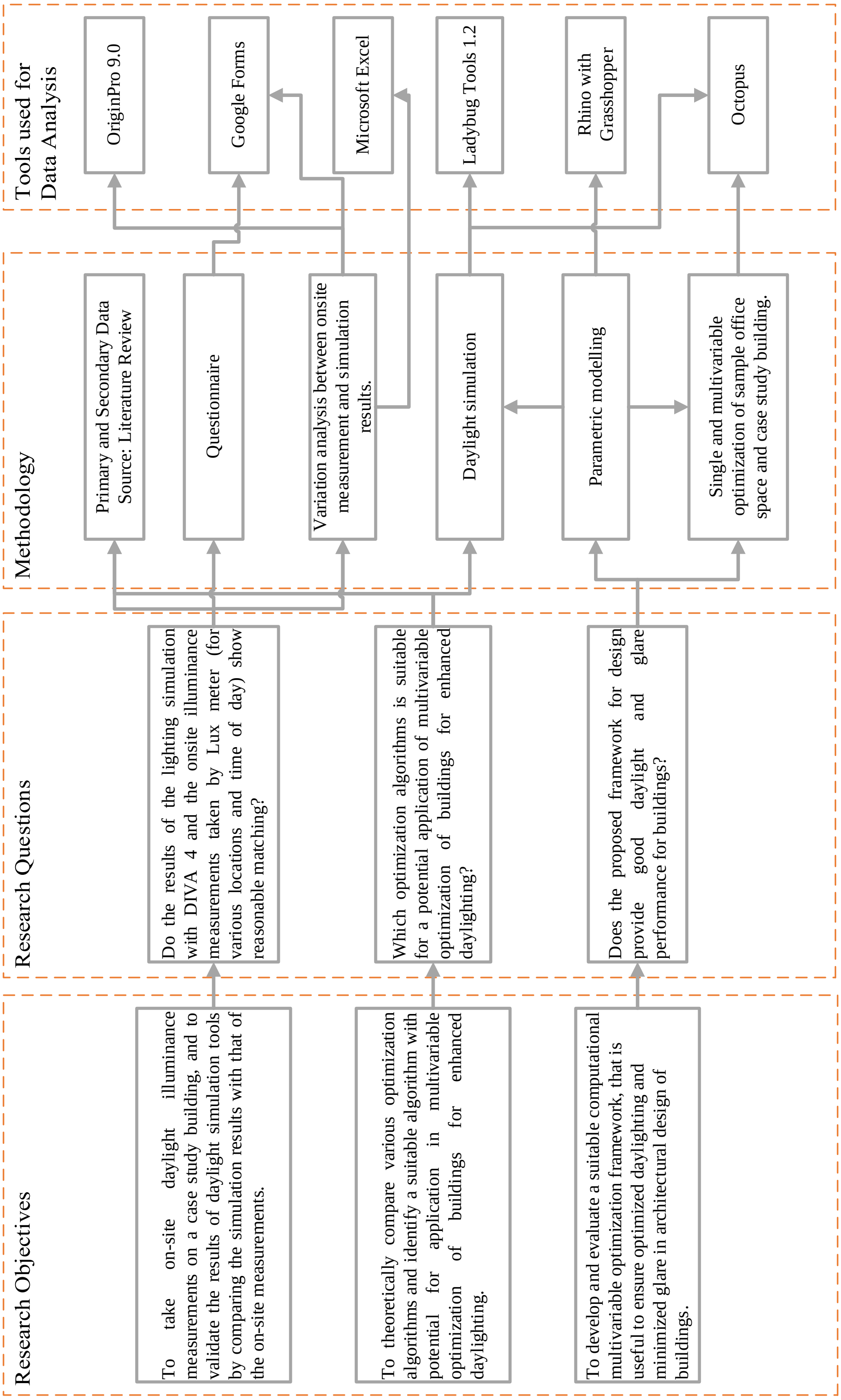


Figure 13: Research process and methodology

3.6 Framework and Evaluation

The development of the framework has been accomplished based on the theoretically review, contextual review, empirical review, optimization algorism, and various computational optimization and simulation tools. Then the application of the proposed framework is tested by application on sample office space and case study building.

i) Framework for computational multivariable design optimization of buildings

The proposed framework for multivariable optimization of daylight and glare is to be integrated into the schematic design phase with a possibility of integrating it at any stage of the design process in architectural design. The framework for multivariable optimization of indoor daylighting and glare in architectural design is developed with the following consideration:

1. Parametric building design is proposed as a method of parameterizing design variables for the framework. Various design alternatives can be assessed with changes in design variables. The design variable proposed to be integrated in the framework are building orientation and facade opening ratio (WWR).
2. For Daylight Simulation, the application of DIVA 4 for Rhino 6 is used in this study. sDA and ASE are identified as a proxy for daylight and glare respectively as set by Illuminating Engineering Society (IES) and LEED 4.
3. Genetic algorism is integrated in the framework for multivariable optimization of daylight and glare by the use of octopus plugin for grasshopper.
4. For the multivariable optimization and framework, ASE and sDA are identified as a fitness for daylight and glare optimization while building orientation and facade opening ratio (WWR) design variables are identified as the variables for the optimization of the fitness (See Figure 14).

The proposed framework enables a designer to manipulate variables until a desired ASE and sDA is achieved without compromising the design concepts. Figure 14 shows the developed framework for multivariable optimization of indoor daylighting and glare in architectural design.

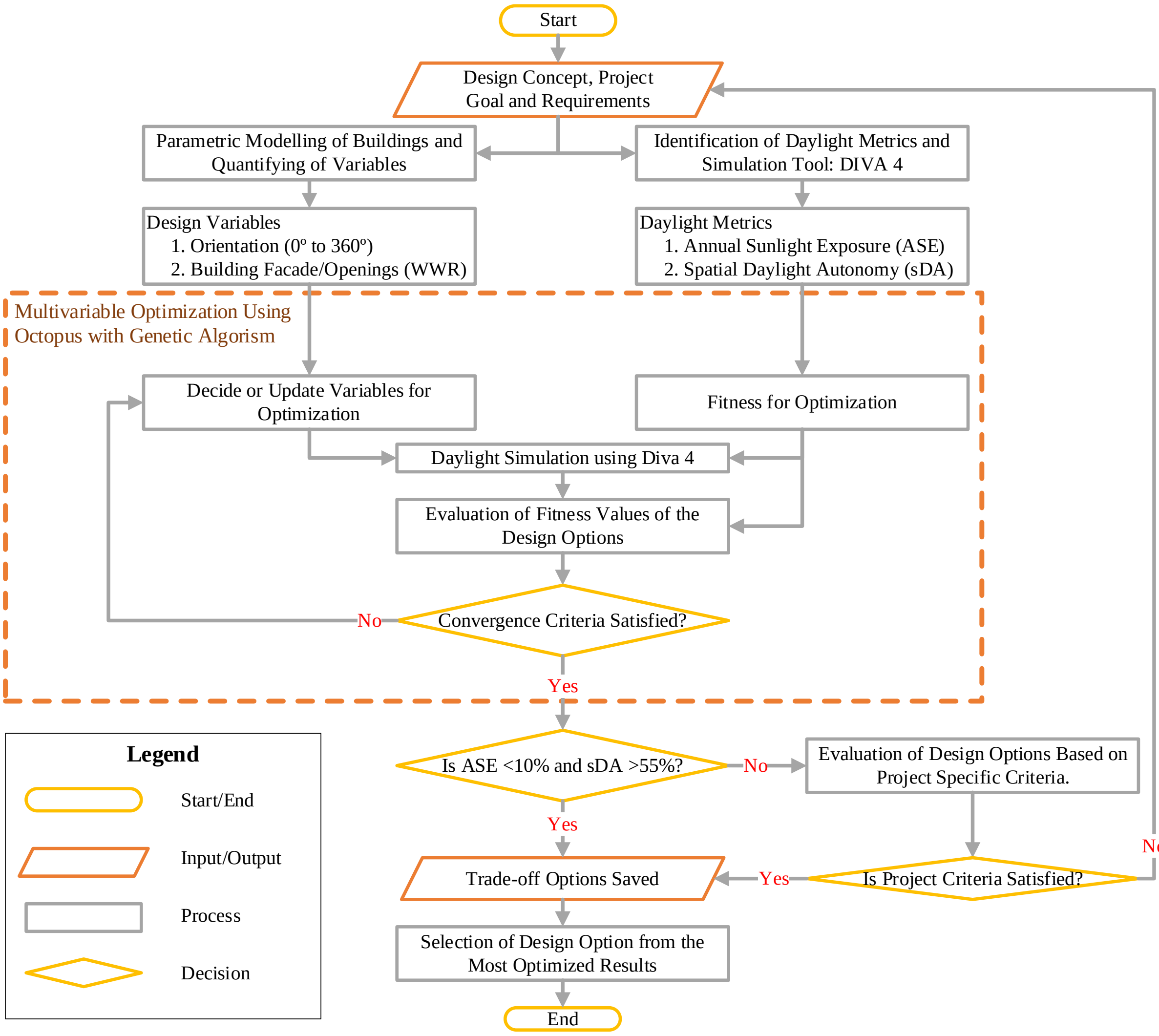


Figure 14: Framework for computational multivariable design optimization of buildings.

3.7 Data Analysis

The data analysis stage is accomplished by using inputs data and information to output quantitative and qualitative results. Ladybug Tools 1.2 has been used to analysis the existing case study building direct sun hour as well as incident solar radiation on the facade, DIVA 4 is used for daylight simulation and Octopus is used for optimization using genetic algorism. In addition, OriginPro 9.0, Microsoft Excel sheets as well as Google Forms is used for further analysis and interpretation of questionnaire, numerical outputs from simulation and onsite daylight measurements taken by instrument.

3.7.1 Daylight and Glare Performance Analysis of the Existing National Oil Company (NOC) Building.

3.7.1.1 Direct sun hours on NOC building facade

Direct sun hour is the amount hours in which direct sun reaches the facade of a building. Annual direct sun hours on existing NOC building facade have been simulated and the result are showed in the Figure 15 and Appendix E. From the 16167 points taken on existing NOC building facade, the simulation result shows that 44.016 % of the facade receives more than 2000 hours for direct sunlight yearly. On average, 1419 Hours and 56 Minutes of direct sunlight will be, received by a point on the facade each year. This accounts for an average 3 hours 53 minutes each day on a point.

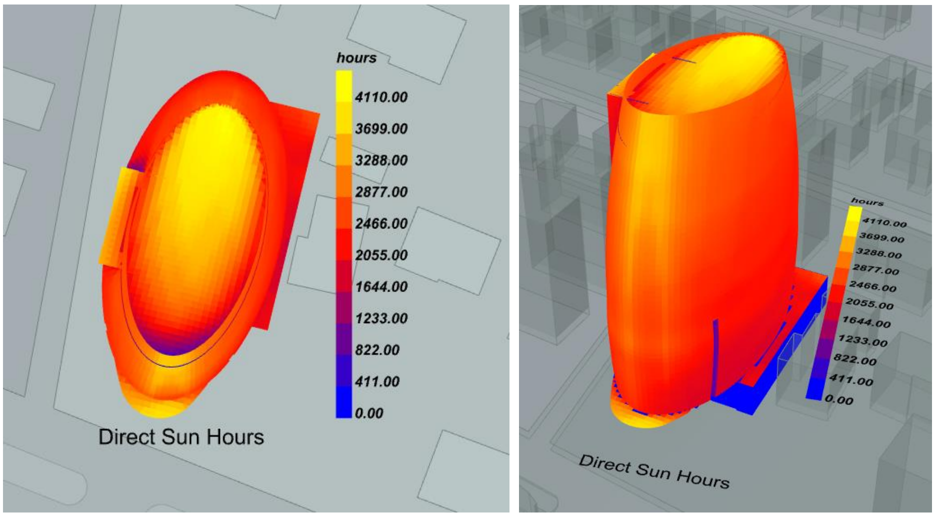


Figure 15: Annual direct sun hour for National Oil Company (NOC) building.

The direct sun hour analysis of NOC building façade shows that the is an average of 3 hours and 53 minutes of direct sun which promotes to direct glare in the interior space. This will directly or indirectly affect occupant's visual comfort.

3.7.1.2 Incident radiation on NOC building facade

Incident radiation measurement is the amount of electromagnetic radiation that strike the specific surface. Annual incident radiation on NOC building facade have been simulated and the result are shown the Figure 16 and Appendix F. From the 13052 points on existing NOC building facade, the simulation result shows that 66.363% of the facade receives more than 500 kWh/m^2 yearly. On average, 839.246 kWh/m^2 is received each year on the facade. This shows that the, average,839.246kWh/m^2, incident radiation has a significant potential for energy production from solar energy.

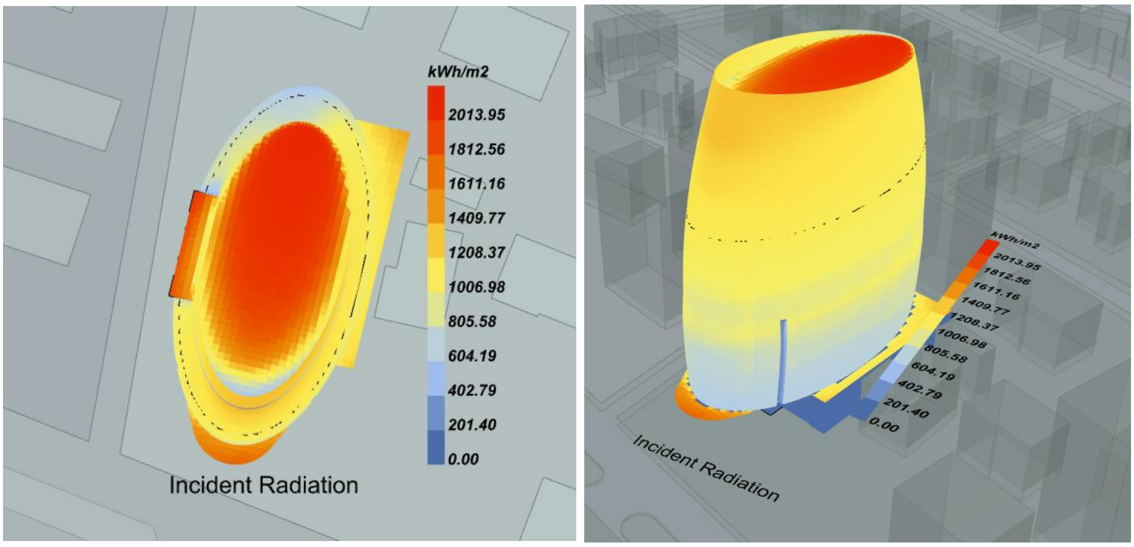


Figure 16: Annual incident radiation of National Oil Company (NOC) building.

3.7.1.3 Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA) analysis of Existing Selected Space in the Building.

The Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA) for the 10th Floor of NOC Building have been simulated and are shown in Figure 17.

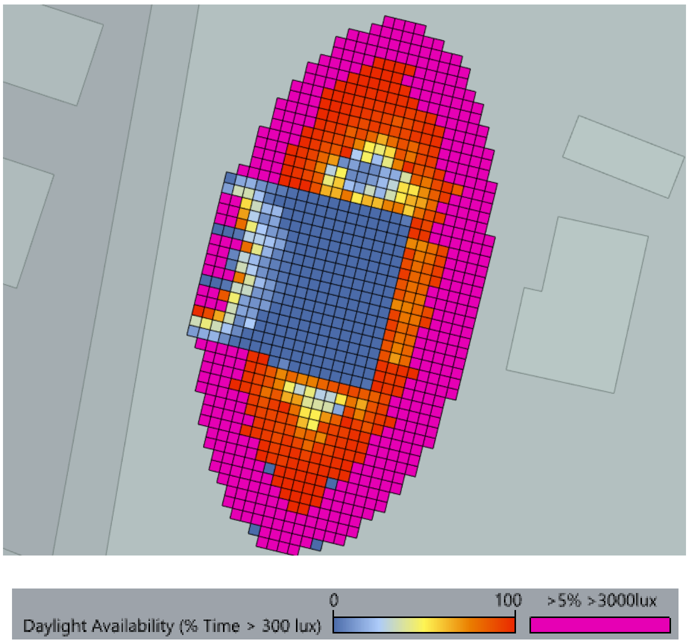


Figure 17: 10th floor grid based Spatial Daylight Autonomy and Annual Sunlight Exposure simulation result of existing NOC building.

An Annual Sunlight Exposure ($ASE_{1000,250}$) of 33% and Spatial Daylight Autonomy (sDA) of 70.6% is found from the simulation result. The results showed a significant similarity with that of the onsite measurement taken by lux meter form the space as well as the excessive glare that is perceived by occupants (See Figure 18, Figure 19 and Figure 21).

When the result is compared with standard set by IES and LEED 4, NOC building have an excessive glare (ASE) of 23% with the recommended being (ASE) less than 10 %. But the building shows sufficient daylight in the space (sDA>55%).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Comparison of Measured Illuminance Values and Simulation Results for the Case Study Building.

Several daylight illuminance measurements were taken from March 25th 2021 to April 25th 2021. The observed measurement from Lux meter show that there are some parts of the floor space that has excess level of illuminance (>1000 lux) in the morning while other space has excess level of illuminance (>1000 lux) in the afternoon.

Based on consideration of sky condition, lighting condition, accessibility and unwanted user interventions, measurements taken on April 2nd 2021 from D1, D2, D3, D4 and D5 as a point of measurement for comparing simulation tools illuminance results with illuminance level measured by Lux meter (Figure 12). From the graph shown in, Figure 18, Figure 19, Figure 20, and Appendix C, the variation between the simulated results with DIVA 4 and measurements taken from case study building is about ± 10%. This result shows that the simulation results and the onsite illuminance measurements taken by Lux meter (for various locations and time of day) show reasonable matching.

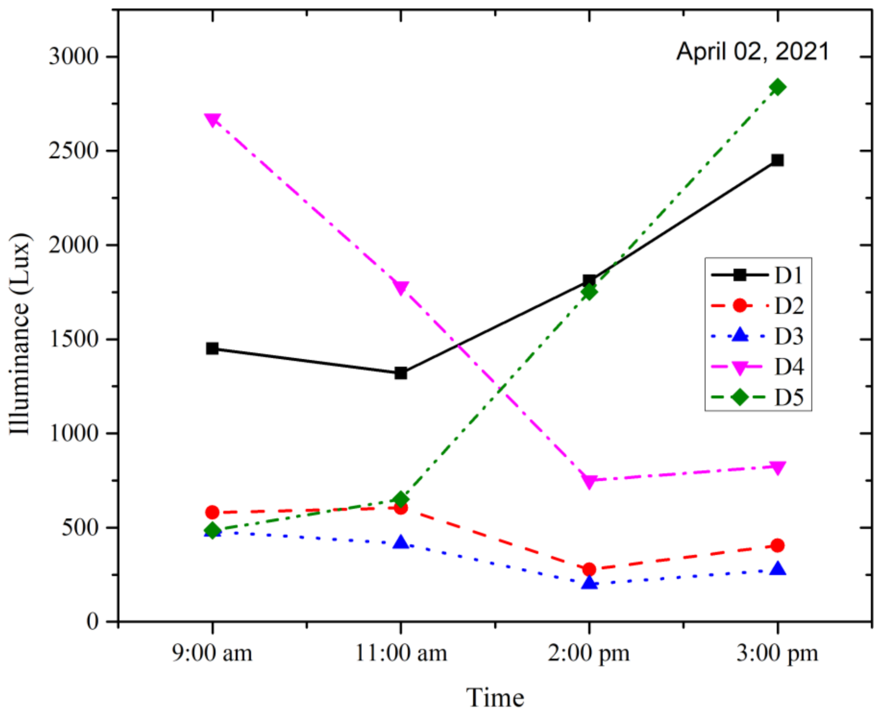


Figure 18: Average illuminance measurements taken at 10th floor of NOC buildings by using Lux meter.

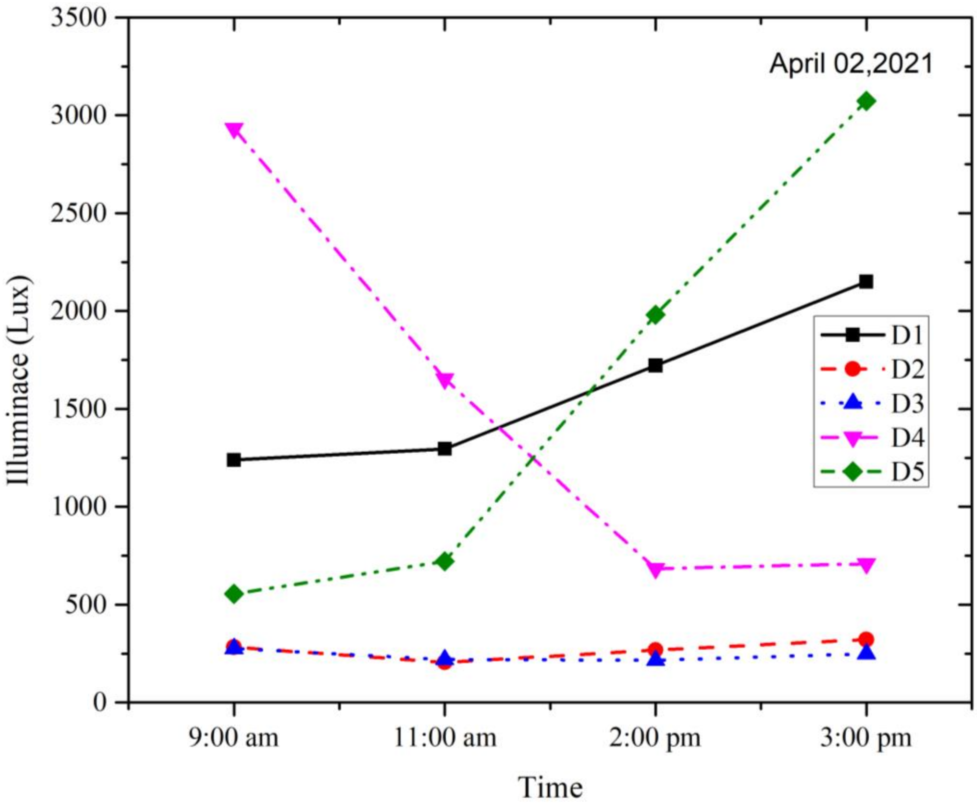
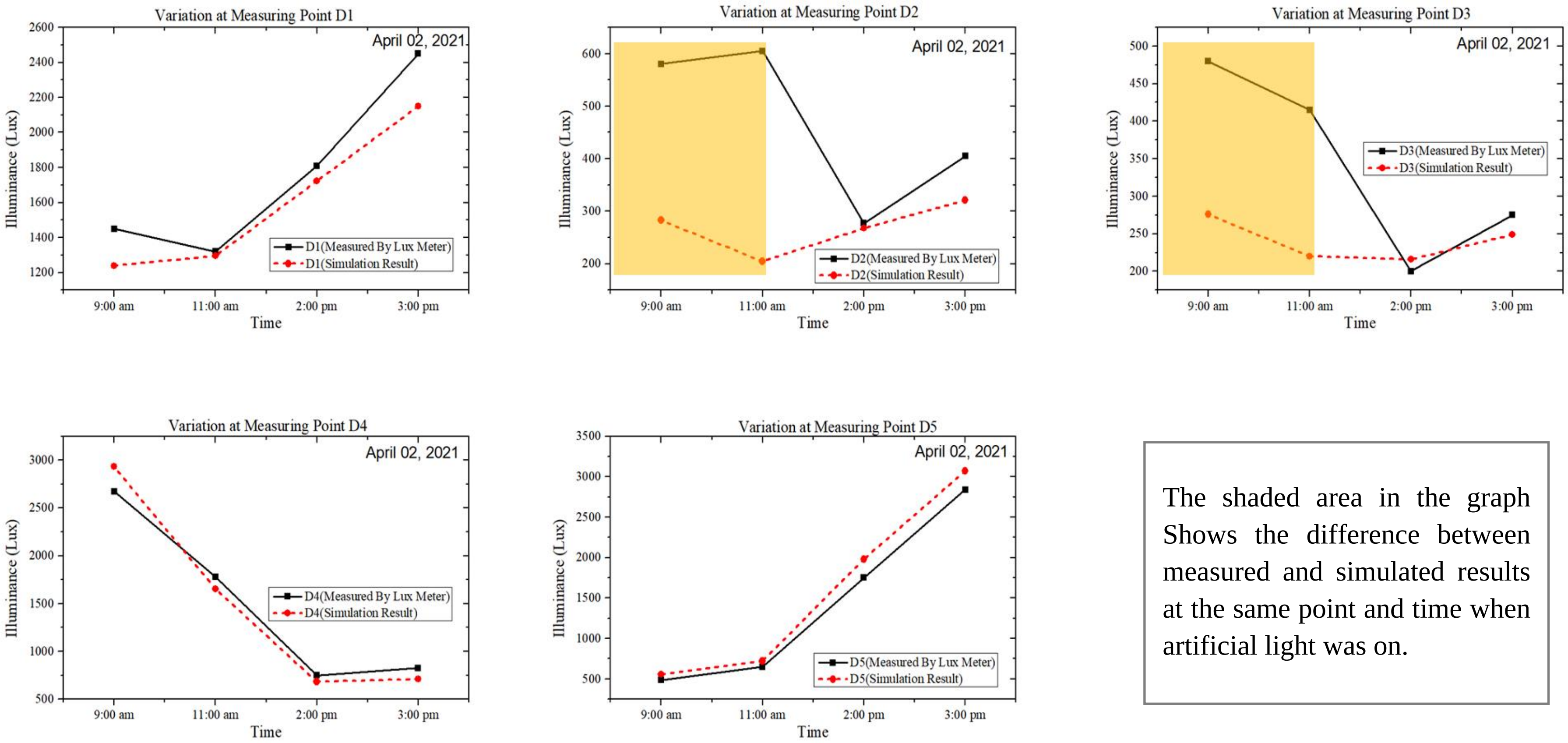


Figure 19: Average illuminance measurements from simulation Results at 10th Floor of NOC building.

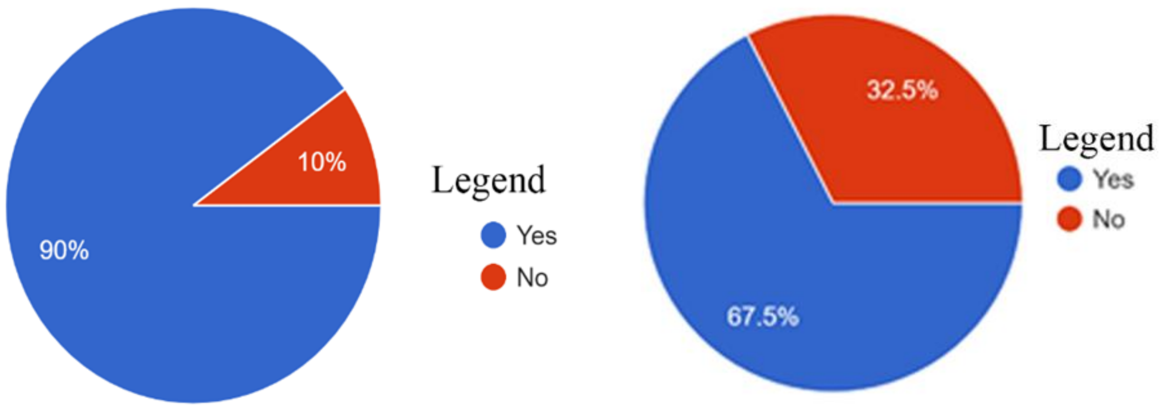


The shaded area in the graph Shows the difference between measured and simulated results at the same point and time when artificial light was on.

Figure 20: Variation between simulation tools measurements and on-site measurements taken by Lux meter on 10th floor of NOC building

4.1.1 Occupants response on National Oil Company (NOC) building's daylight quality.

The qualitative measurement is taken from occupants by means of questionnaire from the office building. The analysis of the questionnaire shows that 90 % of respondents believe that there is sufficient light for their work. While 67.5% of respondents say that excessive bright light or glare create visual discomfort or affect their activity. Based on the 57.5% of respondent's perspective, the existing daylight quality of their working space interfere with the ability to do their job. In addition, 55% of respondents prefer mostly daylight as a source of light in the workspace (See Figure 21 and Appendix D: Summery of Questionary Analysis).



(a) (b)

Figure 21: (a) Occupant response on availability of sufficient light and (b) Existence of excessive bright light or glare creating visual discomfort.

4.2 Optimization of Sample Office Space for an Office Building.

Based on a space standards guideline by UCL and Nufert's Architects Data as well as case study, a pool office with floor area of 140sqm is taken as a sample model with opening on one side is used to further develop, test and evaluate the optimization process. The Figure 22 bellow show floor plan of the selected office space.

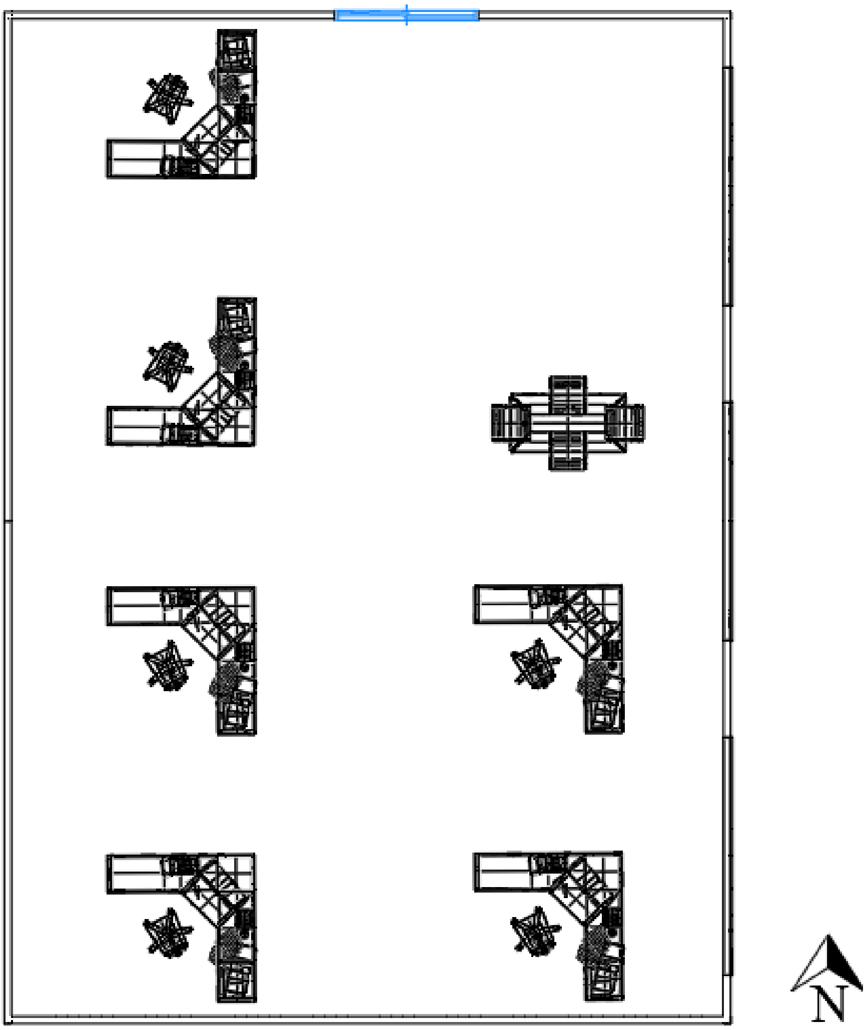


Figure 22: Sample office space floor plan.

4.2.1 Optimization by orientation for improving daylighting conditions of Sample Space.

The optimization of indoor daylighting and glare by orientation variable is achieved mainly by changing the building orientation to identify Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for the space in consideration at different orientation of building and to compare result with the standards set by Illuminating Engineering Society (IES) and LEED 4. Figure 24 shows the optimization result of orientation variable was analyzed with fixed contextual variable and 50% window to wall ratio.

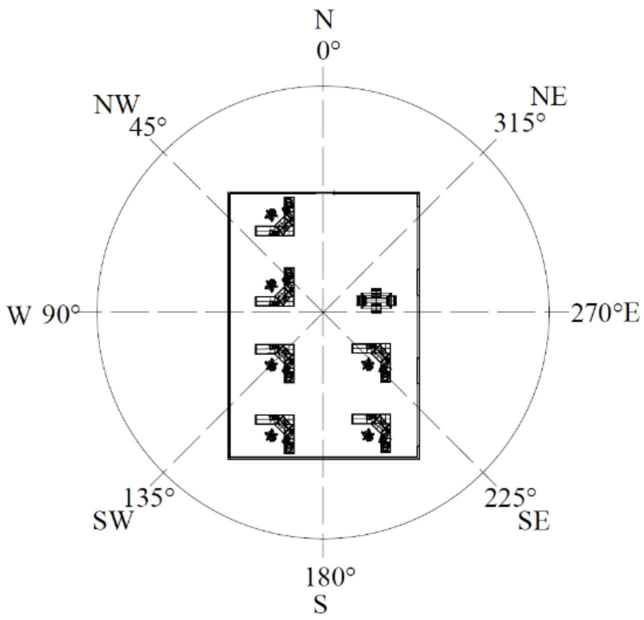


Figure 23: Sample office space floor plan and orientation angle for simulation.

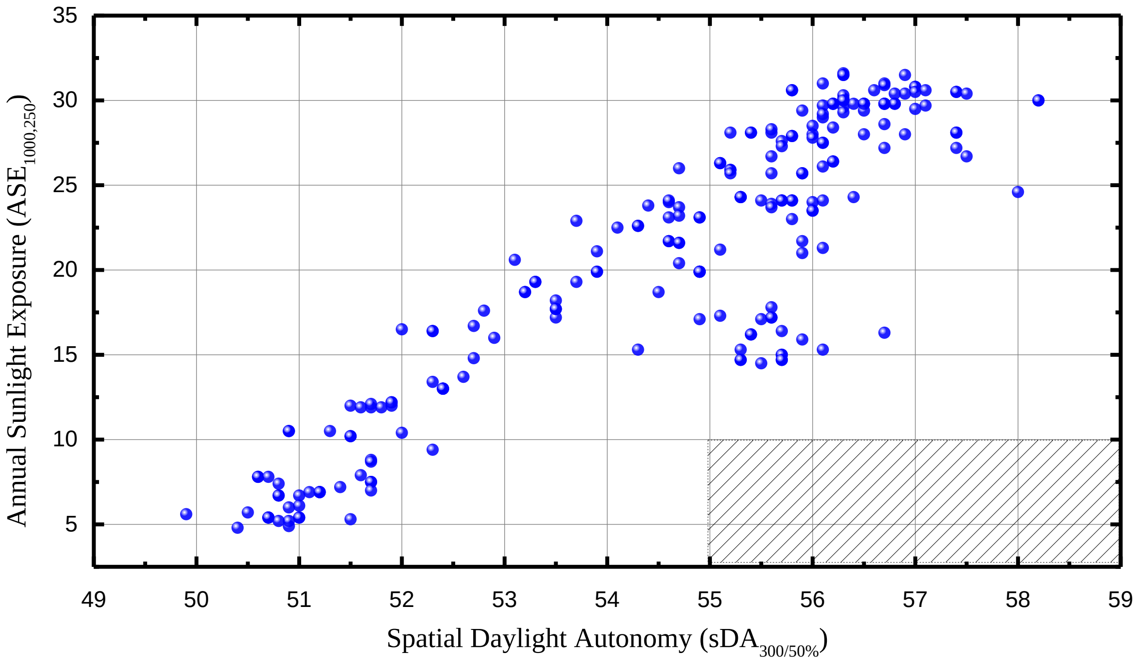


Figure 24: Optimization by orientation for improving daylighting conditions of sample office space.

Based on the set parameters, the results of optimization of ASE and sDA by orientation did not achieve the required level of minimum of < 10% $ASE_{1000,250}$ and > 55% $sDA_{300/50\%}$ set by Illuminating Engineering Society (IES) and LEED 4. This result shows that single variable optimization by orientation considered in this study did not achieve sufficient daylight with acceptable level of glare.

4.2.2 Optimization by facade openings (WWR) for improving daylighting conditions of Sample Office Space.

The optimization of indoor daylighting and glare by facade opening variable is achieved by changing the building facade openings to wall ratio (WWR) to identify Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for the space in consideration at different window to wall ratio (WWR) and to compare result with the standards. Figure 26 shows the optimization result by facade openings where the longest side of the office space face East-West direction and orientation at 0 degree.

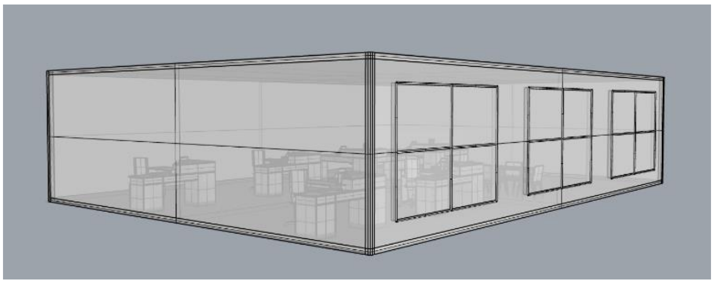


Figure 25: Sample office space 3D model and opening for simulation.

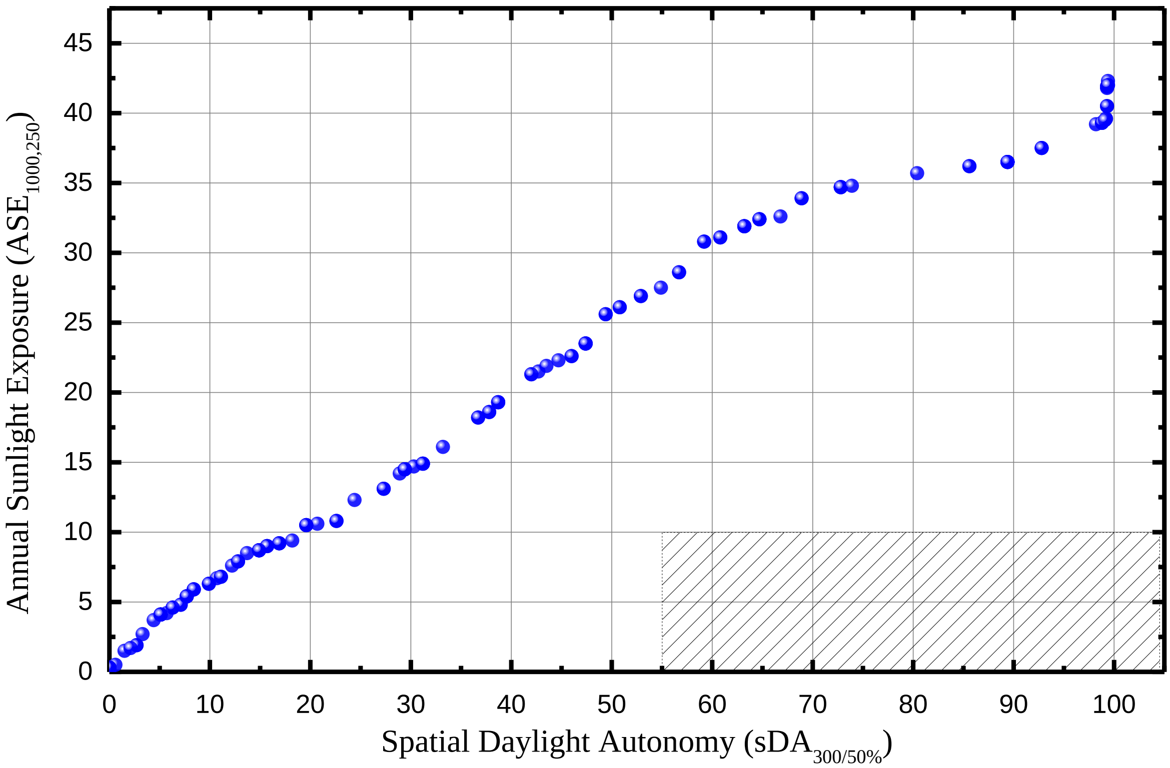


Figure 26: Optimization by facade openings ratio for improving daylighting conditions of sample office space.

Based on the preset parameters, the results of optimization of ASE and sDA by Facade opening ratio (WWR) shown in Figure 26 did not achieve the required level of < 10% $ASE_{1000,250}$ and > 55% $sDA_{300/50\%}$ set by Illuminating Engineering Society (IES) and LEED 4 for sufficient daylight availability with minimum glare.

4.2.3 Multivariable optimization of Sample Office Space.

The multivariable optimization of indoor daylighting and glare is achieved by changing the building orientation and building facade openings to wall ration (WWR) to identify best result with balanced Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for the sample space in consideration. Figure 27 shows the multivariable optimization results for facade opening and orientation variables.

Several results of multivariable optimization for ASE and sDA by Facade opening ratio (WWR) and orientation shown in Figure 27 have achieved the required level of $ASE_{1000,250}$ and $sDA_{300/50\%}$ set by Illuminating Engineering Society (IES) and LEED 4.

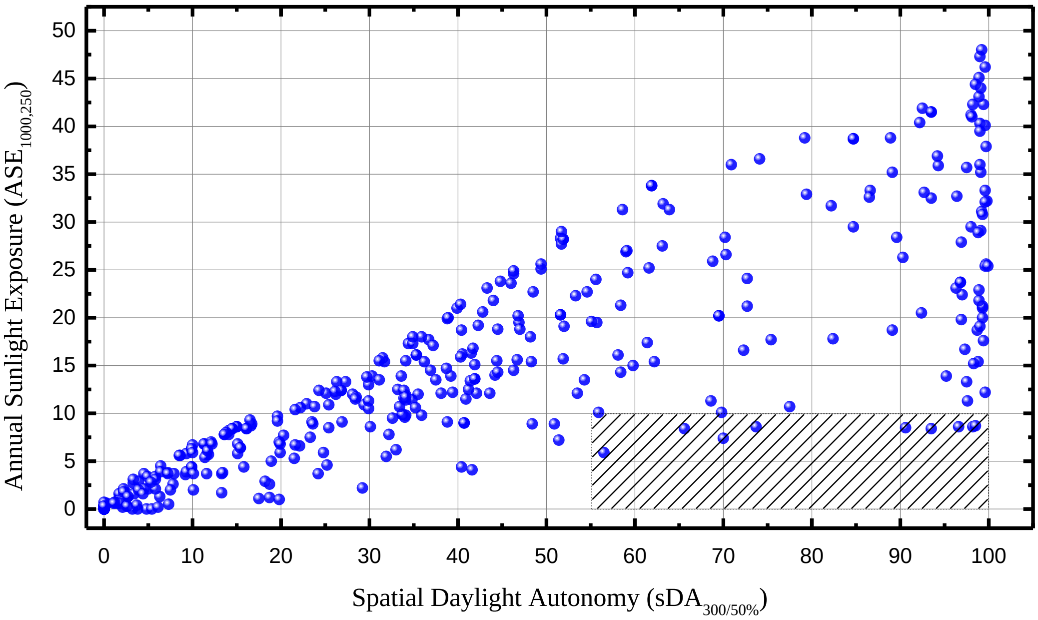
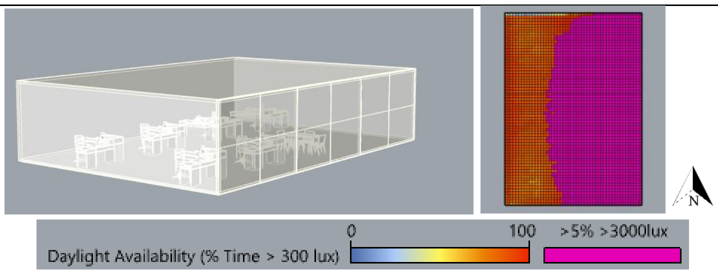


Figure 27: Multivariable optimization for improving daylighting conditions of sample office space.

The selected optimized results with the application of the framework on the sample office space is shown in Table 8. The simulation starts from base sample office space with 98% WWR and 0-degree orientation. Out of the optimization results, the most significant drop in $ASE_{1000,250}$ is optimization result 7 with decrease form 42.3% from simulation result before optimization to 5.9% while maintaining a 56.5% $sDA_{300/50\%}$.

Table 8: Simulation result of sample office space and selected multivariable optimized results of sample office space.

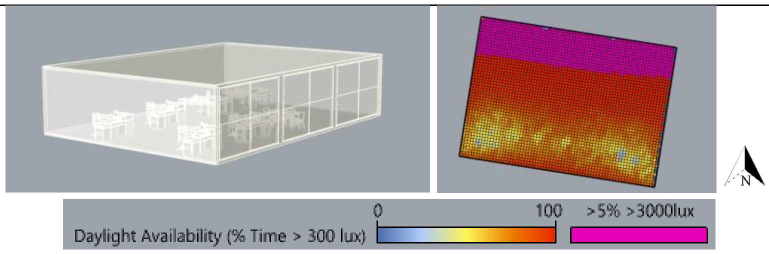
Simulation result before optimization.



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.99	360/0	99.4%	42.3%

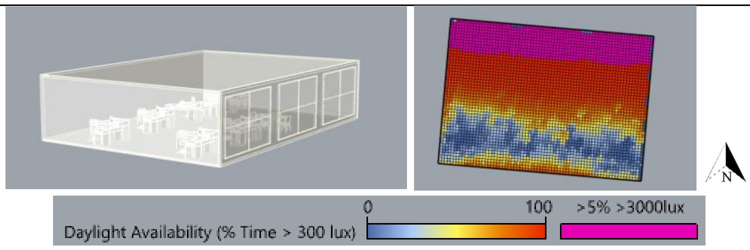
Optimization result 1



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.91	81	96.6%	8.6%

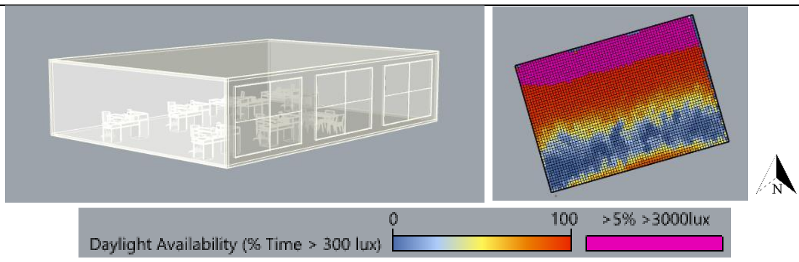
Optimization result 2



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.82	85	70%	7.4%

Optimization result 3

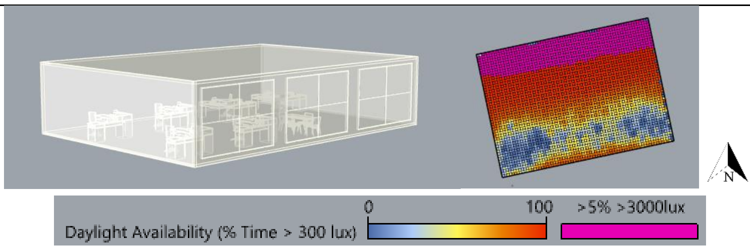


3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.8	106	65.6%	8.4%

Table 8: Simulation result of sample office space and selected multivariable optimized results of sample office space. - Continued

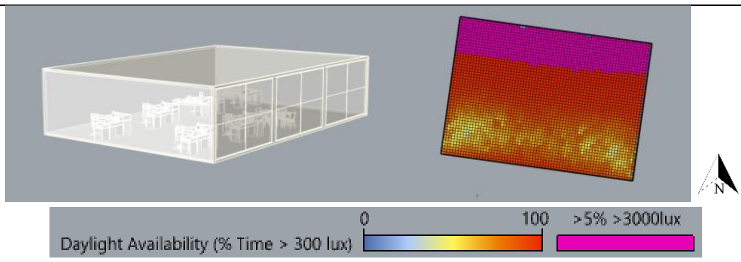
Optimization result 4



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.83	102	73.7%	8.6%

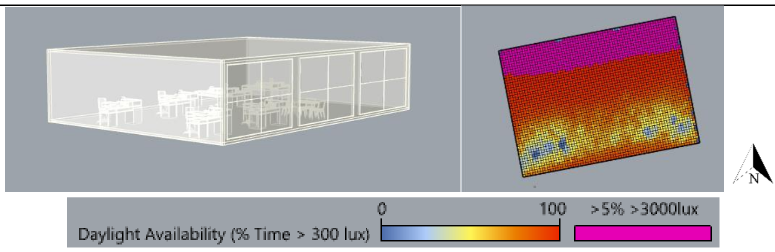
Optimization result 5



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.92	82	98.2%	8.6%

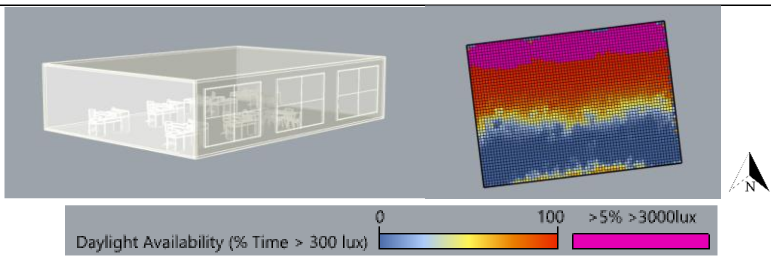
Optimization result 6



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.88	101	90.6%	8.5%

Optimization result 7

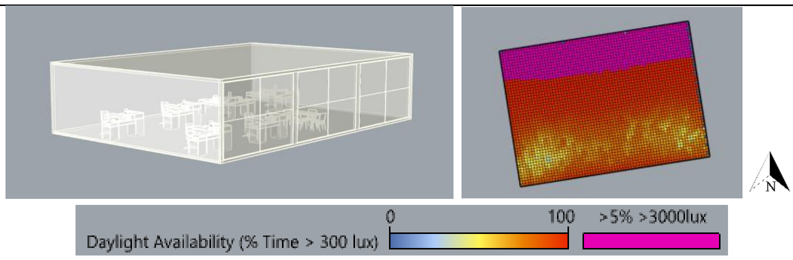


3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.75	97	56.5%	5.9%

Table 8: Simulation result of sample office space and selected multivariable optimized results of sample office space. - Continued

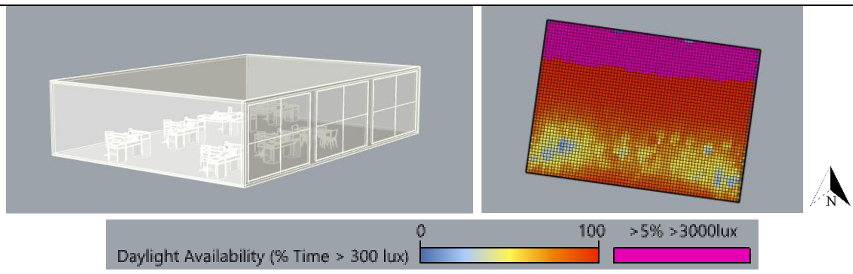
Optimization result 8



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.93	99	98.5%	8.7%

Optimization result 9



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	**sDA**	**ASE**
0.89	82	93.5%	8.4%

The other significant optimization tradeoffs with significant reduction in ASE and minimum reduction in sDA is optimization result 8 with 8.7% $ASE_{1000,250}$ and 98.5% $sDA_{300/50\%}$, optimization result 5 with 8.6% $ASE_{1000,250}$ and 98.2% $sDA_{300/50\%}$, optimization result 1 with 8.6% $ASE_{1000,250}$ and 96.6% $sDA_{300/50\%}$, optimization result 9 with 8.4% $ASE_{1000,250}$ and 93.5% $sDA_{300/50\%}$, optimization result 6 with 8.5% $ASE_{1000,250}$ and 90.6% $sDA_{300/50\%}$, the multivariable optimization tradeoff results shows a more optimized result than simulation result before optimization as well as single variable optimization.

The application of the multivariable optimization framework on sample office space has provided several design options with sufficient daylight and minimized glare in the interior space. It was possible to provide several design options which achieve the LEED and IES standard of spatial daylight autonomy of >55% for daylight and annual sunlight exposure of <10% for visual discomfort (glare).

4.3 Multivariable Optimization of Case Study Building

The multivariable optimization process of the case study building is tested with consideration of the building at preliminary design stage without changing conceptual consideration and facade design concept of the building.

4.3.1 National Oil Company (NOC) building multivariable optimization by orientation and facade openings with varying window to wall ratio (WWR).

The multivariable optimization of National Oil Company (NOC) building has been computed based on the conceptual consideration of the existing facade design and with consideration of an existing context as well as other constant variables to evaluate the capability of multivariable optimization in existing building. Figure 28 shows the multivariable optimization results by orientation and facade opening ratio (WWR).

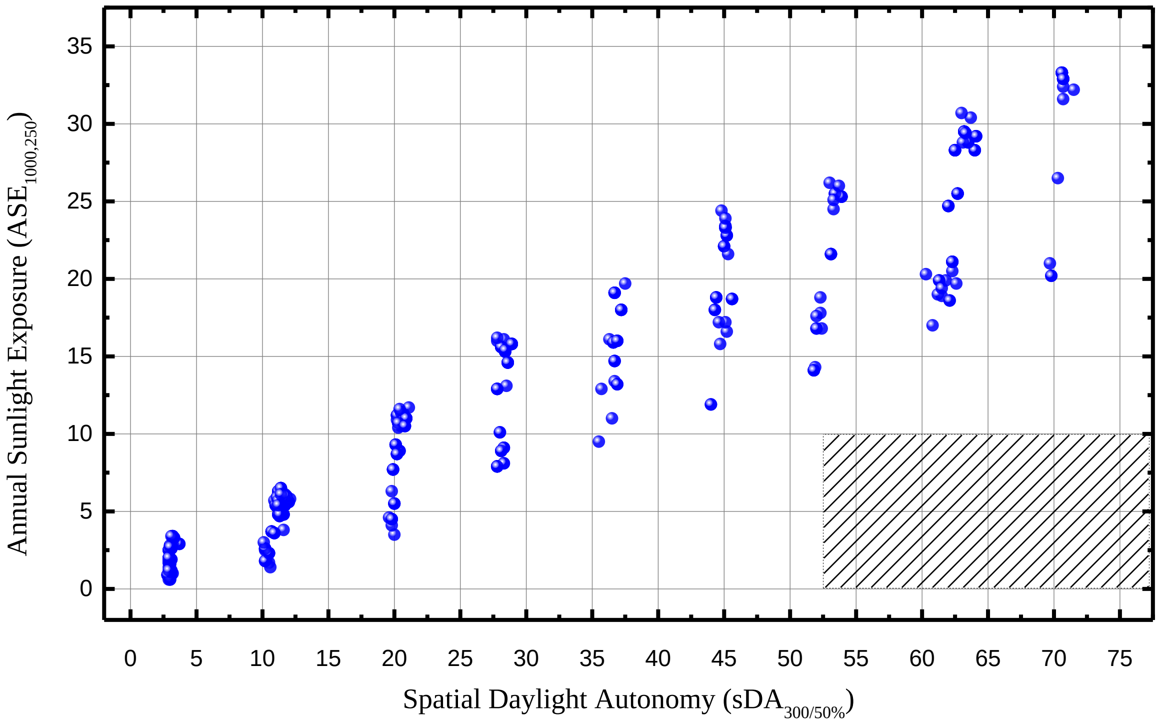


Figure 28: Multivariable optimization of National Oil Company (NOC) building.

Out of the optimization results shown in Table 9 shows the respective optimized Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA) for the selected orientation and window to wall ratio with respect to the existing NOC building window to wall ratio (WWR) which is 85.3%.

Table 9: Simulation result of existing and selected multivariable optimized results of NOC building's 10^{th} floor.

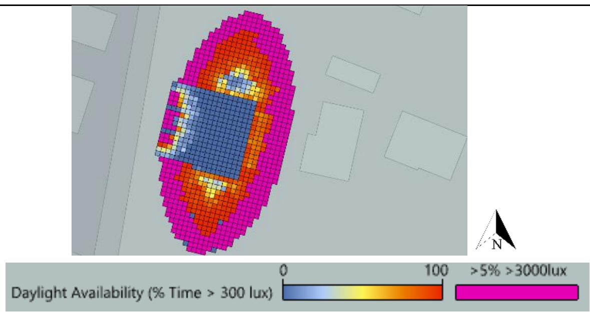
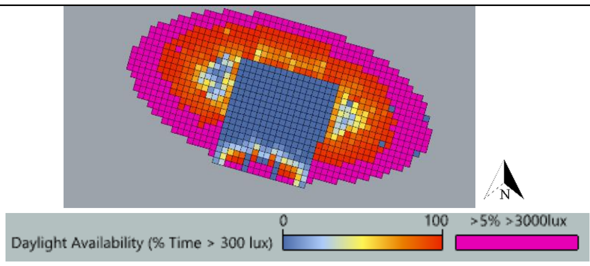
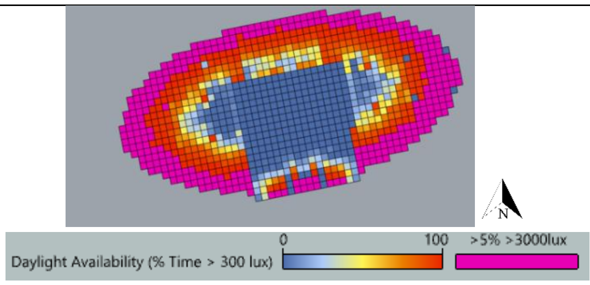
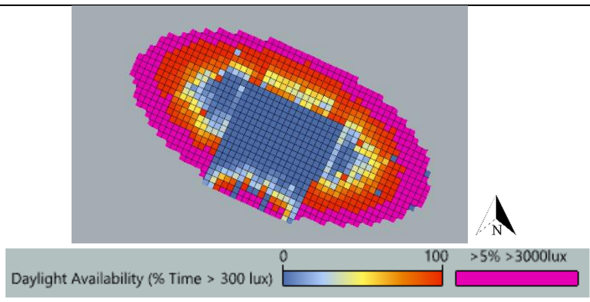
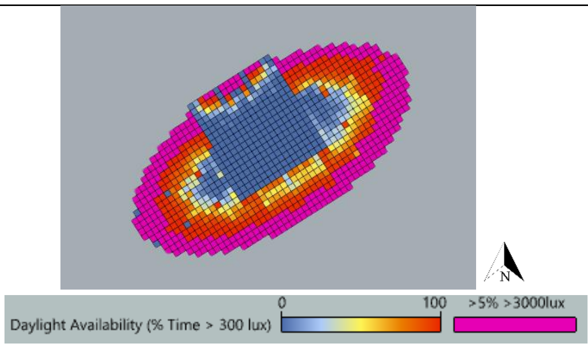
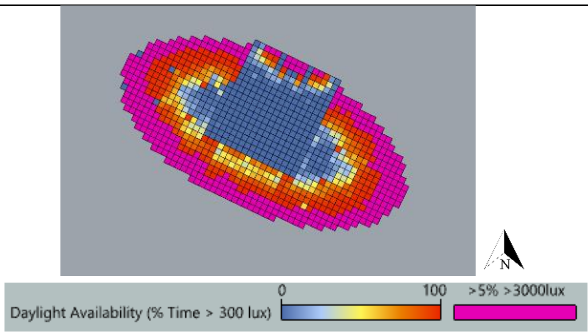
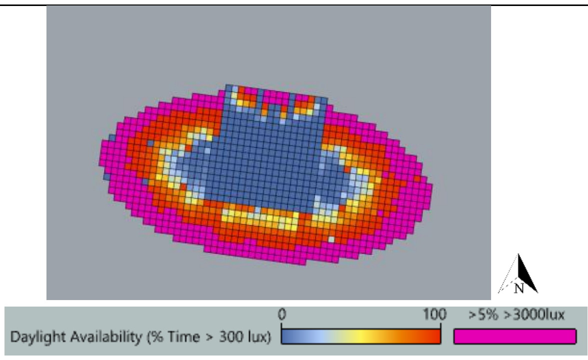
<table>
<tr><th colspan="4">Existing NOC building simulation</th></tr>
<tr><td colspan="4">
</td></tr>
<tr><td>Orientation</td><td>WWR</td><td>ASE</td><td>sDA</td></tr>
<tr><td>0</td><td>1 (85.3%)</td><td>33%</td><td>70.6%</td></tr>
<tr><th colspan="4">Optimization result option 1</th></tr>
<tr><td colspan="4">
</td></tr>
<tr><td>Orientation</td><td>WWR</td><td>ASE</td><td>sDA</td></tr>
<tr><td>88</td><td>1 (85.3%)</td><td>20.2%</td><td>69.8%</td></tr>
<tr><th colspan="4">Optimization result option 2</th></tr>
<tr><td colspan="4">
</td></tr>
<tr><td>Orientation</td><td>WWR</td><td>ASE</td><td>sDA</td></tr>
<tr><td>115</td><td>0.9 (76.77%)</td><td>17%</td><td>60.8%</td></tr>
<tr><th colspan="4">Optimization result option 3</th></tr>
<tr><td colspan="4">
</td></tr>
<tr><td>Orientation</td><td>WWR</td><td>ASE</td><td>sDA</td></tr>
<tr><td>79</td><td>0.9 (76.77%)</td><td>18.9%</td><td>61.5%</td></tr>
</table>

Table 9: Simulation result of existing and selected multivariable optimized results of NOC building’s 10th floor. - Continued

Optimization result option 4			
			
Orientation	WWR	**ASE**	**sDA**
316	0.9 (76.77%)	19.9%	61.8%
Optimization result option 5			
			
Orientation	WWR	**ASE**	**sDA**
258	0.9 (76.77%)	19.7%	62.6%
Optimization result option 6			
			
Orientation	WWR	**ASE**	**sDA**
276	0.9 (76.77%)	19%	61.2%

The optimization tradeoffs that are selected in Table 9 shows that the standard set by Illuminating Engineering Society (IES) and LEED 4 for daylight availability is not fully achieved. But the tradeoff shows a significant reduction in Annual Sunlight Exposure (ASE) without achieving <10% $ASE_{1000,250}$ while maintaining the requirement for Spatial Daylight Autonomy (sDA). This will result in reduction in glare while maintaining sufficient daylight level for occupants. But in order for NOC Building to achieve a minimum of < 10% $ASE_{1000,250}$ and > 55% $sDA_{300/50\%}$, standard set Illuminating Engineering Society (IES) and LEED 4, further facade design changes or interventions are required for NOC building.

The most significant drop in $ASE_{1000,250}$ is optimization result option 2 with decrease from 33% in existing NOC Building simulation to 17% while maintaining a 60.8% $sDA_{300/50\%}$. The other significant optimization tradeoff with significant reduction in ASE with minimum reduction in sDA is optimization result option 1 with 20.2% $ASE_{1000,250}$ and 69.8% $sDA_{300/50\%}$, optimization result option 5 with 19.7%% $ASE_{1000,250}$ and 62.6% $sDA_{300/50\%}$ and optimization result option 3 with 18.9% $ASE_{1000,250}$ and 61.5% $sDA_{300/50\%}$. The conceptual multivariable optimization tradeoff results of the case study show a more optimized result than that of existing NOC building simulation.

CHAPTER FIVE
CONCLUSION AND RECOMMENDATION

5.1 Conclusions

In this study, a computational multivariable optimization framework, which can be used to optimize daylighting and glare presence in buildings, is developed and evaluated. The suitability and the performance of the proposed computational multivariable optimization framework is investigated by applying the strategy for the optimization of a sample office space and a case study building. The following conclusions are drawn based on the results obtained from the study.

1. The results of the lighting simulation with DIVA 4 and the onsite illuminance measurements taken by Lux meter (for various locations and time of day) show reasonable matching. The average variation between the results of the lighting simulation and the onsite measurements taken by Lux meter is about 10%.
2. The application of the multivariable optimization framework on the case study building as well as the sample office space has helped to achieve a significant reduction in glare while maintaining sufficient daylight availability and distribution.
3. The application of multivariable optimization framework on the sample office space has provided several optimized solutions with minimized glare availability in the space. For instance, it was possible to achieve low $ASE_{1000,250}$ value of 5.9% while ensuring availability of sufficient daylighting, i.e., $sDA_{300/50\%} > 55\%$.
4. The application of single variable optimization with orientation as well as facade opening (WWR) on the sample office space considered in this study did not achieve the required daylight and glare levels, i.e., sDA > 55% and ASE < 10%, set by Illuminating Engineering Society (IES) and LEED. However, it was possible to satisfy the stipulated criteria using the proposed multivariable optimization framework.
5. The application of multivariable optimization framework on the case study building has provided several optimized design alternatives. For instance, significant reduction of ASE (i.e., 12% reduction) was achieved with only minimal reduction of sDA (i.e., 0.8% reduction) as compared to the existing building daylight performance.

6. The proposed multivariable optimization framework, if implemented properly, has the potential to provide multiple viable design options, i.e., orientation and facade opening, that could achieve optimized daylight and glare performance.

5.2 Recommendations

Architects, designers and architectural firms are recommended to consider the application of the multivariable optimization framework proposed in this research while designing facade opening (WWR) and building orientation to succeed on minimizing glare while maintaining sufficient daylight availability and distribution in building spaces. In addition, further research is recommended for:

1. Conducting practical experimentation by building physical models of the designed building using the framework to validate the parametric multivariable optimization framework.
2. Integration of additional variables to the multivariable optimization framework.
3. Implementing the proposed framework of this research for other building type to optimize their visual comfort needs.
4. Integrating life cycle cost study for daylight within the same proposed framework of this research.
5. Integrating of shading device in the proposed framework of this research.
6. Integrating digital fabrication techniques together with the proposed framework of this research.

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APPENDICES

Appendix A: Publishable Manuscript

Computational Multivariable Optimization of Indoor Daylighting and Glare in Architectural Design

Dagmawi H. Zeleke[1], Mekonnen Agonafer[2]

Abstract— Buildings with daylighting problems may lead to compromised psychological and physiological wellbeing, and decreased productivity of occupants. Although there exists some research on design optimization for enhanced daylight and glare performance of buildings, most studies considered single design variable in the optimization. In this study, a computational multivariable optimization framework is developed for enhanced interior daylighting and glare performance of buildings. The proposed framework is derived considering the influence of (a) building orientation and (b) facade opening. The suitability of the proposed optimization framework is assessed through implementation on a sample office space and a selected case study building. To ensure the accuracy of the computational results, the illuminance level obtained from the simulations are compared with that of on-site measurements taken using Lux meter. The performance of the proposed framework is evaluated in terms of the acceptable values of annual sunlight exposure (ASE) and spatial daylight autonomy (sDA). For the sample office space, multiple optimized design solutions that satisfy the criteria specified by Illuminating Engineering Society (IES) and Leadership in Energy and Environmental Design (LEED) are obtained using the proposed framework. The application of the framework on case study building, based on the existing facade design, has provided several optimized solutions. The solutions have resulted in a significant reduction of glare/ASE (i.e., up to 12% reduction) without significant compromise in the daylighting/sDA (i.e., 0.8% reduction). Therefore, it is concluded that the proposed framework has the potential to provide multiple design options that could achieve optimized daylight and glare performance.

Index Terms— Parametric Design, Genetic Algorism, Daylight Metrics, Building Orientation, Facade Opening, Multivariable Optimization, Architectural Design

1 INTRODUCTION

There are several challenges associated with the development of different infrastructure projects, such as buildings and other habitable spaces. Some of the paramount challenges include ensuring sustainability, efficient energy usage, water efficiency, indoor environmental quality, and efficient use of materials/resources. The advancements in various design strategies, computer aided design, two-dimensional (2D) design, three-dimensional (3D) design, and building information modelling (BIM) are providing significant contribution to tackle these challenges. One of the prominent challenges in building design is ensuring superior indoor environmental quality. The planned and optimized use of daylight with a controlled level of glare is an essential part of ensuring enhanced indoor environmental quality. Such implementation of innovative, advanced daylighting strategies and systems also contributes to energy efficiency of buildings [2].

The lack of appropriate, low-cost, high-performance daylight systems and simple tools to predict the building performance has led to weak daylight strategies and systems in the past. Also, different architectural studies have also shown the need for further experiments and computational methods of analysis to provide the best and optimized solution for daylight and building performance (Brooks, 2011; Soliman et al., 2019). This has given birth to the application of new techniques, such as generative modeling, genetic algorithm, daylight simulation, and parametric design in architecture. Various computational software/tools, such as DIVA, Radiance, Ladybug+Honeybee, and Ecotect, have also been developed to assess daylighting in buildings. Moreover, in recent years, research in three broad areas: (1) assessment of the performance of systems and lighting control strategies, (2) development of integrated design tools, and (3) case studies to provide evidence of daylight and glare performance in actual buildings have contributed in providing better solutions for daylighting design of buildings [16]. However, there is still a need for further research to enhance the daylight and glare performance of buildings, especially in the consideration of various design variables/parameters to arrive at optimized output.

One of the design strategies to enhance indoor environmental quality is the utilization of natural light to provide the required illuminance for habitable spaces. This is an important factor, especially for buildings located in areas with limited or excessive sunlight. Buildings designed in an area with sufficient sunlight may also fail to make optimum use of the daylight or end up with excessive glare in the interior space. For example, various high-rise office buildings located in Addis Ababa that are designed with curtain wall facade have been observed to have internal spaces exposed to excessive direct glare. In these buildings users are forced to resort to the use of various do-it-yourself (DIY) interventions, that potentially completely block the much-needed adequate light. On the other hand, there are several buildings located in Addis Ababa with internal spaces that do not get sufficient daylight due to their design and construction. The lack of sufficient daylight in the interior spaces forces occupants to use artificial light, which increases the energy consumption of the buildings.

Various design strategies and processes could be implemented to tackle the challenge of ensuring adequate interior space daylight without presence of excessive glare. Various research has been conducted and different optimization strategies have been proposed and implemented regarding daylighting. However, most of the available literature considers single-variable optimization techniques, whereas there is lack of strategies that consider multivariable optimization.

The core objective of the proposed research is to develop and evaluate a suitable computational multivariable optimization framework, that is useful to ensure optimized daylighting and minimized glare in architectural design of buildings. Furthermore, the following specific objectives has been considered in order to achieve and strengthen the core objective:

1. To take on-site daylight illuminance measurements on a case study building, and to validate the results of daylight simulation tools by comparing the simulation results with that of

the on-site measurements,

2. To theoretically compare various optimization algorithms and identify a suitable algorithm with potential for application in multivariable optimization of buildings for enhanced daylighting.

The utilization of daylight when designing buildings has been one of the major design aspects of architecture. A study conducted by Borisuit, A, and Linhart, F. [3] shows that poor lighting conditions in workplaces contribute to a lack of work satisfaction, productivity, and well-being. They found a higher acceptance score under daylight than electrical lighting. This shows that qualitative daylighting design is not only the aesthetic aspects of design rather includes the impact of daylight on human health and work performance.

A well-daylit building space requires both adequate lighting levels and distribution. In recent years, the building industry considers daylighting as a building performance measure in green building certification programs such as Illuminating Engineering Society (IES), the society of Light and Lighting (SLL), and Leadership in Energy & Environmental Design (LEED). The contribution of daylight to the recommended lighting level determines the daylighting performance of a building. Illuminating Engineering Society (IES) and LEED 4 have approved two metrics for evaluation of daylighting performance: Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for daylight and glare respectively.

Spatial Daylight Autonomy (sDA) is the percentage of area that meets the minimum daylight illuminance during analysis hours [7]. It evaluates the special and temporal characteristics of daylight performance. As a result, it is used to know how much of the space receives sufficient daylight. Based on the standard set by Illuminating Engineering Society (IES) and LEED4 a minimum of 55% of space must achieve the identified sDA in order to have sufficient daylight for occupants. A value of $sDA_{300/50\%}$ is taken as a minimum requirement for simulation in this research.

Annual Sunlight Exposure (ASE) is the percentage of the area where the illuminance of space exceeds the required level for more than a specific occupied hour in a year. This causes visual discomfort or increases cooling loads [7]. A value of $ASE_{1000,250}$ is taken as a minimum require-ment for simulation in this research.

Visual comfort of users of buildings refers to the condition where there is suitable amount of light for human eye without any distress or pain for the visual task on hand. DiLaura et al., [5] identified that visual comfort is strongly related to illumination levels inside the working space either from natural or artificial light sources.

According to Carlucci et al., [4] daylight visual comfort indexes can be established in regards to the amount and distribution of light, and the risk of glare for building occupants in specific space. The indexes that are used to describe visual comfort can be point in Time and annual based daylight metrics. Table 1 shows a simplified selected metrics currently used in daylight visual comfort analysis by various scholars and practitioners for amount and distribution of light as well as glare.

In Architectural design, there are various design variables to consider to accomplish the required design output. Design variables are the parameters or units which are kept constant in one case and varied at different to achieve the required design output. Among the various design variables, building plan shape, size of building, average story height, number of stories, building envelope, circulation space, grouping of buildings (obstruction and reflections), floor span constructability, material and orientation are some of them. From this list,

TABLE 1: Point-in Time and Annual-Based Metrics (Source: Gabriela (2017))

Type of metric	Metric	Descriptions
Point-in-Time Metrics (P)	Illuminance (Ep)	Amount and distribution of light
	Luminance (L)	Surface 'brightness'
	Daylight Factor (DF)	Amount and distribution of light
	CIE Glare Index (CGI)	Glare
Annual-Based Metrics (A)	Daylight Autonomy (DA)	Annual amount and distribution of light
	Discomfort Glare Probability (DGP)	Glare from point of view
	Continuous Daylight Autonomy (DAcon)	Annual amount and distribution of light
	Useful Daylight Illuminance (UDI)	Annual amount and distribution of light
	Spatial Daylight Autonomy (sDA)	Annual amount and distribution of light
	Annual Sunlight Exposure (ASE)	Glare proxy: direct sun in space

building orientation, and building facade are the major determinant variables for consideration in daylight performance.

Building orientation is one of the most significant decision architects make to achieve efficient daylighting as well as energy saving. Optimum building orientation is used in various climatic condition as a strategy by designers to orient buildings to attain a specific result. In addition, various researchers have also identified and verified a well-oriented building maximize daylighting through building facades and reduce the need for artificial lighting ([10], [9], [12]).

Building facade is the exterior boundary between interior space and the outside environment. It functions as a protective cover and allows regulation and exchange of energy, light, and air. Because of its significant, envelop requires efficiency by complementing environmental condition. Facade design is impacted by different factor. Among them Abdel-Aziz and Shuqair [1] stated that responsive environmental parameters such us orientations, voids and openings, vertical and horizontal shading devices, building material and surface texture and colors.

Some of the envelop design parameters complement the design strategies for providing visual comfort of the users such us opening and material parameter which allows light to enter a space, building orientation which determine the building surface which faces the light source, shading device which limits direct light entering the space while surface texture and color determine how much of the light will be reflected from a surface. This parameter impacts the amount of direct and indirect glare in a space. While opening, material and orientation affect direct glare, surface texture and color affect indirect glare significantly.

Openings perform various functions including permitting daylight to enter a room, ventilation, creating a view, and connection with the surrounding environment. Daylight level will differ depending on the time of day, time of year, and location. Light enters a building in a number of ways including direct sunlight, skylight, and diffused light, reflected external and internal light from surfaces. (Fig. 1.)

Identifying constant and changing variables/parameters that can impact daylighting and glare is significant to find optimal daylighting in buildings. material Furnitures spacedimentions, building form, wetherdata and location have been set as a constant variable for this research. While time of simulation, building orientation and facade opening ratio (window to wall ratio (WWR)) are the changing variable used for simulation and optimization.

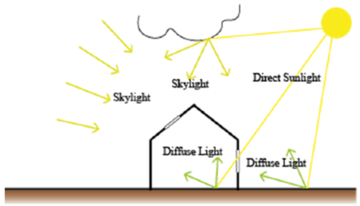


Fig. 1. Direct Sunlight, Skylight and Diffused Light.

One of the most common approaches that designers and engineers use to find the best design solution to a problem is to consider different variables to establish multiple design alternatives. The ideal design solution is found through a comparison of the performances of the design alternatives. This approach is used widely in research and practice. For example, Ho et al [8] explored 4 types of shading design with different height and width combinations to find the optimal design with maximum uniform illumination level and distribution. However, this type of approach is limited to certain options.

Optimization is an act, process, or methodology of making something (such as a design, system, or decision) as fully perfect, functional, or effective as possible (Merriam Webster Online, 2020). The development of parametric design, building simulation, and optimization technologies in recent years has enabled the possibility of optimization of building performance. The application of optimization has been used since the 1980s and 1990s but the application in building performance flourished in the late 2000s [14].

The optimization process requires variables and objectives functions as input. In Building performance optimization, variables are values controlling the design while objectives are the building performance metrics usually calculated by simulation tools (Machairas, Tsangrassoulis, & Axarli, 2014). Numerous design variables are considered in building design. Some of the design variables include orientation of building, form of building, materials and openings [6].

Different optimization problem requires different optimization algorithms. In recent years, numerous optimization algorithms have been developed and used for building performance optimization.

Genetic algorithm is the most popular optimization algorithm in building performance studies [14]. The algorithm randomly selects solutions of good performance from the current population and uses them as parents to produce the next generation, and the population "evolves" toward an optimal solution [13].

In solving building design problems, designers usually tackle various variables to reach to a solution. Multivariable optimization is much more difficult than the simpler problem-solving techniques used by various designers of using a single variable. In a multivariate optimization problem, multiple variables act together for making decision in the optimization problem-solving process. Mathematical representation of multiple variable optimizations can simply be represented as $z = f\left(x_1, x_2, x_3, \ldots\ldots.x_n\right)$, Where " $x_1, x_2, x_3, \ldots\ldots.x_n$ " represents the various variable while " Z " represents the objective.

The daylight performance of a building is affected by various design parameters or variables. These parameters or variables affect daylighting in a different manner. Some of the design variables are building plan shape, size of building, average story height, number of stories, building envelope, circulation space, material and orientation. In optimization of daylight, because of its multivariable nature, multivariable optimization has a higher potential in producing a more optimal solution to a problem of lighting than a single-variable optimization.

Daylighting simulation is a computer-based analysis of the amount of daylight available inside or outside of a building under one or several sky conditions. Simulation outputs could be illuminance or luminance for selected sensor points in a space. Wong [17] finding related to daylight simulation show that, of the various methods used to evaluate the daylight performance of a building, computer simulation is the most commonly used in the building design stage because of its capability of involving design variants and its accurate result. The research also identified and review computer daylighting simulation tools, and the most frequently used tools used by researchers and practitioners are Radiance, Adeline, Ecotect, DOE, Daysim, and EnergyPlus.

Yu & Su, [18] identified two mostly utilized illumination algorithms in daylighting simulation programs: ray-tracing (view-dependent algorithm) and radiosity (scene-dependent algorithm), which can be represented by Radiance and Relux respectively. From the two, Radiance is widely used in daylighting simulation-related research topics, and it has extensively validation by researchers ([11] and [15]). One of the major drawbacks of the program is the lack of user interface. But it is usually incorporated within other tools. Because of its validation and availability Radiance is used as a simulation tool for this research. The following radiance parameters as well as material property are used for daylight simulation:(Table 2 and Table 3)

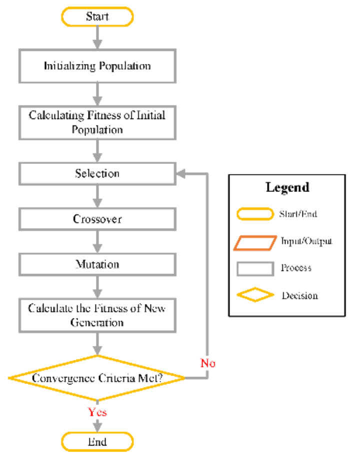


Fig. 2. Flowchart outlining details of generic algorithm

Table 2:Material information for DIVA 4-Radiance daylight simulations (Source: Building materials report of case study building).

Building Component	Reflectivity	Visual Transmissivity
Walls and Partitions	0.4	-
Ceiling	0.8	-
Floor	0.4	-
External ground	0.2	-
Glass Partition	-	0.88
Glazing	-	0.80

Table 3:Selected radiance parameter (Source: Truesdell, 2018)

Radiance Parameter	Value
Ambient accuracy (aa)	0.15
Ambient bounces (ab)	2
Ambient divisions (ad)	512
Ambient resolution (ar)	256
Ambient super-samples (as)	128
Direct relays (dr)	2
Source substructuring (ds)	0.2
Limit reflection (lr)	6
Limit weight (lw)	0.004
Source jitter (dj)	0
Specular jitter (sj)	1
Specular threshold (st)	0.01

2 Materials and Methods

2.1 Description of the Study Area

This research was conducted in area located in Addis Ababa, Ethiopia, as shown in Fig 3. It is geographically found between 38.75° E longitude and 8.98° N latitude. Because of its location in respect to angle of sunlight coming from the sun Addis Ababa has an average of 12 hours of daylight per day. The 55.6% of daylight hours is with an average of 6 hours and 40-minute of sunlight per day while the remaining 44% daylight hours are most likely cloudy, shaded, haze or low sun intensity. The research is mainly focused on daylight performance of selected case study building located in the study area. (Source: https://www.addis-ababa.climatemps.com/)

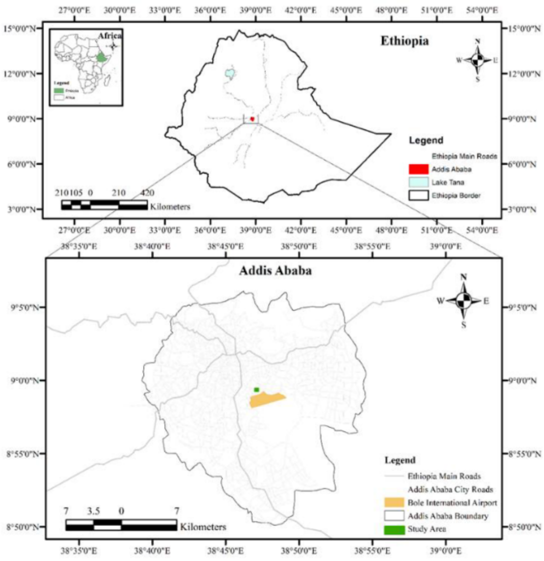


Fig. 3. Location of Study Area

2.1.1 Case study

The selection criteria for case study are based on four primary considerations. The first is the building must be high rise office building built in the past decades. The second is the location in relation to the weather data used for simulation for accurate comparison between simulation and field measurement. The third is consideration of the type of facade system, and orientation. The fourth is the availability of resource for case study as well as access to the building.

The selected case study based on the above criteria is National Oil Company (NOC) of Ethiopia Headquarters Building due to availability of sufficient data, built time, type of facade, building orientation and access. The existing building have been used as a case for measuring and analysis of existing condition as well as in the evaluation of the framework.

i) National Oil Company (NOC) of Ethiopia Headquarter Building Project

National Oil Company (NOC) is one of the key players in Ethiopia's oil industry. The company announced the completion of the construction of their new headquarters building on July 8, 2017. The new building is one of the tallest buildings in Ethiopia.

2.2 Research Method

2.2.1 Data Sources and Data Collection

In this study, both qualitative and quantitative data have been utilized to achieve the objectives of this research. The qualitative and quantitative data used in this study, which are presented subsequently, are grouped into primary data and secondary data.

ii) Primary data

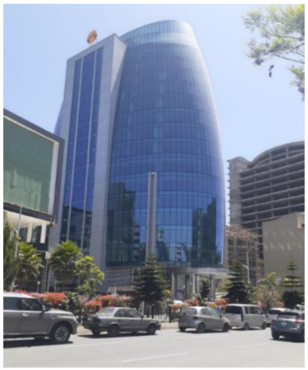


Fig. 4. Picture of National Oil Company (NOC) of Ethiopia headquarter building.

There are two important primary data collected in this study. The first primary data collected during the study is the on-site daylight illuminance measurements taken at different location from the inside of a case study building. This quantitative data is later used to validate the accuracy and reliability of the daylight simulation conducted using software. The second primary data is qualitative information regarding the daylight and glare perception of occupants of the case study building, which is collected by means of questionnaire.

iii) Secondary data

The secondary data used in this study include the radiance parameters and weather data for Addis Ababa, Ethiopia. The radiance parameters are obtained from standard literature, whereas the weather data is obtained from the Solar and Wind Energy Resource Assessment (SWERA) global data set. Also, additional construction documents such as plan, elevation and material property for the case study building are obtained from the owners of the building, i.e., National Oil Company (NOC) of Ethiopia. In addition, acceptable values of the annual sunlight exposure (ASE) and spatial daylight autonomy (sDA) are taken based on international standards.

2.2.2 Sample size and sampling technique

Accessible population technique has been implemented for questionary distribution. It was accomplished by distributing the questionary to all population (40 occupants) throughout the case study building were the researcher has access too.

2.3 Research process

The general research process that is taken to accomplish and answer the research objectives and questions are shown in Fig 4.

2.4 Computational Simulation Tool and Validation.

Computational simulations have the power to analyze the daylighting condition of building space much faster and detailed than calculations or model testing. It predicts the possible daylighting condition of a design before it is constructed with the effects of climate with hourly weather data from a typical meteorological year.

Ladybug tools 1.2.0 and DIVA 4 plugin for Rhinoceros 6 have been used for conducting point in time and grid-based analysis. Radiance is used as a calculation and simulation engine for lighting in this program. Ladybug tools 1.2.0 and DIVA 4 act as interfaces that facilitate conducting simulations with Radiance. Radiance has been validated by various research as well as International Commission on Illumination (CIE test cases 171:2006) (Reinhart and Walkenhorst 2001). While Rhino version 6 with grasshopper is used for modeling as well as a parametric design tool.

Further analysis is done to compare the variation between illuminance measurements taken by Lux meter from the case study building and simulation tools results for the case study building. The illuminance level at the working plane is measured using lux-meter at different point and time of the day in selected spaces from the case study building. For office buildings, the study considered the European assumption of 0.85m as a working plane level for analysis and simulation of daylighting of the study model as well as case study building (Source: https://www.schorsch.com/en/kbase/glossary/work-plane.html. Retrieved: April,10 2021).

The result of the illuminance level measurement taken by one Lux meter from March 25th 2021 to April 25th 2021from points shown Figure 12 on the 10th floor of the case study building is compared with the illuminance level result from simulation to identify the variation between the simulation tools results and real measurements. The effect of sky condition (i.e., clear sky condition) as well as occupants' intervention were considered in selecting measurements for variation analysis.

2.5 Framework and Evaluation

The development of the framework has been accomplished based on the theoretically review, contextual review, empirical review, optimization algorism, and various computational optimization and simulation tools. Then the application of the proposed framework is tested by application on sample office space and case study building.

i) Framework for computational multivariable design optimization of buildings

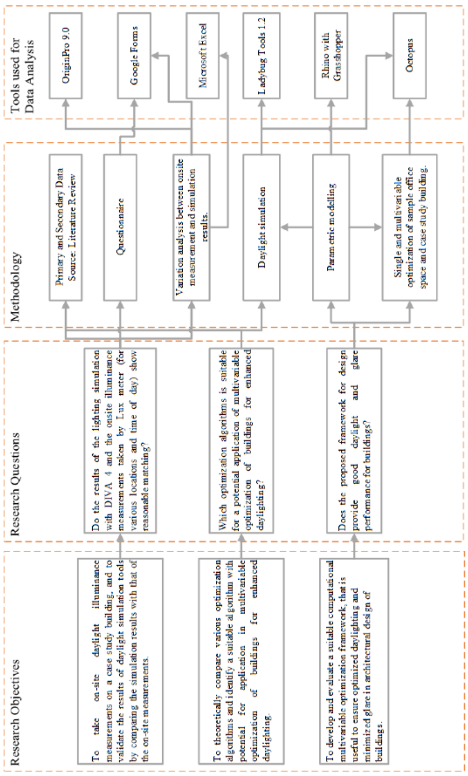


Fig. 5. Research process and methodology

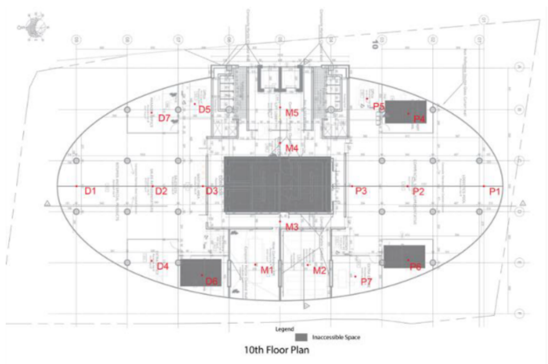


Fig. 6. Point of measurement at 10th floor of the NOC building.

The proposed framework for multivariable optimization of daylight and glare is to be integrated into the schematic design phase with a possibility of integrating it at any stage of the design process in architectural design. The framework for multivariable optimization of indoor daylighting and glare in architectural design is developed with the following consideration:

1. Parametric building design is proposed as a method of parameterizing design variables for the framework. Various design alternatives can be assessed with changes in design variables. The design variable proposed to be integrated in the framework are building orientation and facade opening ratio (WWR).
2. For Daylight Simulation, the application of DIVA 4 for Rhino 6 is used in this study. sDA and ASE are identified as a proxy for daylight and glare respectively as set by Illuminating Engineering Society (IES) and LEED 4.
3. Genetic algorism is integrated in the framework for multivariable optimization of daylight and glare by the use of octopus plugin for grasshopper.
4. For the multivariable optimization and framework, ASE and sDA are identified as a fitness for daylight and glare optimization while building orientation and facade opening ratio (WWR) design variables are identified as the variables for the optimization of the fitness (See Fig. 7).

The proposed framework enables a designer to manipulate variables until a desired ASE and sDA is achieved without compromising the design concepts. Fig 7 shows the developed framework for multivariable optimization of indoor daylighting and glare in architectural design.

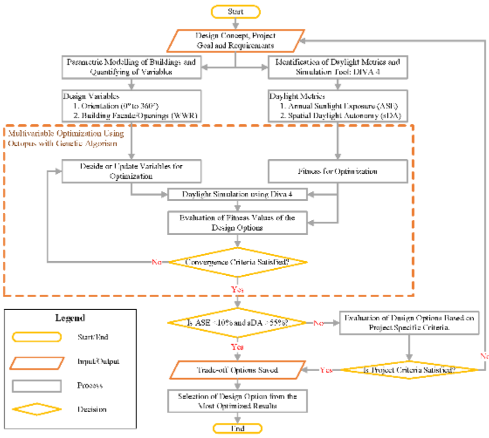


Fig. 7. Framework for computational multivariable design optimization of buildings.

2.6. Method of Data Analysis

The data analysis stage is accomplished by using inputs data and information to output quantitative and qualitative results. Inputs are gathered from site measurement, literature review, questionnaire, and modeling of the case study building. The main data analysis process used in this thesis is through quantitative method of analysis. This is accomplished by Ladybug Tools 1.2, DIVA 4 and Octopus, simulation and optimization tools, based on the type of quantitative data collected and the variables considered as well as their interoperability and better accuracy. In Addition, Excel sheets as well as Google Forms is used for further analysis of questionnaire, numerical outputs from simulation and actual illumination measurement taken by Lux Meter from selected space in the case study. Finally, the output of the above different tools has been discussed and compared.

3 RESULTS AND DISCUSSIONS

3.1 Occupants response on National Oil Company (NOC) building's daylight quality

The qualitative measurement is taken from occupants by means of questionnaire from the office building. The analysis of the questionnaire shows that 90 % of respondents believe that there is sufficient light for their work. While 67.5% of respondents say that excessive bright light or glare create visual discomfort or affect their activity. (Fig. 8).

3.3 Comparison of Measured Illuminance Values and Simulation Results for the Case Study Building.

Several daylight illuminance measurements were taken from March 25th 2021 to April 25th 2021. The observed measurement from Lux meter show that there are some parts of the floor space that has excess level of illuminance (>1000 lux) in the morning while other space has excess level of illuminance (>1000 lux) in the afternoon.

Based on consideration of sky condition, lighting condition, accessibility and unwanted user interventions, measurements taken on April 2nd 2021 from D1, D2, D3, D4 and D5 as a point of measurement for comparing simulation tools illuminance results with illuminance level measured by Lux meter (Fig 6). From the graph shown in Fig. 9 and Fig. 10, the variation between the simulated results with DIVA 4 and measurements taken from case study building is about ± 10%. This finding of measurement and result shows that the simulation results and the onsite illuminance measurements taken by Lux meter (for various locations and time of day) show reasonable matching.

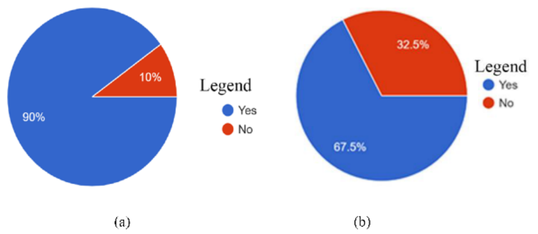


Fig. 8. (a) Occupant response on availability of sufficient light and (b) Existence of excessive bright light or glare creating visual discomfort.

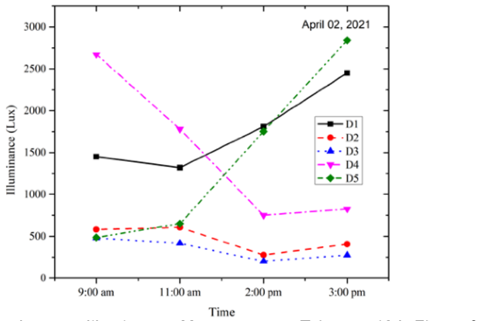


Fig. 9. Average Illuminance Measurements Taken at 10th Floor of NOC Buildings by Using Lux Meter.

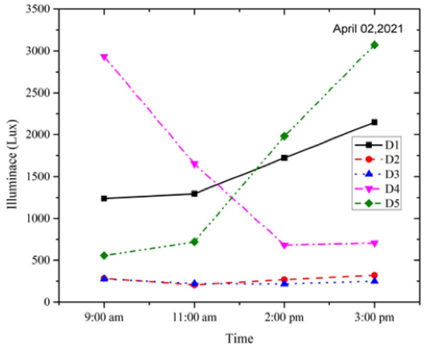


Fig. 10. Average Illuminance Measurements from Simulation at 10th Floor of NOC Buildings in Lux.

3.4 Optimization of Sample Office Space for an Office Building.

Based on a space standards guideline by UCL and Nufert's Architects Data as well as case study, a pool office with floor area of 140sqm is taken as a sample model with opening on one side is used to further develop, test and evaluate the optimization process. The Fig. 11 shows floor plan of the selected office space.

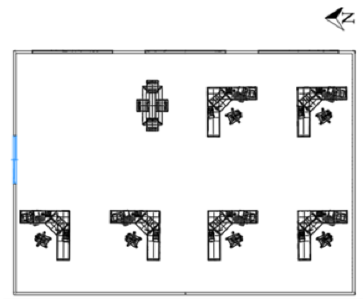


Fig. 11. Sample Office Space Floor Plan.

3.4.1 Optimization by Orientation for Improving Daylighting Conditions of Sample Space.

The optimization of indoor daylighting and glare by orientation variable is achieved mainly by changing the building orientation to identify Special Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for the space in consideration at different orientation of building and to compare result with the standards set by Illuminating Engineering Society (IES) and LEED 4. Fig. 13 shows the optimization result of orientation variable was analyzed with fixed contextual variable and 50% window to wall ration. (Fig. 12)

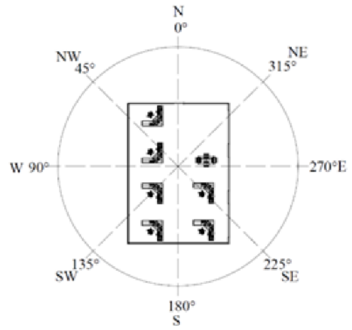


Fig. 12. Sample Office Space Floor Plan and Orientation Angle for Simulation.

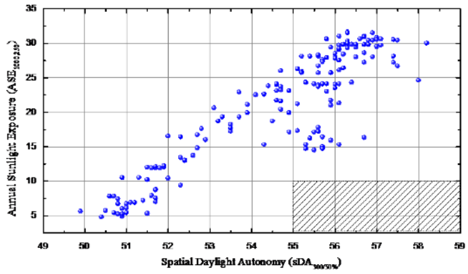


Fig. 13. Optimization by Orientation for Improving Daylighting Conditions of Sample Office Space.

Based on the set parameters, the results of optimization of ASE and sDA by orientation did not achieve the required level of minimum of < 10% ASE1000,250 and > 55% sDA300/50% set by Illuminating Engineering Society (IES) and LEED 4. This result shows that single variable optimization by orientation considered in this study did not achieve sufficient daylight with acceptable level of glare.

3.4.2 Optimization by facade openings (WWR) for improving daylighting conditions of Sample Office Space.

The optimization of indoor daylighting and glare by facade opening variable is achieved by changing the building facade openings to wall ration (WWR) to identify Special Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for the space in consideration at different window to wall ration (WWR) and to compare result with the standards. Fig. 10 shows the optimization result by facade openings where the longest side of the office space face East-West direction and orientation at 0 degree.

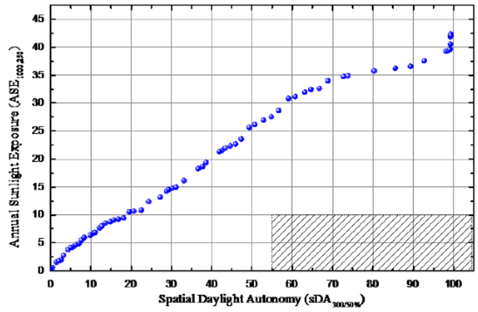


Fig. 14. Optimization by Facade Openings Ratio for Improving Daylighting Conditions of Sample Office Space

Based on the preset parameters, the results of optimization of ASE and sDA by Facade opening ratio (WWR) shown in Fig 14 did not achieve the required level of < 10% $ASE_{1000,250}$ and > 55% $sDA_{300/50\%}$ set by Illuminating Engineering Society (IES) and LEED 4 for sufficient daylight availability with minimum glare.

3.4.3 Multivariable Optimization of Sample Office Space.

The multivariable optimization of indoor daylighting and glare is achieved by changing the building orientation and building facade openings to wall ration (WWR) to identify best result with balanced Special Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) for the sample space in consideration. Fig 15 Shows the multivariable optimization results for facade opening and orientation variables.

Several results of multivariable optimization for ASE and sDA by Facade opening ratio (WWR) and orientation shown in Fig. 15 have achieved the required level of $ASE_{1000,250}$ and $sDA_{300/50\%}$ set by Illuminating Engineering Society (IES) and LEED 4.

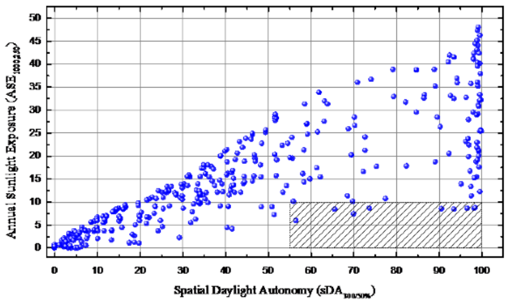
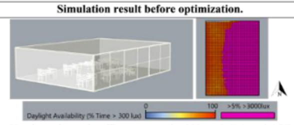


Fig. 15. Multivariable Optimization for Improving Daylighting Conditions of Sample Office Space

The selected optimized results with the application of the framework on the sample office space is shown in Table 4. The simulation starts from base sample office space with 98% WWR and 0-degree orientation. Out of the optimization results, the most significant drop in $ASE_{1000,250}$ is optimization result 7 with decrease form 42.3% from simulation result before optimization to 5.9% while maintaining a 56.5% $sDA_{300/50\%}$.

Table 4:Simulation Result of Sample Office Space and Selected Multivariable Optimized Results of Sample Office Space

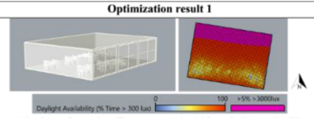
Simulation result before optimization.



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE
0.99	360/0	99.4%	42.3%

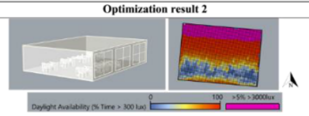
Optimization result 1



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE
0.91	81	96.6%	8.6%

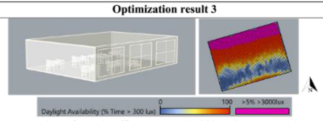
Optimization result 2



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE
0.82	85	70%	7.4%

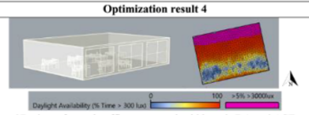
Optimization result 3



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE
0.8	106	65.6%	8.4%

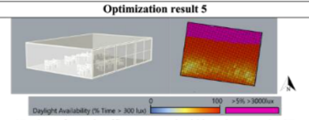
Optimization result 4



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE
0.83	102	73.7%	8.6%

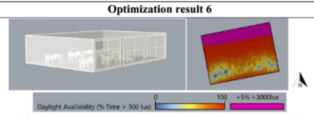
Optimization result 5



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE
0.92	82	98.2%	8.6%

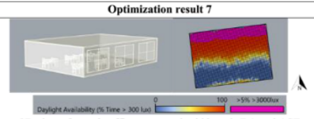
Optimization result 6



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE
0.88	101	90.6%	8.5%

Optimization result 7

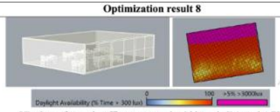


3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE
0.75	97	56.5%	5.9%

Table 4:Continued…

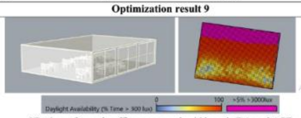
Optimization result 8



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE
0.93	99	98.5%	8.7%

Optimization result 9



3D view of sample office space and grid based sDA and ASE

WWR	Orientation	sDA	ASE

The other significant optimization tradeoffs with significant reduction in ASE and minimum reduction in sDA is optimization result 8 with 8.7% $ASE_{1000,250}$ and 98.5% $sDA_{300/50\%}$, optimization result 5 with 8.6% $ASE_{1000,250}$ and 98.2% $sDA_{300/50\%}$, optimization result 1 with 8.6% $ASE_{1000,250}$ and 96.6% $sDA_{300/50\%}$, optimization result 9 with 8.4% $ASE_{1000,250}$ and 93.5% $sDA_{300/50\%}$, optimization result 6 with 8.5% $ASE_{1000,250}$ and 90.6% $sDA_{300/50\%}$, the multivariable optimization tradeoff results shows a more optimized result than simulation result before optimization as well as single variable optimization.

The application of the multivariable optimization framework on sample office space has provided several design options with sufficient daylight and minimized glare in the interior space. It was possible to provide several design options which achieve the LEED and IES standard of spatial daylight autonomy of >55% for daylight and annual sunlight exposure of <10% for visual discomfort (glare).

3.5 Multivariable Optimization of Case Study Building

The multivariable optimization of National Oil Company (NOC) building has been computed based on the conceptual consideration of the existing facade design and with consideration of an existing context as well as other constant variables to evaluate the capability of multivariable optimization in existing building. Fig 16 shows the multivariable optimization results by orientation and facade opening ratio (WWR).

Out of the optimization results shown in Fig. 10 and Table 5 shows the respective optimized Annual Sunlight Exposure (ASE) and Suitable Daylight Anatomy (sDA) for the selected orientation and window to wall ratio with respect to the existing NOC building window to wall ratio (WWR) which is 85.3%.

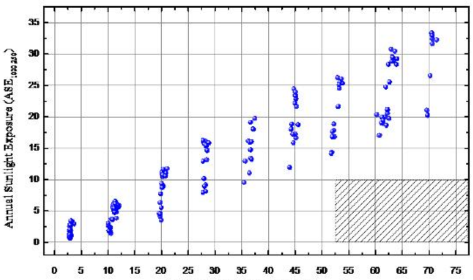
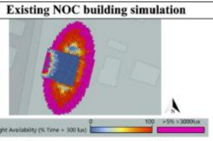


Fig. 16. Multivariable Optimization of National Oil Company (NOC) Building

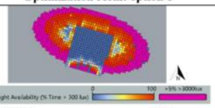
Table 5: Simulation Result of Existing and Selected Multivariable Optimized Results of NOC Building's 10th Floor

Existing NOC building simulation



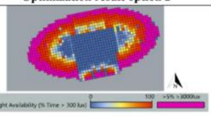
Orientation	WWR	ASE	sDA
0	1 (85.3%)	33%	70.6%

Optimization result option 1



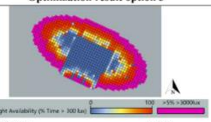
Orientation	WWR	ASE	sDA
88	1 (85.3%)	20.2%	69.8%

Optimization result option 2



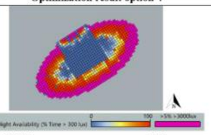
Orientation	WWR	ASE	sDA
115	0.9 (76.77%)	17%	60.8%

Optimization result option 3



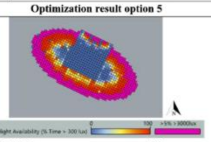
Orientation	WWR	ASE	sDA
79	0.9 (76.77%)	18.9%	61.5%

Optimization result option 4



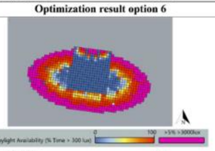
Orientation	WWR	ASE	sDA
316	0.9 (76.77%)	19.9%	61.8%

Optimization result option 5



Orientation	WWR	ASE	sDA
258	0.9 (76.77%)	19.7%	62.6%

Optimization result option 6



Orientation	WWR	ASE	sDA
276	0.9 (76.77%)	19%	61.2%

The optimization tradeoffs that are selected in Table 5 shows that the standard set by Illuminating Engineering Society (IES) and LEED 4 for daylight availability is not fully achieved. The tradeoff shows a significant reduction in Annual Sunlight Exposure (ASE) without achieving <10% ASE1000,250 while maintaining the requirement for Spatial Daylight Autonomy (sDA). This will result in reduction in glare while maintaining sufficient daylight level for occupants. But in order for NOC Building to achieve a minimum of < 10% $ASE_{1000,250}$

and > 55% $sDA_{300/50\%}$, standard set Illuminating Engineering Society (IES) and LEED 4, further facade design changes or interventions are required for NOC building.

The most significant drop in $ASE_{1000,250}$ is optimization result option 2 with decrease from 33% in existing NOC Building simulation to 17% while maintaining a 60.8% $sDA_{300/50\%}$. The other significant optimization tradeoff with significant reduction in ASE with minimum reduction in sDA is optimization result option 1 with 20.2% $ASE_{1000,250}$ and 69.8% $sDA_{300/50\%}$, optimization result option 5 with 19.7%% $ASE_{1000,250}$ and 62.6% $sDA_{300/50\%}$ and optimization result option 3 with 18.9% $ASE_{1000,250}$ and 61.5% $sDA_{300/50\%}$. The conceptual multivariable optimization tradeoff results of the case study show a more optimized result than that of existing NOC building simulation.

4 CONCLUSION

In this study, a computational multivariable optimization framework, which can be used to optimize daylighting and glare presence in buildings, is developed and evaluated. The suitability and the performance of the proposed computational multivariable optimization framework is investigated by applying the strategy for the optimization of a sample office space and a case study building. The following conclusions are drawn based on the results obtained from the study.

1. The results of the lighting simulation with DIVA 4 and the onsite illuminance measurements taken by Lux meter (for various locations and time of day) show reasonable matching. The average variation between the results of the lighting simulation and the onsite measurements taken by Lux meter is about 10%.
2. The application of the multivariable optimization framework on the case study building as well as the sample office space has helped to achieve a significant reduction in glare while maintaining sufficient daylight availability and distribution.
3. The application of multivariable optimization framework on the sample office space has provided several optimized solutions with minimized glare availability in the space. For instance, it was possible to achieve low $ASE_{1000,250}$ value of 5.9% while ensuring availability of sufficient daylighting, i.e., $sDA_{300/50\%}$ > 55%.
4. The application of single variable optimization with orientation as well as facade opening (WWR) on the sample office space considered in this study did not achieve the required daylight and glare levels, i.e., sDA > 55% and ASE < 10%, set by Illuminating Engineering Society (IES) and LEED. However, it was possible to satisfy the stipulated criteria using the proposed multivariable optimization framework.
5. The application of multivariable optimization framework on the case study building has provided several optimized design alternatives. For instance, significant reduction of ASE (i.e., 12% reduction) was achieved with only minimal reduction of sDA (i.e., 0.8% reduction) as compared to the existing building daylight performance.
6. The proposed multivariable optimization framework, if implemented properly, has the potential to provide multiple viable design options, i.e., orientation and facade opening, that could achieve optimized daylight and glare performance.

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Appendix B: Design Proposal and Intervention

In the response to findings shown in Table 9, this study proposed a new facade design intervention for the optimization of NOC building to achieve a minimum of < 10% $ASE_{1000,250}$ and > 55% $sDA_{300/50\%}$, standard set Illuminating Engineering Society (IES) and LEED 4. This proposed new facade aims in providing sufficient available and distribution of daylight with minimized glare for office spaces in the buildings.

The proposed intervention for NOC Building is addition of external shading to minimize glare while maintaining the required level of daylight availability and distribution in the interior space. This is achieved first by testing the effect of horizontal and vertical shading on the ASE and sDA on sample office space because of limitation of computational power. Then the application of the shading together with multivariable optimization is implanted on a conceptual design of NOC building.

B.1. Location of Project Site

The site for the design intervention is considered to be on the existing site with the addition of adjacent site acquired by the company (See Figure 29).

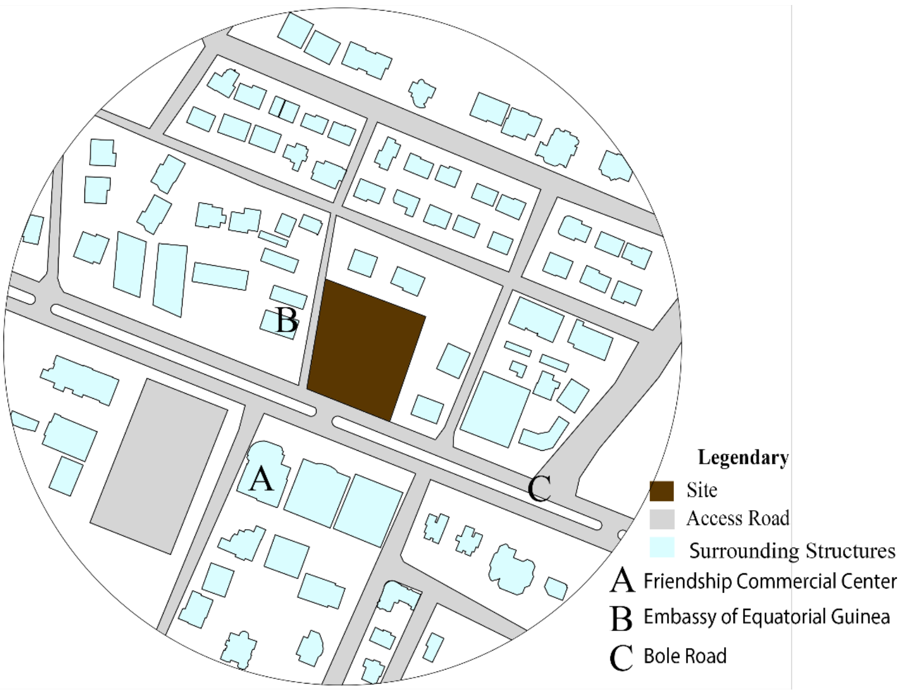


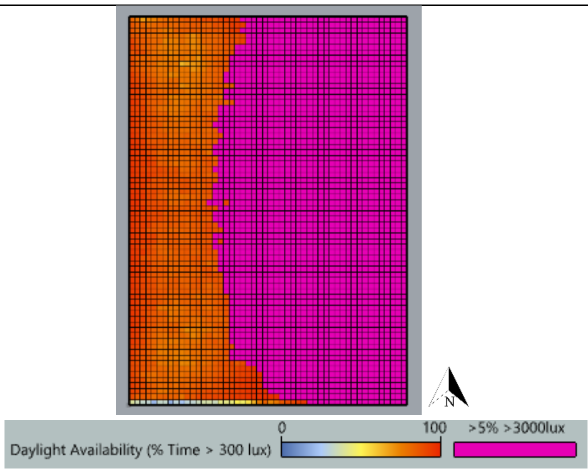
Figure 29: Project site location

B.2. Testing Shading Device for Application

Testing the effect of horizontal and vertical shading on the ASE and sDA was accomplished with the use of the sample office space used for optimization in Figure 22. From the simulation done on vertical shading devices as well as horizontal shading devices shown on Table 10, Vertical Shading 1 shows a significant reduction in sDA with minimal reduction in ASE as compared to Horizontal Shading 1. This shows the application of horizontal shading devices is preferable for minimizing glare while maintaining sufficient daylight availability and distribution.

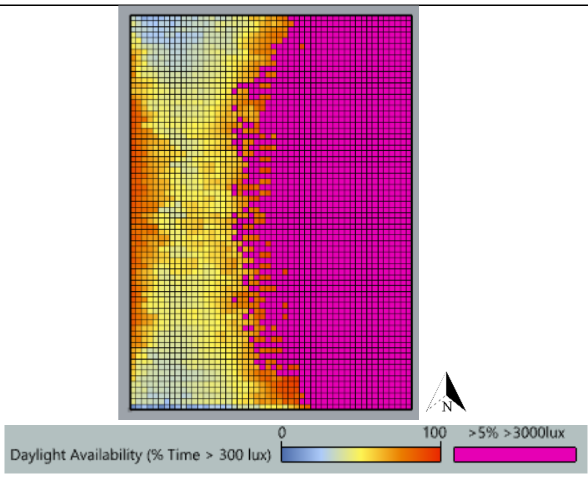
Table 10: Results of shading device test simulation for application.

Simulation without shading device



Orientation	WWR	Shading Element in between Distance (centimeter)	**ASE**	**sDA**
0	0.99 (98%)	No Shading Element	42.3%	99.4%

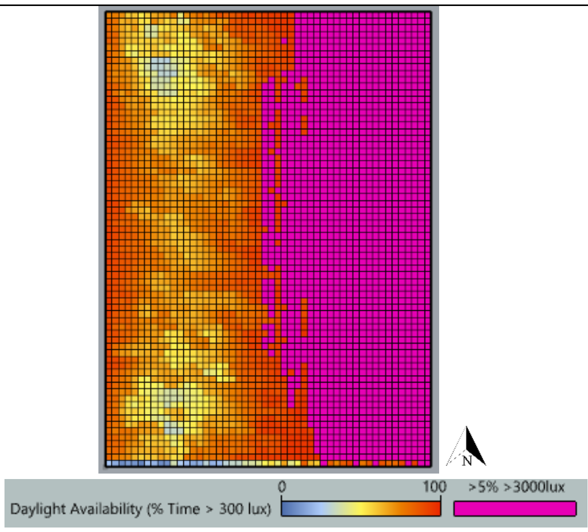
Simulation result with vertical shading 1



Orientation	WWR	Shading Element in between Distance (centimeter)	**ASE**	**sDA**
0	0.99 (98%)	29 (cm)	39.4%	78.3%

Table 10: Results of shading device test simulation for application.- Continued

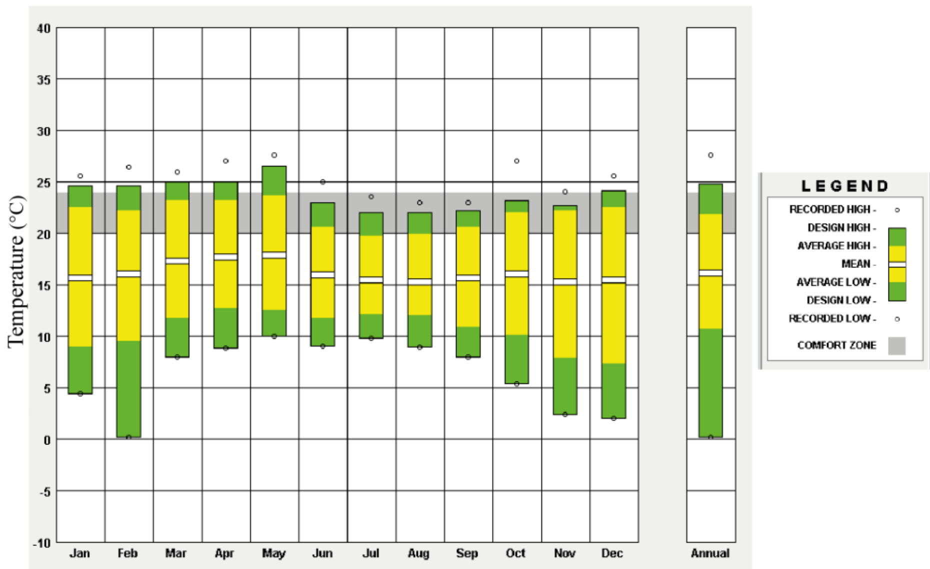
Simulation result with horizontal shading 1



Orientation	WWR	Shading Element in between Distance (Centimeter)	**ASE**	**sDA**
0	0.99 (98%)	29 (cm)	31.9%	96.2%

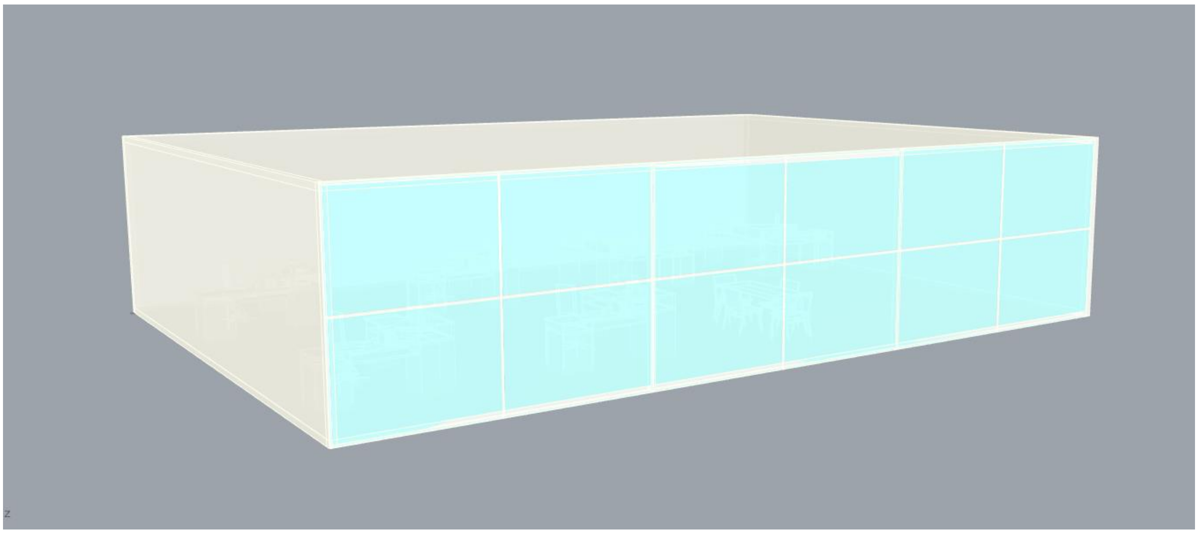
i) Shading Device Design

Melaku (2016) has identified the average indoor thermal comfort for office buildings in Addis Ababa to be between 20 °C to 24 °C. Figure 30 bellow shows the Annual temperature range compared to the comfort level. The figure shows that March, April and May has some days where the sun exposure is higher than that of the comfort zone.

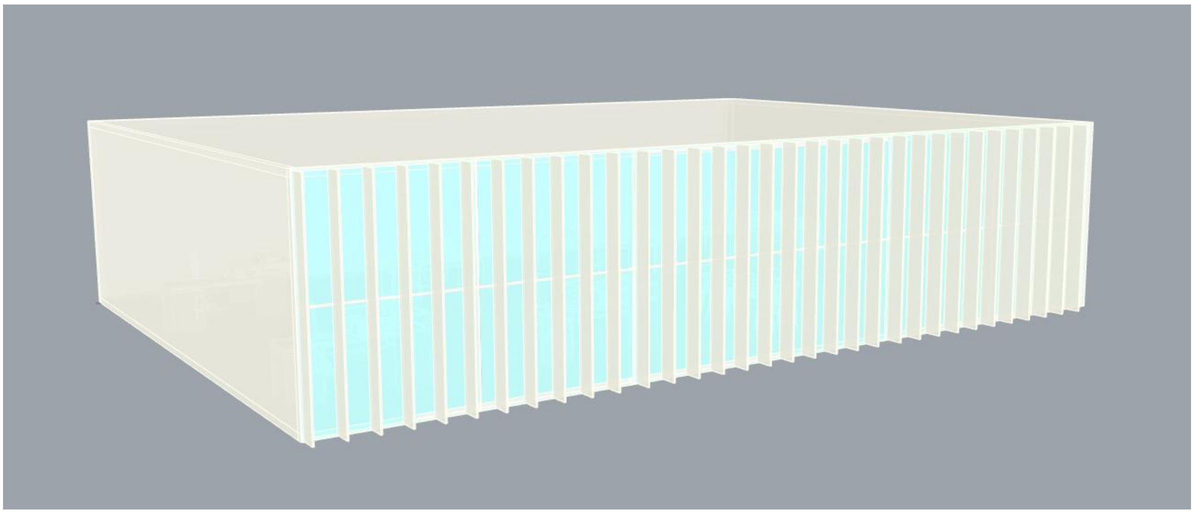


Annual Average Temperature Range

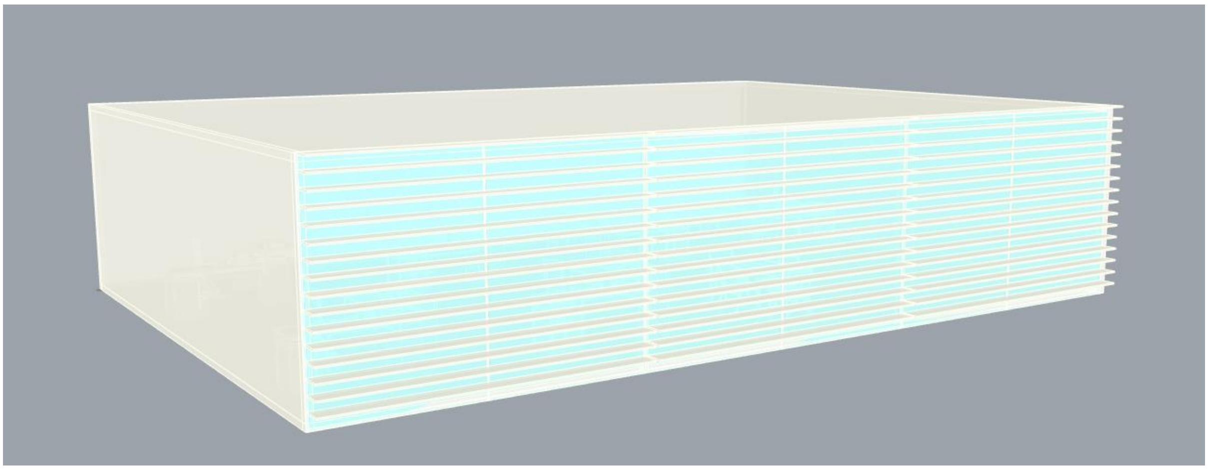
Figure 30: Addis Ababa Annual Average Temperature range



(a)



(b)



(c)

Figure 31: (a) 3D without shading device (b) 3D with horizontal shading 1 (c) 3D with vertical shading 1.

Finding from respondents and measurements taken by Lux meter from case study building showed that north and south facing office space has relatively lower glare in the space than that of east and west facing office spaces. Because of the elliptical form of the building and majority of the spaces are open office, excessive sunlight (glare) coming from east and west side of the building have been noticed impacting occupants working in north and south facing closed office space. Finding showed that the excessive sunlight (glare) entering the space from the north facing window is happening during 9:00 am to 5:30 am in the morning while the south facing window is happening between 02:30 pm to 05:00 pm.

Annual sun exposure analysis of Addis Ababa done by Climate Consultant 6.0 shows that there is high sun exposure from December to June as compared to that of June to December. The high sun exposure is mainly perceived in between 10:00 am and 4:30 pm. This shows that a shading device design is required for December, January, February, March, April, May and June to avoid direct sun exposure to minimize glare while maintaining sufficient daylight in the interior space of a building (See Figure 33).

The vertical shadow angle (VSA) and horizontal shadow angle (HAS) is required for designing horizontal and vertical shading devices for a building. The vertical shadow angle is the angle between the horizontal plane of the building facade under consideration and a tilted plane which contains the sun or the edge of the shading device while the horizontal shadow angle is the difference in azimuth between the sun's position and the orientation of the building facade openings (See Figure 32).

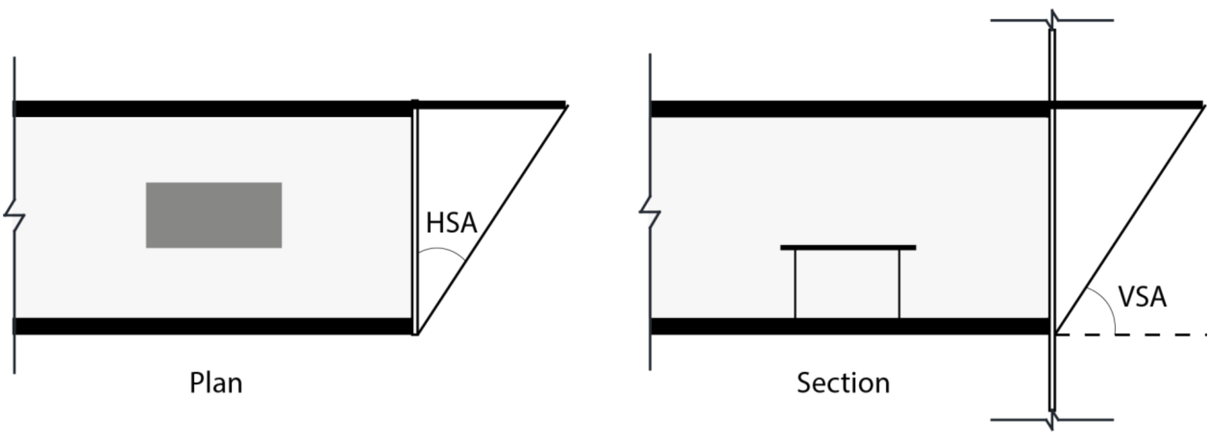
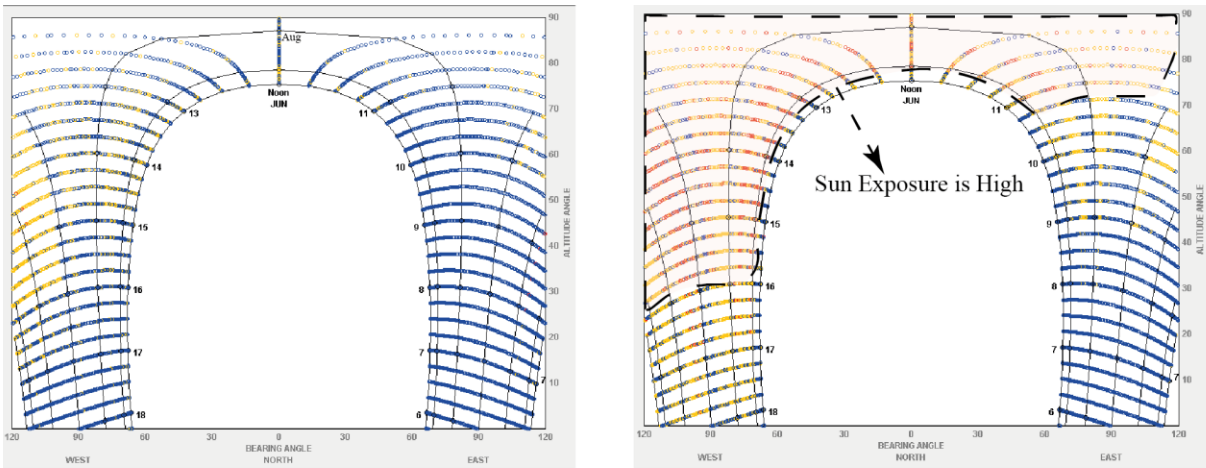
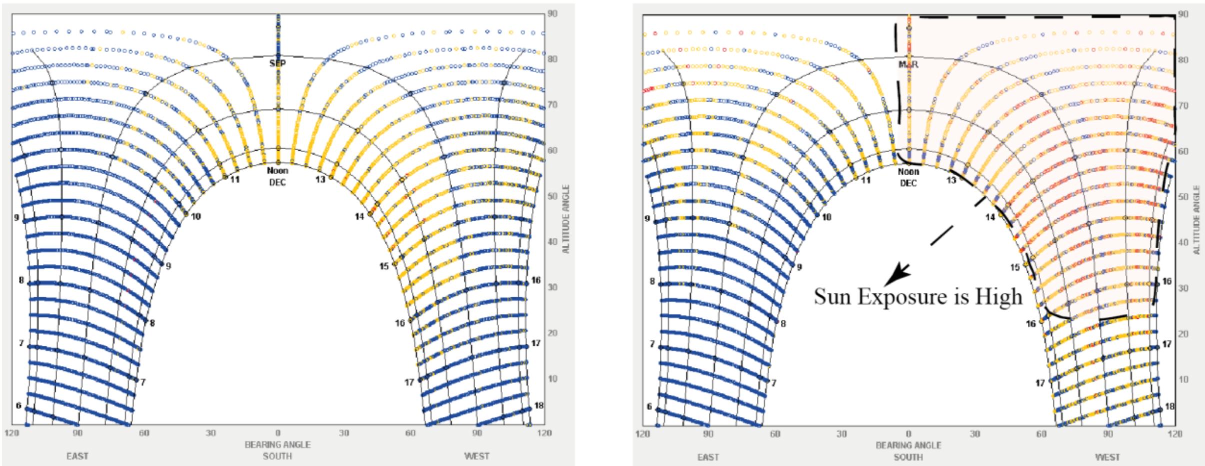


Figure 32: Vertical shadow angle (VSA) and Horizontal shadow angle (HAS)



June to December December to June

Sun Shading Chart of North, East and West



June to December December to June

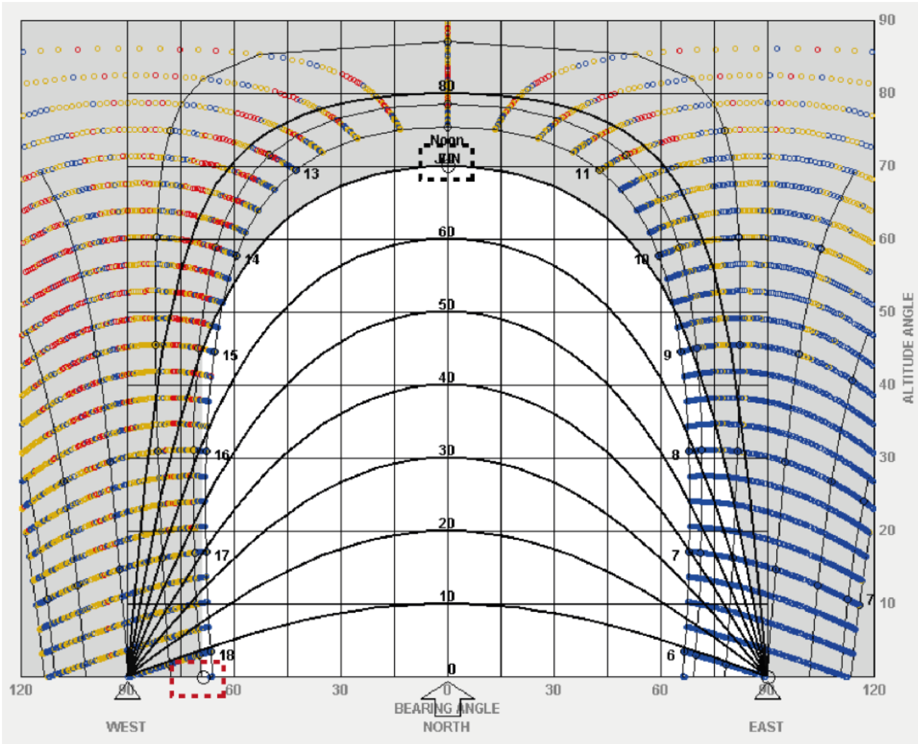
Sun Shading Chart of North, East and West

Legend ○ **Warm/Hot > 24⁰C** | ○ **Comfort > 20⁰C** | ○ **Cool/Cold > 20⁰C** | High Sun Exposure

Figure 33: Annual sun shading chart of Addis Ababa

1. North Facing window

The vertical shadow angle (VSA) and horizontal shadow angle (VSA) for North facing window is identified using shading calculator (solar protractor) on sun path chart for December to June months. Figure 34 shows that the vertical shadow angle is about 70° for North facing windows while the horizontal shadow angle required is about 20° to provide shading of the excessive direct sun exposure.



Legend ○ Warm/Hot > 24^{0}C | ○ Comfort > 20^{0}C | ○ Cool/Cold > 20^{0}C | VSA | HSA

Figure 34: Horizontal shadow angle (HSA) and Vertical shadow angle (VSA) for North facing windows.

2. Shading design for South facing windows

The vertical shadow angle (VSA) and horizontal shadow angle (VSA) for South facing window is identified using shading calculator (solar protractor) on sun path chart for December to June months. Figure 35 shows that the vertical shadow angle is about 58° for South facing windows while the horizontal shadow angle required is about 30° to provide shading of the excessive direct sun exposure (See Figure 40).

3. East Facing window

The vertical shadow angle (VSA) for East facing window is identified using shading calculator (solar protractor) on sun path chart for December to June months. Figure 36 shows that the vertical shadow angle is about 74° for East facing windows to provide shading of the excessive direct sun exposure.

4. West Facing windows

The vertical shadow angle (VSA) for West facing window is identified using shading calculator (solar protractor) on sun path chart for December to June months. Figure 37 shows that the vertical shadow angle is about 43° for West facing windows to provide shading of the excessive direct sun exposure.

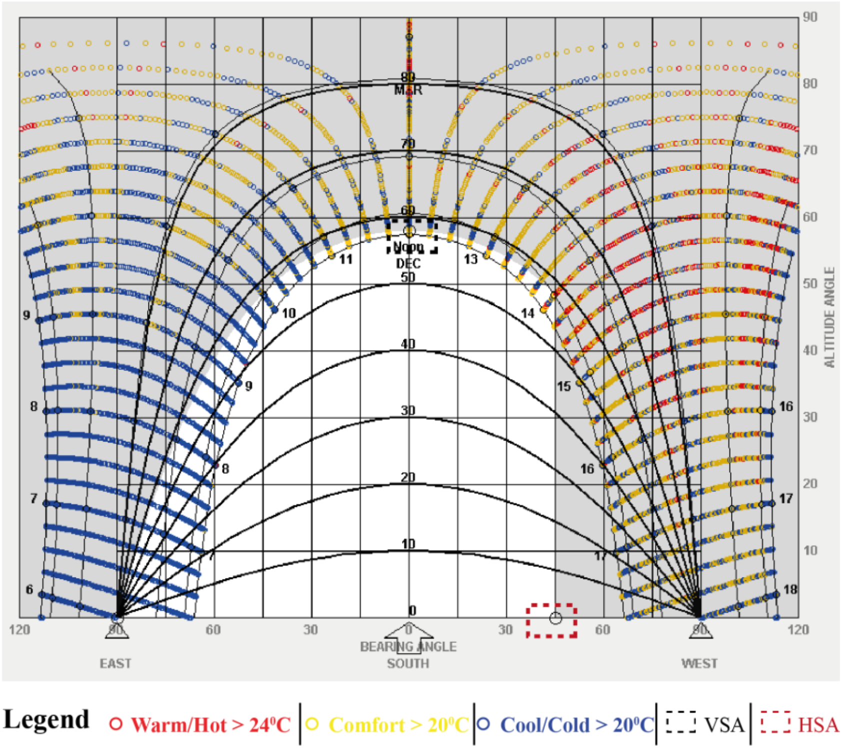


Figure 35: Horizontal shadow angle (HSA) and Vertical shadow angle (VSA) for South facing windows

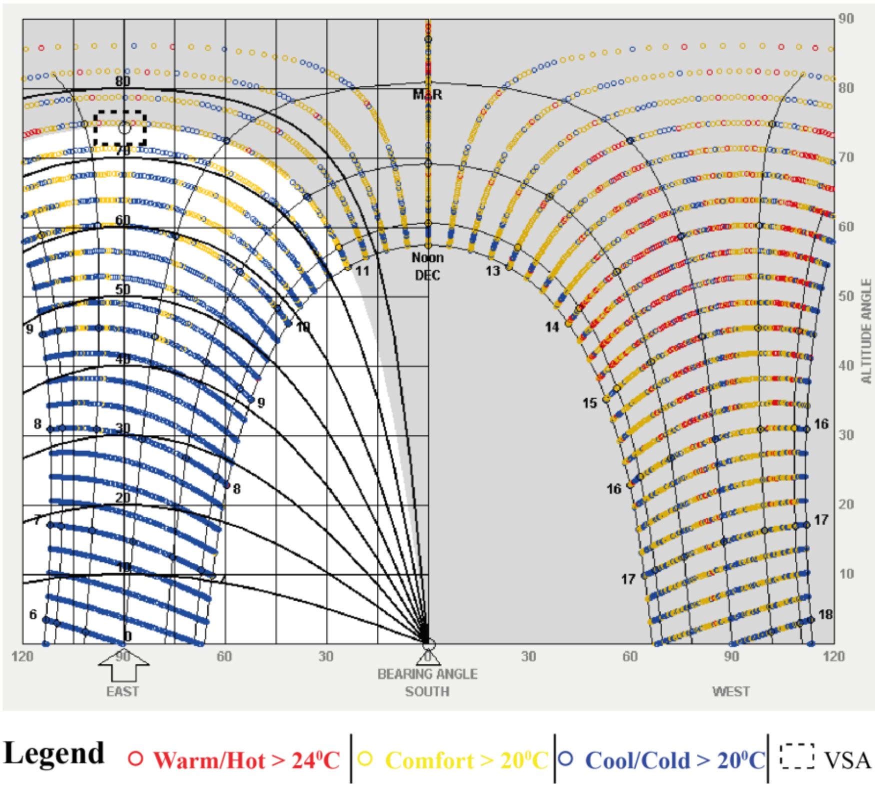
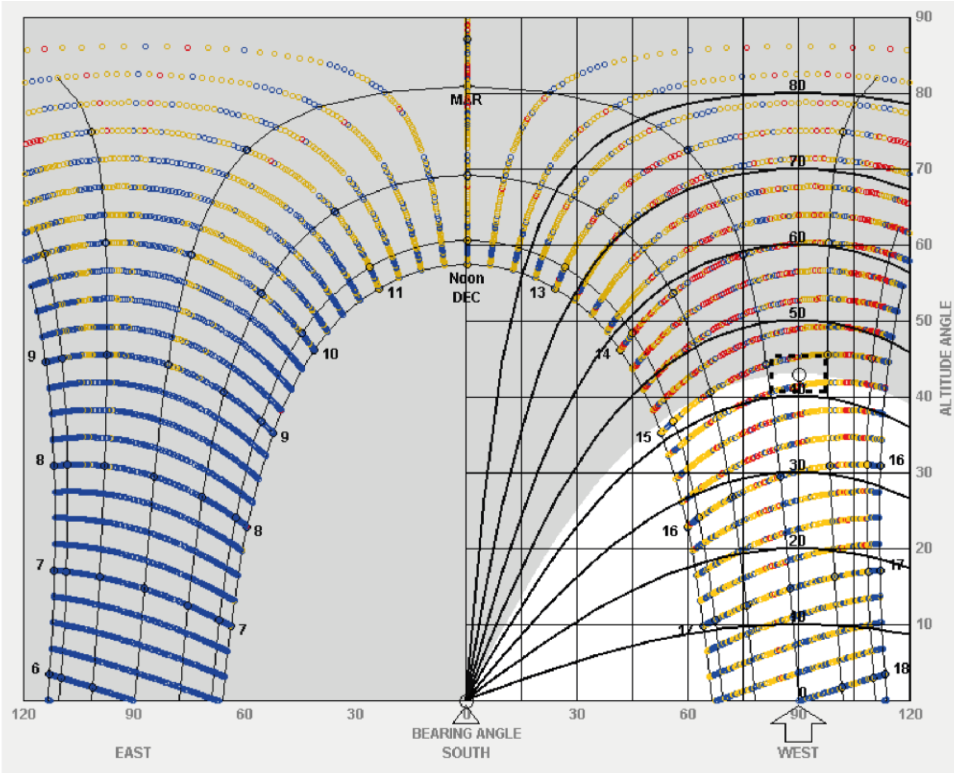


Figure 36: Vertical shadow angle (VSA) for East facing windows



Legend ○ Warm/Hot > 24°C | ○ Comfort > 20°C | ○ Cool/Cold > 20°C | VSA

Figure 37: Vertical shadow angle (VSA) for West facing windows

From the identified vertical shadow angles (VSA) of the main four direction, i.e., North, South, East and West, the lowest angle (43°) is selected to provide sufficient shade for the facade of NOC building. A uniform fixed shading device is proposed with: (a)43cm in between shading device and with a length of 46 cm and (b) 60cm in between shading device and with a length of 64 cm (See Figure 38, Figure 39 and Figure 41). The proposed shading devices with the application of the multivariable optimization framework is shown in Table 11.

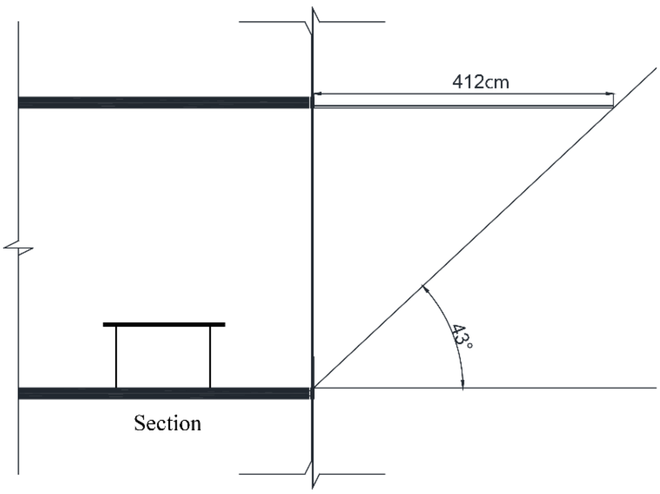
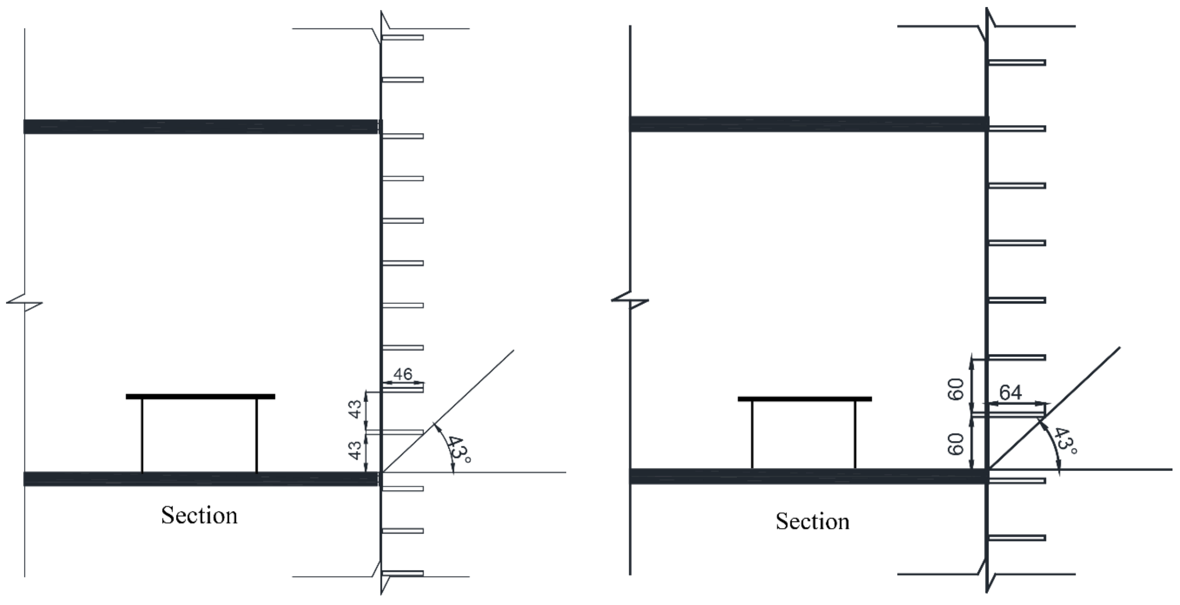


Figure 38: One shading device with the identified vertical shadow angles (VSA)



(a) (b)

Figure 39: Identified vertical shadow angles (VSA) and shading devices with in-between distance of: (a) 43cm (b) 60 cm

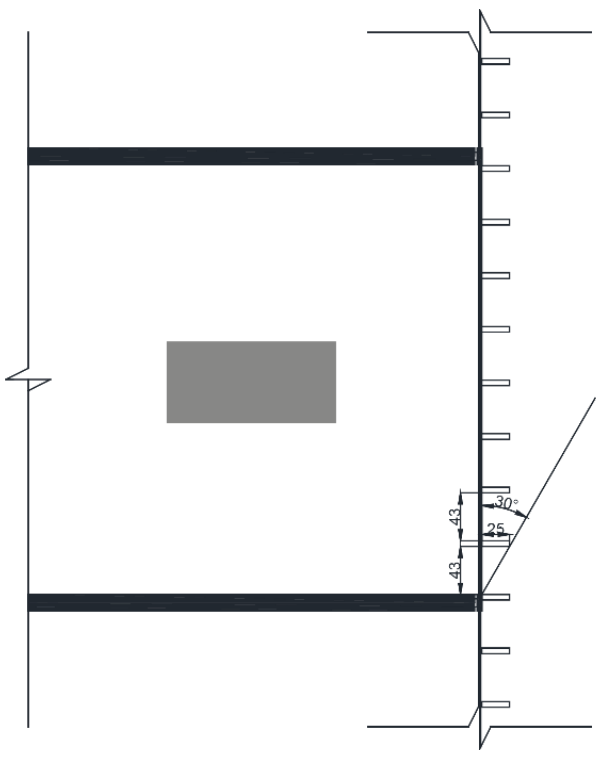


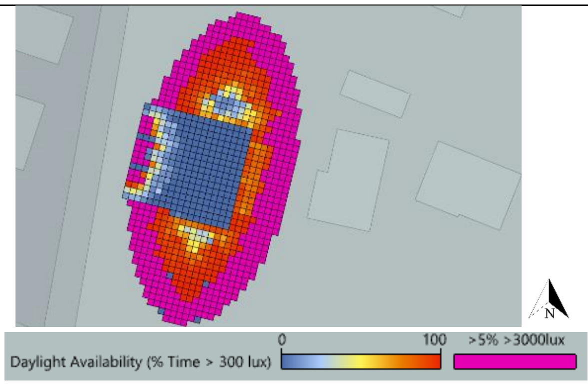
Figure 40: Identified horizontal shadow angle (VSA) and shading devices with in-between distance of 43cm.

B.3. Proposed Intervention with Multivariable Optimization to Minimize Glare while Maintaining Sufficient Daylight Availability and Distribution.

The proposed intervention on NOC building optimization and simulation based on the findings on Table 11 is the use of external horizontal shading and vertical shading devices together with the multivariable optimization to result in ASE of 8.2% and sDA of 58.7% for shading element in-between distance of 43cm for horizontal and 43cm for vertical shading. In Addition, the vertical shading act as a structural component which connects the horizontal shading with facade structure. The length of the shading elements is 50cm and 25cm for horizontal and vertical respectively. The shading device is made up of aluminum sheet because of its ease of fabrication, workability, lightweight and ease of transportation. The shading device is fixed by vertical structure with the curtain system. This intervention allows clear view to the outside and inside the building while maintaining sufficient daylight and glare performance.

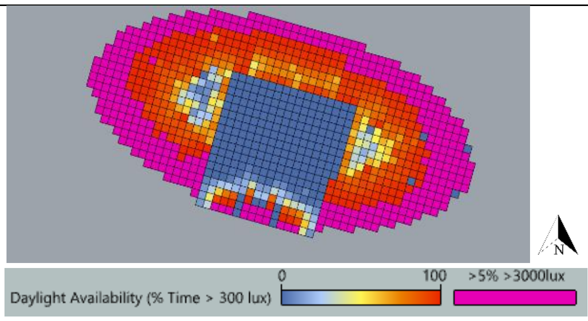
Table 11: Proposed interventions for optimization result option 1 and existing building simulation.

Existing NOC building simulation



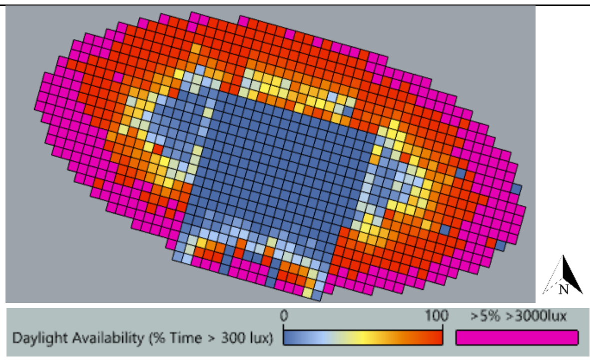
Orientation	WWR	Shading Element in between Distance (Centimeter)	**ASE**	**sDA**
0	1 (85.3%)	No Shading Element	33%	70.6%

Optimization result option 1



Orientation	WWR	Shading Element in between Distance (Centimeter)	**ASE**	**sDA**
88	1 (85.3%)	No Shading Element	20.2%	69.8%

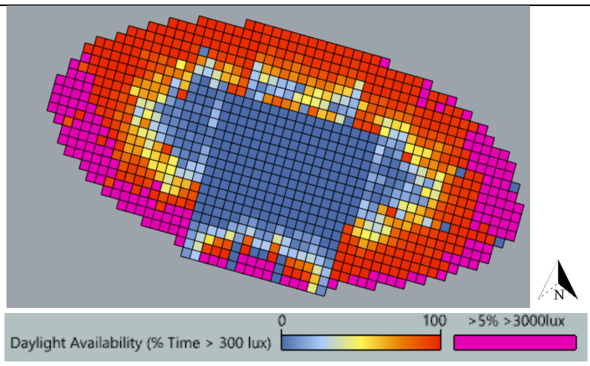
Optimization result option 1 with horizontal and vertical shading 1



Orientation	WWR	Shading Element in between Distance (Centimeter)	**ASE**	**sDA**
88	1 (85.3%)	60 cm Horizontal and 43 cm Vertical	11.4%	63.4%

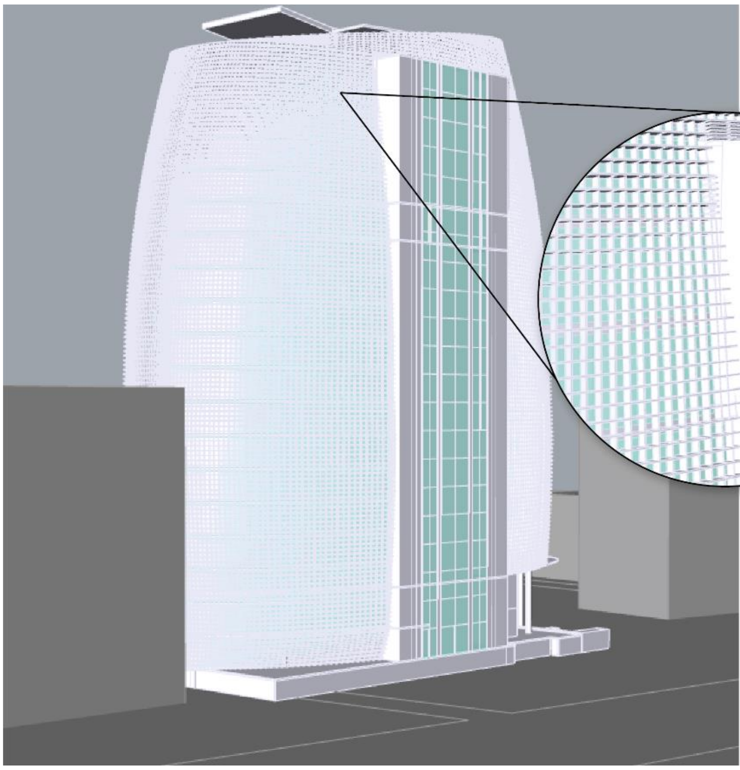
Table 11: Proposed interventions for optimization result option 1 and existing building simulation.- Continued

Optimization result option 1 with horizontal and vertical shading 2



Orientation	WWR	Shading Element in between Distance (Centimeter)	**ASE**	**sDA**
88	1 (85.3%)	43 cm Horizontal and 43 cm Vertical	8.2%	58.7%

(a)



(b)

Figure 41: (a) Existing NOC building picture and (b) Optimized NOC building 3D with horizontal and vertical shading.

Appendix C: Average illuminance measurements with Lux meter, simulation, and variation analysis between on-site illuminance measurement and simulation results of 10th floor space of NOC building.

Table 12: Average illuminance measurements taken on 10th floor of NOC building by Lux meter.

Average illuminance measurements taken on 10th floor of NOC building by Lux meter (in Lux)				
Points (0.85m above the floor level)	**9:00 am (Morning)**	**11:00 am (Morning)**	**2:00 pm (Afternoon)**	**10:00 pm (Afternoon)**
P1	1820	1416	1520*	1520*
P2	570*	430*	797*	868*
P3	590*	596*	670*	715*
P4	415	515	1156	2125
P5	3452	2610	691*	615*
M1	615	312	171	150
M2	30*	20*	15*	17*
M3	61*	65*	75*	120*
M4	107*	103*	140*	150*
D1	1450	1320	1810	2450
D2	580*	605*	277	405
D3	480*	415*	200	275
D4	2672	1780	750	825.7
D5	485	650	1752	2840
D6	575*	605*	1727	3010

* Artificial light was on during measurement.

Appendix C: Average illuminance measurements with Lux meter, simulation, and variation analysis between on-site illuminance measurement and simulation results of 10th floor space of NOC building.– Continued

Table 13: Average illuminance results from simulation on 10th floor of NOC building in Lux

Average illuminance results from simulation on 10th floor of NOC building in Lux				
Points (0.85 above the floor level)	**9:00 am (Morning)**	**11:00 am (Morning)**	**2:00 pm (Afternoon)**	**10:00 pm (Afternoon)**
P1	1991	1361	1188*	1148*
P2	335*	237*	222*	359*
P3	339*	249*	225*	268*
P4	474	576	1303	2455
P5	4014	3087	468*	300*
M1	589	357	144	126
M2	36*	25*	10*	13*
M3	64*	76*	141*	436*
M4	80*	95*	120*	125*
D1	1239	1296	1722	2150
D2	283*	205*	268	321
D3	276*	220*	216	249
D4	2933	1653	684	709
D5	555	722	1981	3073
D6	340*	402*	2107	3577

* Artificial light was on during measurement.

Appendix C: Average illuminance measurements with Lux meter, simulation, and variation analysis between on-site illuminance measurement and simulation results of 10th floor space of NOC building.– Continued

Table 14: Variation between on-site illuminance measurements and simulation results in percentage

Variation between on-site illuminance measurements and simulation results in percentage				
Points (0.85 above the floor level)	**9:00 am (Morning)**	**11:00 am (Morning)**	**2:00 pm (Afternoon)**	**10:00 pm (Afternoon)**
P1	9.4	3.9	21.8*	24.5*
P2	41.2*	44.9*	72.1*	58.6*
P3	42.5*	58.2*	66.4*	62.5*
P4	14.2	11.8	12.7	15.5
P5	16.3	18.3	32.3*	51.2*
M1	4.2	14.4	15.8	16
M2	20*	25*	33.3*	23.5*
M3	4.9*	16.9*	88*	263.3*
M4	25.2*	7.8*	14.3*	16.7*
D1	14.6	1.8	4.9	12.2
D2	51.2*	66.1*	3.2	20.7
D3	42.5*	47*	8	9.5
D4	9.8	7.1	8.8	14.1
D5	14.4	11.1	13.1	8.2
D6	40.9*	33.6*	22	18.8

* Artificial light was on during measurement.

Appendix D: Summary of questionnaire response analysis.

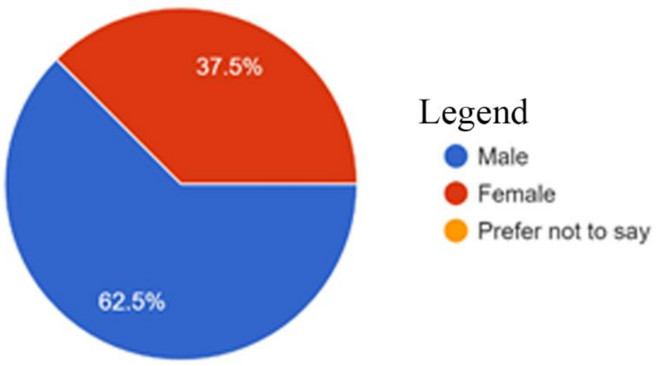


Figure 42: Gender distribution of respondents

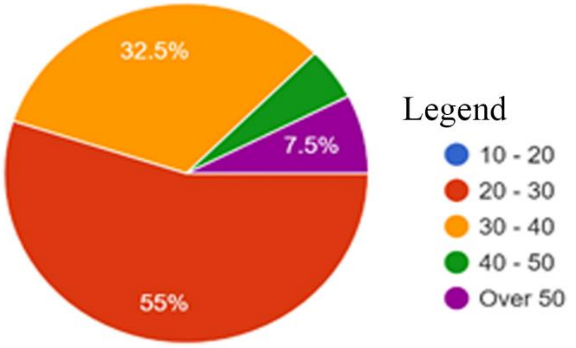


Figure 43: Respondent's age distribution

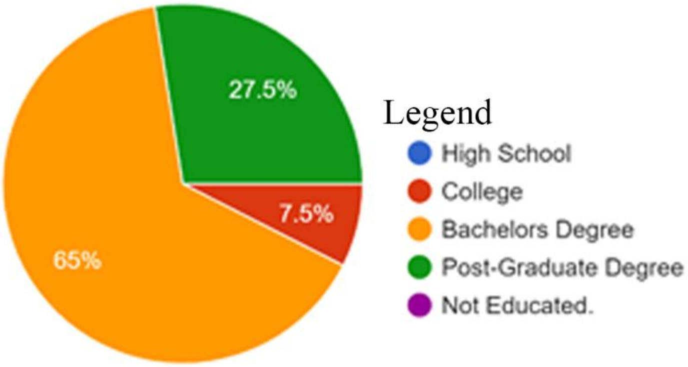


Figure 44: Respondent's education level summery

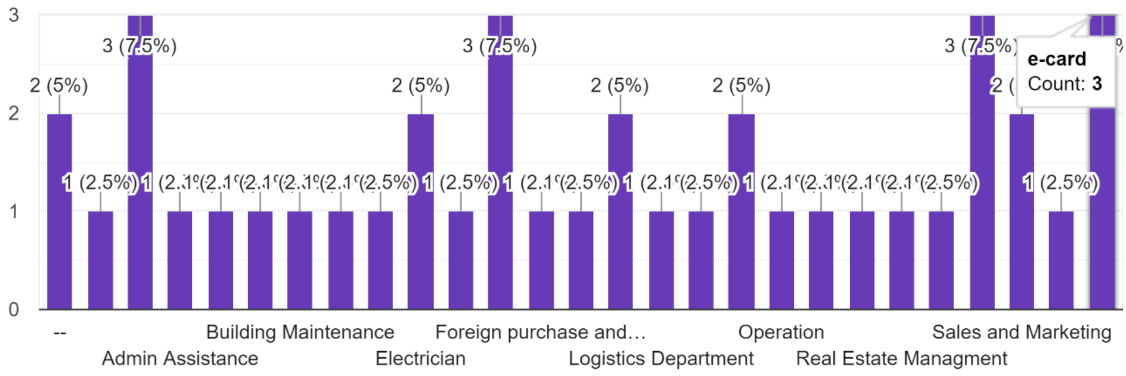


Figure 45: Summery for question: What kind of work do you do?

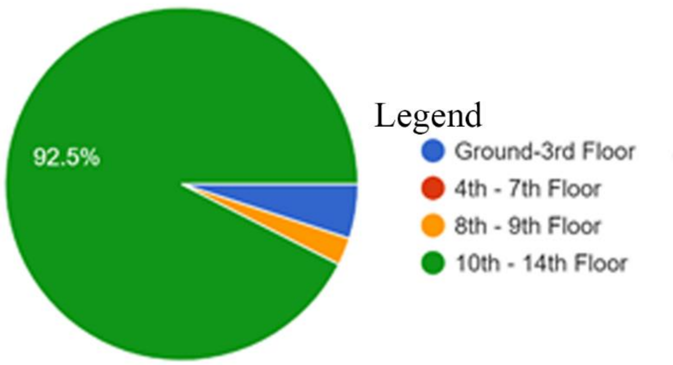


Figure 46: Summery for question: On which floor is your working space located?

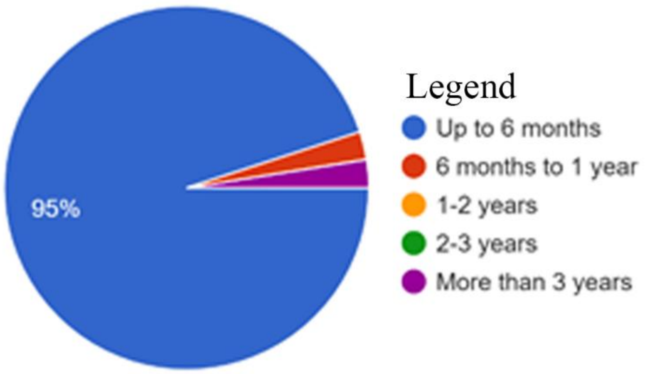


Figure 47: Summery for question: How many years/months have you worked in the building space you are working now?

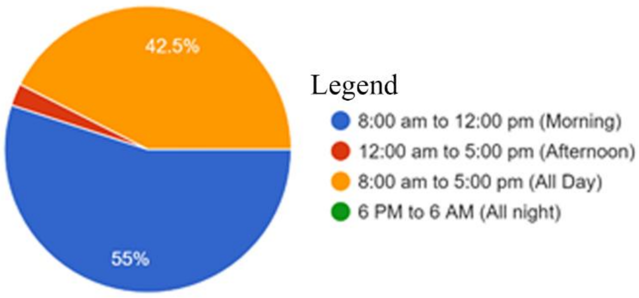


Figure 48: Summery for question: Which working hour better represents your active time?

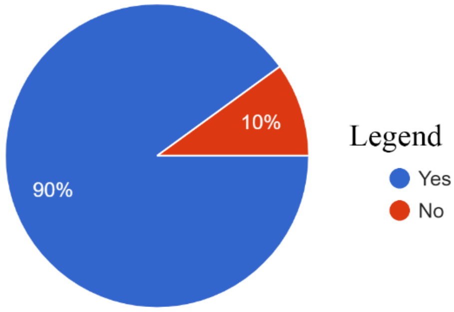


Figure 49: Summery for question: Does your working space have sufficient light for your work task?

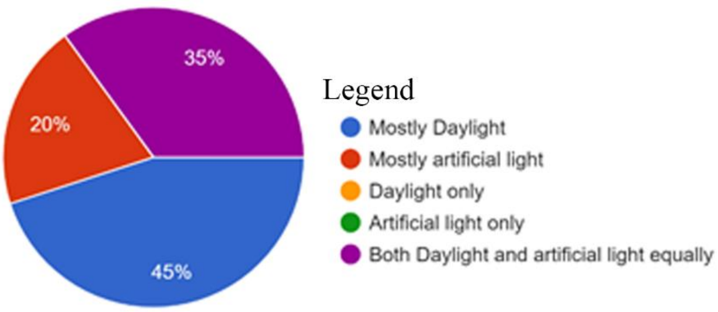
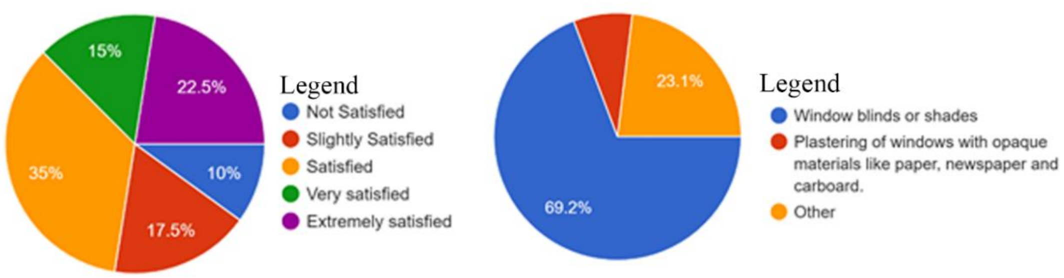


Figure 50: Summery for question: What kind of light source do you use to light your working space?



(a) (b)

Figure 51: Summery for question: (a)How satisfied are you with the amount of daylight in the space? (b) If you say "Not Satisfied" or "Slightly Satisfied" Which of the following, do you personally use to adjust to the situation?

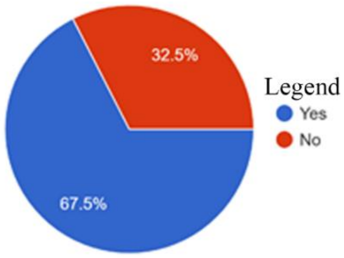


Figure 52: Summery for question: Does excessive bright daylight or glare create visual discomfort or affect your activity at work?

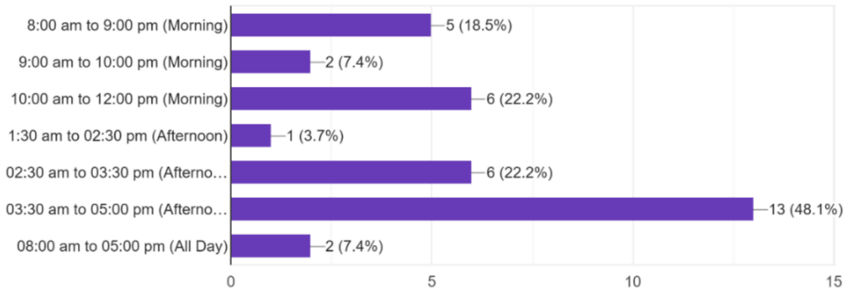


Figure 53: Summery for question: Which time of the day does the visual discomfort occur because of excessive bright daylight or glare?

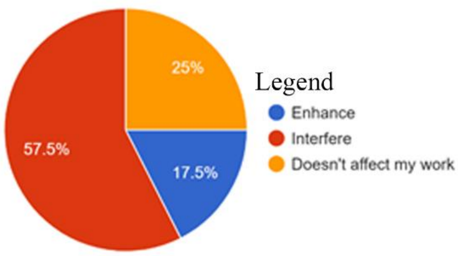


Figure 54: Summery for question: Does the daylight quality of your working space enhance or interfere with your ability to get your job done?

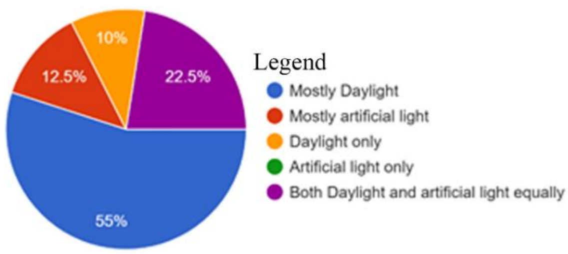


Figure 55: Summery for question: Which source of light do you prefer to have in your workspace?

Appendix E: Annual direct sun hour for National Oil Company (NOC) building.

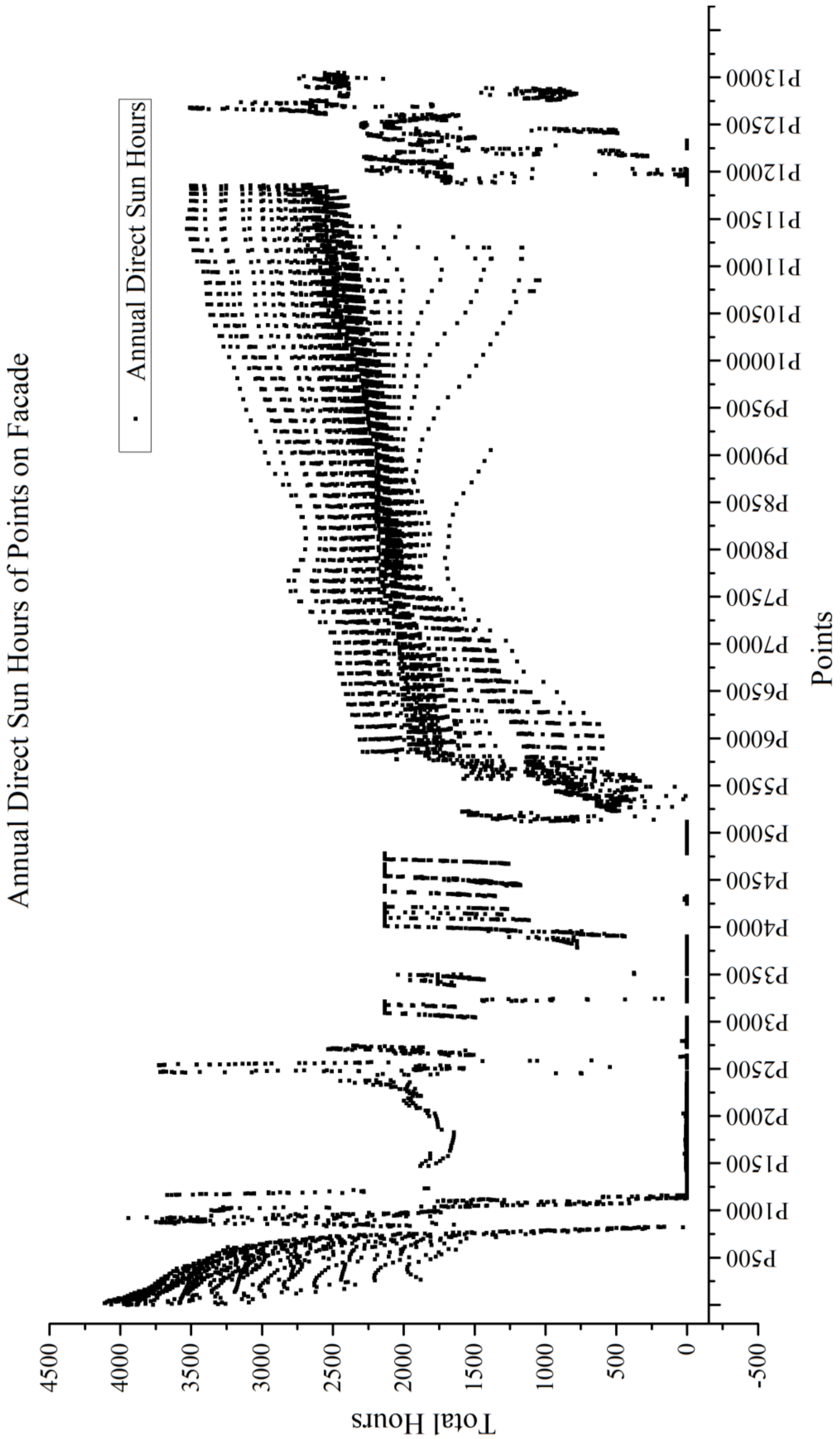


Figure 56: Annual direct sun hours oof points on facade.

Appendix F: Annual incident radiation of National Oil Company (NOC) building.

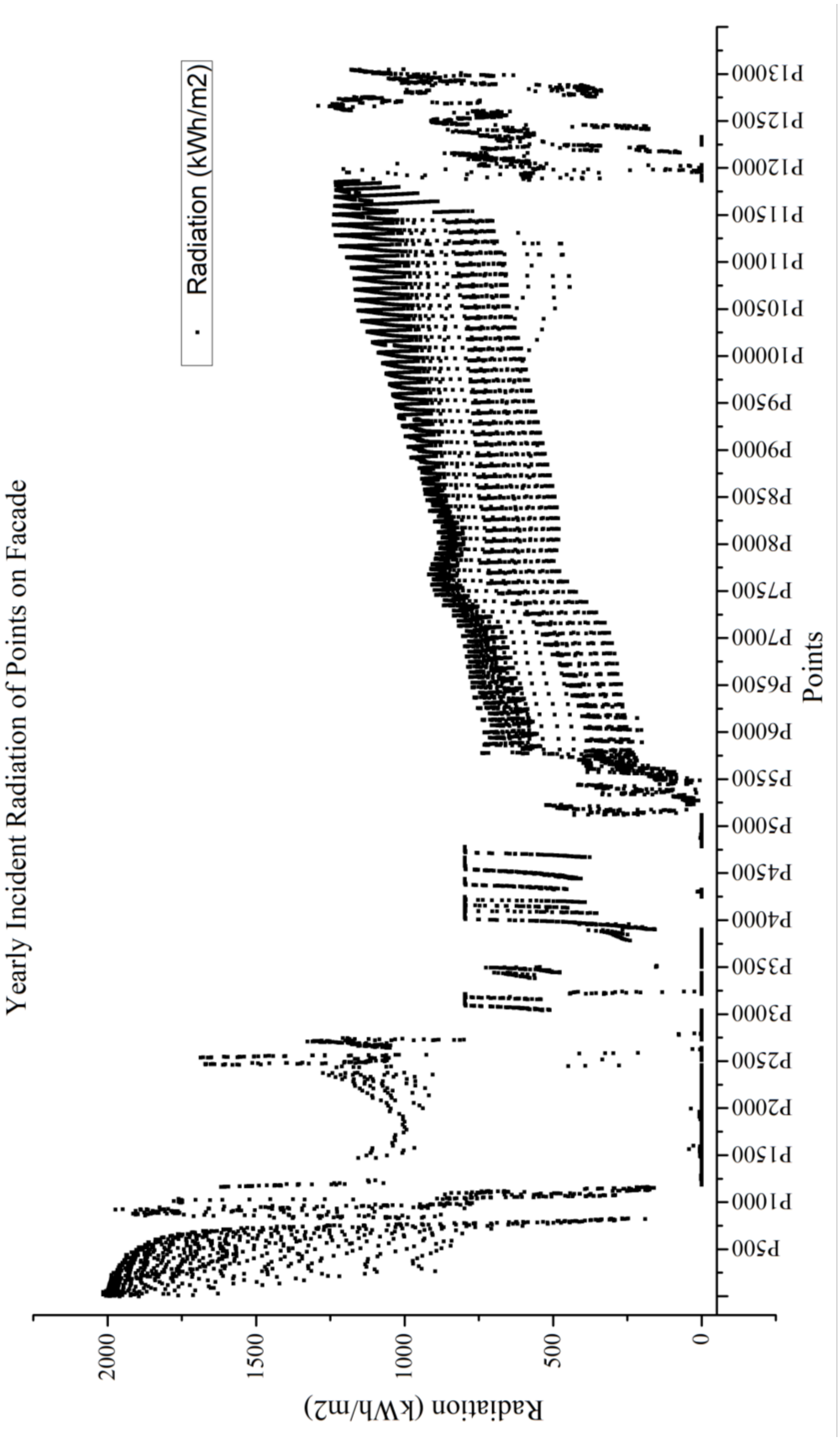
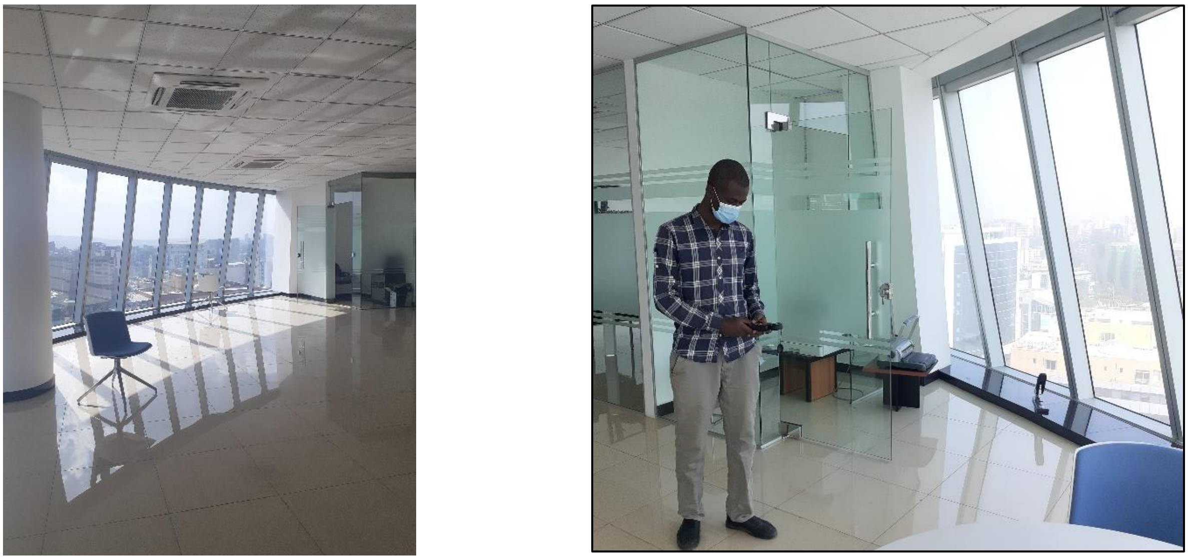


Figure 57: Yearly incident radiation of points on facade.

Appendix G: Exterior and interior building pictures taken during site visit.

(a) (b)

Figure 58: Exterior pictures of NOC building.



(c) (d)

Figure 59: Picture taken inside NOC building during measuring illuminance.

Appendix G: Exterior and interior building pictures taken during site visit.- Continued

(e)

(f)

(g)

Figure 59: Picture taken inside NOC building during measuring illuminance. – Continued

Appendix H: Lux meter specifications and calibration report

Specifications

Range	LUX/FC：1000、10000、100000
Accuracy	±(3%+5Lux) (at 2854°K incandescent lamps) ±(6%+5Lux) others Cosine angle deviation characteristics 30° ±2%; 60° ±6%; 80° ±25%
Calibration	Calibrated to a standard incandescent lamp at color temperature 2854°K
Resolution	1LUX/1FC
Sensor	Silicon photo-diode and spectral response filter
Operating conditions	Temperature:0～40°C，Humidity:<80%RH Altitude :<2000m
Storage conditions	Temperature:-10～50°C，Humidity:<80%RH
Sampling rate	Approx. 2 times per second
Spectral range	320～730nm
Auto power off	10 minutes
Power	3 x 1.5VAAA(LR03) batteries

Figure 60: Lux meter specifications

Appendix H: Lux meter specifications and calibration report. – Continued

Calibration / Test Report

HTC™
INSTRUMENTS

Features:

- Large Range up to 200000Lux
- Large LCD Display with Back Light and Bar Graph
- Auto Power Off
- MAX/MIN and Data Hold

Lux Meter - **HTC LX-103**
Instrument Serial No : H12A- D49221

HTC INSTRUMENTS MUMBAI

Basic Functions	Range	Resolution	Basic Accuracy
Measurement Range	0~200000Lux/ 0~20000FC	0.01Lux/0.01FC	+3%

Display	2000 counts	Analog Bar Indication	√
Auto Range	√	Manual Range	√
Auto Power Off	√	MAX/MIN Function	√
Relative Measurement	√	Peak Measurement	√
FC/Lux Unit Selection	√	Data Hold	√
Display Backlight	√	Low Battery Indication	√

- **Standard Accessory** : Battery, Carry Case & Manual
- **Dimension** : 170mm x 89mm x 43mm

HTC INSTRUMENTS
13-14 Turbhe Plaza, , Sector 27 Turbhe , Navi Mumbai - 400 705

Figure 61: Lux meter calibration report.