Study of the Effect of Light Emitting Diode (LED) on the Optimum Window-to-Wall Ratio and Whole-Building Energy Consumption in Open Offices

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ABSTRACT

Daylight harvesting is an essential strategy that is often used to enhance both the design and performance of an architectural project. Windows, as crucial architectural elements, not only admit natural light into spaces but also provide the occupants with visual connections. However, the excessive usage of windows brings an uncontrolled amount of solar energy to the spaces and negatively affect the building's energy performance.

When utilizing passive design strategies such as daylight harvesting, several factors, including the electrical lighting system, can impact the outcome. The current study investigates the role of the lighting system on daylight harvesting effectiveness and its impact on window dimension and total energy consumption. In this study, the optimum window-to-wall ratio of an open office in the presence of two different light sources (LED and fluorescent) is explored through a computer simulation method. A combination of tools including AGi32, ElumTools, OpenStudio, EnergyPlus, Radiance, and MATLAB helps to conduct the simulation and deliver optimal results.

In the results and conclusion chapter, the study provides specific guidelines to specify optimal window percentages considering two lighting system scenarios in each cardinal direction. Importantly, the guideline focuses only on energy performance and not on the spatial quality of the design.

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GENERAL AUDIENCE ABSTRACT

Harnessing daylight with the use of windows helps to offset parts of the electric lighting needs, and decrease the total building energy consumption. This is accomplished by using glazed materials to admit daylight and lighting control systems, which can respond to the dynamic light level. However, improper implementation of a passive daylighting strategy may cause increased energy consumption. Sunlight is accompanied by solar heat radiation which can increase the HVAC load of a space and compromise the energy savings achieved by daylighting. Therefore, a balance between solar heat and light gain is required to fully take advantage of solar energy without reverse impacts.

Concerning the mentioned balance, recent advancements in lighting technology question the effectiveness of natural light in reducing whole-building energy consumption. Due to the high energy efficiency of LED luminaires, lighting power consumption is rather low, even when the lighting system operates at full capacity. Therefore, it is unclear whether the solar energy coming through glazed materials works to the advantage or disadvantage of total building energy consumption. This study hypothesized that the total energy consumption of an open office with LED luminaires would be less in absence of solar energy compared to a scenario which utilizes the solar energy. A simulation-based methodology, using a combination of photometric computation and building energy simulation tools, was utilized to examine the hypothesis and explore the impacts of lighting systems on the optimum window-to-wall ratio.

The results provide a helpful guideline which highlights the impact of lighting systems on window dimensions and their mutual effect on whole-building energy consumption. Although the optimum window-to-wall ratios suggested by this study only concern energy consumption, integration of them with occupants' preferences can propose an acceptable window-to-wall ratio that satisfies both design quality and performance of a building.

Dedication:

I want to dedicate this book to my loving parents, Farahnaz and Hasan, who have been by my side every step of the way. They taught me to be strong, ambitious, and hard-working and I would not be the person I am today if it was not for their support, guidance, and encouragement.

Thank you for the love you gave me all these years.

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Chapter 1 : **Introduction**

1.1 Background

Given concern regarding harmful effects of fossil fuel on the environment, along with the unavailability of fossil fuel resources for an infinite time, recent attention has focused on the importance of energy savings. Since the global movement toward a more sustainable environment has begun, two primary strategies have been proposed and exerted all over the globe. First, research has begun to investigate renewable energy resources, which can substitute for fossil fuel resources. Second, with advancements in technology, lower fossil fuel consumption has been proposed, as green solutions are being employed in different industrial fields to reduce energy consumption.

As one of the major energy-demanding sectors, building construction plays a significant role in the energy consumption pattern. Among various building types, construction of commercial buildings has displayed drastic growth over the last few years. Each year, approximately 1.6 billion square feet of commercial development is constructed, which is comparable to 110,000 buildings per year or half of a million buildings every five years [1]. According to the US Energy Information Administration (EIA), in 2016, 19% of the total energy consumption in the United States was devoted to commercial buildings, which accounts for 18% of the carbon dioxide (CO2) emission [2]. The majority of this energy is used for space heating, space cooling, and lighting, which are associated with internal and external loads. Commercial buildings are responsible for about 30% of US electricity consumption, of which 15% accounts for lighting [3]. As a result, daylighting strategies through fenestration can significantly impact lighting energy reduction. On the other hand, the Lawrence Berkley National Laboratory estimated 34% of commercial building energy use in the US is window-related, and energy-efficient fenestration design can save between 10%-40% of the whole energy consumption based on climate [4]. According to these records, a critical amount of energy could be saved by implementing energy conservative strategies in building design and construction. In recent years, numerous studies have explored the energy-saving potentials in various building categories. Findings from these studies on energy optimization have contributed to substantial advancements in building technology and energy science.

Among building categories, lighting has demonstrated rapid improvement during the past few years. This was measured by tracking the transition from energy-inefficient incandescent light sources to compact fluorescent lights and then light-emitting diode (LED) with very high efficacy. According to Khan and Abas, a 23-Watt compact fluorescent(CFL) light bulb produced the same luminous flux as a 100 Watt incandescent bulb. CFL consumes 2-5 times less power and lasts 8-10 times longer than incandescent light bulbs [5]. Also, switching to LED luminaires, which are semiconductor-based light sources, over the next 20 years would result in a deduction of approximately 2700 terawatt-hours of electricity and 1800 million metric tons of carbon emissions while providing nearly $250 billion savings in energy costs nationwide [6]. Research conducted by Jenkins et al. in the UK, estimated that energy savings of 56–62% could be achieved in a typical 6-story office building by changing the fluorescent luminaires to LED luminaires [7]. Also, integrating the lighting with the HVAC and other building systems can effectively reduce the building's reliance on fossil fuel. Moreover, adopting passive solutions such as utilizing natural light and its integration with artificial light can significantly improve building performance.

Glazing material is another building element that has shown significant advances during the recent years. Specifically, transparent glazing materials embedded in windows allow natural light into the

spaces and provided better views for occupants. The operable window systems also allow for natural ventilation and higher indoor air quality. As a result, window openings have a highly influential role in improving space quality. They are considered one of the crucial building elements required for occupants' mental and physical health. Other than their qualitative benefits, high-performance glazing systems with higher R values help to improve the thermal comfort and building energy performance by reducing energy transfer through the glazed surfaces. The generation of high-performance glazing materials allows designers to increase window areas with less negative effects on whole-building energy consumption.

Since a building is a collection of multiple interconnected systems, changing one building component impacts various related components. For instance, improving the lighting system can open capacity for a higher window-to-wall ratio (WWR) while maintaining energy consumption. Alternatively, improving the glazing material can significantly impact the WWR without changing the lighting system. Importantly, changing each of these building components can distinctly change the whole-building energy equation. It is essential to understand the complicated interaction between building systems and utilize strategies to improve the energy consumption by meaningful integration of these systems. One important example of this interaction is between the lighting system and WWR.

1.2 Problem Statement:

Since the earth's formation and the evolution of organisms, the sun has been the most critical element vital to maintaining life. Living organs need sun for their growth and subsistence; human beings are no exception. Throughout history, from the Stone Age to modern civilization, human beings have adopted various methods for utilizing the light and heat of the sun. For instance, primitive people who dwelled in caves took advantage of the light coming through the cave entry hole. Later in history, before the invention of electricity, architects used daylight to give spiritual qualities to their spaces while providing the necessary level of lighting needs for living. In our contemporary era, designing of openings to take advantage of solar energy in the building construction and architecture field is among the passive design solutions which proven to effectively reduce energy consumption and CO2 emission.

Aside from the energy viewpoint, daylight is considered to be crucial for human health, as it provides Vitamin D for the body, prevents seasonal depression, improves sleep, and reduces stress. These are only the basic effects of natural light on human health. Exposure to daylight and darkness helps to regulate the human body with the circadian rhythm. According to Cuttle, 99% of employees (n=471) that participated in a survey reported that having windows in offices is essential, and 86% preferred daylight over electrical lights [8].

Given the benefits associated with daylighting, careful consideration should be given when utilizing daylight in the design, as infrared radiation that accompanies visible light works bidirectionally. Heat gain through the glazed surfaces during hot periods increases the cooling load, while heat loss during the cold periods increases the heating load. As a result, improper implementation of daylight harvesting strategies can produce a negative effect. Thus, the balance between heat transfer and light gain through the glazed surfaces is a critical factor to maintain acceptable building energy performance. The percentage of WWR is one potential solution to maintaining this balance. It is important to examine the degree WWR can be affected by different systems in the building.

1.3 Research questions and Hypothesis:

As previously outlined, different influential factors can impact the extent of passive design solutions' efficiency, including electrical light sources, Window-to-wall ratio, and building orientation. The type of light source impacts the overall energy consumption of the building. The development of lighting industry in recent years has led to the introduction of Low Emitting Diode (LED) lamps with higher efficacy than previously utilized artificial light sources. Window-to-wall ratio, which can express the balance between heat transfer and light gain through the glazed window surfaces, is another parameter that significantly affects building performance and energy efficiency. WWR depends on myriad factors such as glazing material, wall construction layers (thermal performance), and climate zone. Finally, due to the change of sun angle at different hours, spaces facing each cardinal direction experience varying energy consumption patterns, making geographical orientation another factor that affects the passive strategies.

It is hypothesized that the overall energy savings achieved by using LED lighting system in the absence of daylight (window openings) may exceed the energy savings achieved by the combination of the same light source with natural light. As a result, it is imperative that the scope of daylighting effectiveness in the presence of efficient LED light sources be tested. This will significantly add to the existing literature in this field, given that research has not yet determined the specific changes that occur to the optimum window-to-wall ratio in the presence of LED light sources.

1.4 Research Goals and Objectives:

To fill the gaps in the literature and address the research questions, this research intends to study the effect of three variable parameters including type of light source(x_1), window-to-wall ratio(x_2), and cardinal direction (x_3) on the energy consumption of the perimeter zone in the third floor of Cowgill Hall in Blacksburg.

- The results provide new recommendations and guidelines regarding the optimal value for the WWR of open offices with an LED lighting system.

- The energy pattern over a range of different WWR, help to choose the appropriate window ratio with regard to other design aspects. For instance, integrating the occupant's preferred WWR with the energy-based optimum WWR can suggest a final percentage that satisfies both design aspects.

- The illumination map from the Radiance daylighting calculation in each WWR alternative provides a useful guide to locate the furniture in the space. The furniture layout in the space is a function of the window position and dimension. Hence, moving toward optimum WWR can change the entire layout of open offices and make the spaces more efficient.

- Comparing the energy consumption of LED and fluorescent scenarios with different WWR assists in examining their relationship. This relation can be translated into a formula that can estimate the WWR for one light source based on information of the other light source. For instance, if the formula is fed by the LED WWR value, it can estimate the WWR value for the fluorescent case.

- The results will provide energy consumption associated with each of the space cooling, space heating, and lighting categories. As a result, monitoring the changes in each category

throughout all the scenarios will reveal the one responsible for the most change in final energy results.

1.5 Limitations and important assumption

The current study evaluates various window-to-wall ratios in the presence of each light source only based on energy consumption. As a result, the physical and mental effects of daylight and view on occupants have not been considered. Thus, optimal values proposed at study completion may not be the ultimate best solution for designers.

Since the experimental method is costly, time-consuming, and complicated, computer simulation will be used to deliver the results. Given that the simulation method could not exactly and precisely represent the actual condition, a certain level of deviation from reality should be expected. The software limitation discussed in the methodology chapter can be partly responsible for this deviation.

The study has many parameters, and changing any combination of these can greatly impact the results. Except for the three variables of interest, all other parameters will be given standard fixed values. The results of the study are applicable and can be generalized to spaces with similar parameters and climate zone.

Chapter 2 **: Literature Review**

In order to build a proper body of knowledge in the field, it is essential to review previous research in the area. The literature review helps to identify the problem and define the research question. In this chapter, the reviewed articles are organized chronologically under three main topics that cover the findings, theories, enhancements, and limitations related to the subject. Credit goes to the following researchers whose investigations provided the background for this study.

2.1 Window-to-wall Ratio

1) **Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: A literature review**
   (Galasiu, Veitch, 2006)

This paper reviewed over 60 articles to highlight the findings and research gaps related to two main themes:

1. Occupant's preferred daylight illumination level in offices
2. Occupants' response to electric lighting and shading controls linked to the available daylight

According to the peer-reviewed manuscripts, most employees included in the study preferred daylight over electrical light based on their presumptions that daylight impacts their health. These presumptions were associated with overestimation regarding the daylight contribution to space illumination. As a result, most of the employees preferred larger windows. Regarding shading and lighting control, findings revealed that the manually operable shading devices were rarely changed once they had been set. However, occupants still preferred a level of control over the shading devices and lighting levels. The results indicated that the photocontrol lighting and shading systems were accepted only if they provided partial control for employees. The simplicity of operation was another factor in whether automated shading and lighting systems were used. Complicated systems had a low acceptance rate among the employees and facility managers who participated in the study.

2) **Innovative window design strategy to reduce negative lighting intervention in office buildings**
   (Amirkhani, Garcia-Hansen, Isoardi, Alla, 2018)

Results from this study indicated that luminance contrast (LC) between a window and its surrounding walls resulted in intervention in the lighting system. In space with high LC, occupants often switched the lights on to reduce the contrast. When the window-to-wall ratio was lower, higher contrast would occur. Luminance Contrast that fell inside the occupant's field of view or on top of the occupant's desk increased the tendency to change the lighting condition and led to more energy consumption. According to the Heschong Mahone Group Inc., occupant's behavior could reduce the predicted daylight energy savings of an office building by 75% [9]. In this regard, observation on 123 buildings reported that a high luminance contrast in a wall instigated occupants to switch on the lights by 60% to achieve visual comfort[10]. To decrease the luminance contrast in walls with windows, Amirkhani, and colleagues (2018) suggested to locate a linear wall washing luminaire around the window frame.

The research also investigated the relationship between window-to-wall ratio and wall-washing luminaire power level, as well as the effects of power level and WWR on the luminance contrast and occupants 'lighting satisfaction. An experiment was carried out with the aid of virtual reality technology. Participants were asked to complete a questionnaire based on their observations in 4 office rooms with different window-to-wall ratios and luminaire power. Results indicated that "The majority of participants in the current study (54.7%) preferred a combination of daylight and electric lights in their workplaces, and about one-third (34%) preferred to work under daylight only. Approximately 15% of participants were very satisfied with indoor lighting level when their LC rankings on the window wall were "*very high contrast*," while approximately 42% of participants were very satisfied when their LC rankings on the window wall were "*very low contrast*." On the other hand, roughly 51% of participants were very dissatisfied with the indoor lighting level when they reported very high LC on the window wall, while almost 28% of participants were very dissatisfied when they reported *very low contrast* on the window wall"[11].

This study highlighted the effect of luminance contrast on lighting energy consumption. It is important to remember that a low window-to-wall ratio increases the LC and lighting energy consumption. However, the solution proposed by these researchers lacks sufficient evidence to conclude that adding wall-washing luminaires that consume power can still save more energy than occupants' intervention in the lighting level.

3) **The Optimum Window-to-Wall Ratio in Office Buildings for Hot-Humid, Hot-Dry, and Cold Climates in Iran**
(Shaeri, Habibi, Yaghoubi, Chokhachian, 2019)

Shaeri et al. investigated the optimum window-to-wall ratio of an office building with regard to different climate zones and cardinal directions, utilizing a simulation method (DesignBuilder). Three cities with distinct climate zone were selected in Iran with Shiraz being in a hot-dry, Tabriz in a cold, and Bushehr in a hot-humid climate zone.

According to Persson et al. the effect of the optimal window-to-wall ratio is low for heating loads and very high for cooling loads. Contrary to general knowledge, which does not consider the North façade ideal for daylight harvesting, the larger window areas in the north side not only can provide sufficient lighting level but also result in less HVAC energy consumption. [12] The literature review in this study reveals that the WWR is strictly associated with the climate zone and based on their location, buildings might have a different window-to-wall ratio. For instance, a study in Rome stated that the optimal WWR is between 35%-40% while a study in another part of Europe suggested the optimal percentage to be between 30%- 45%[13][14].

Four metrics including Solar heat gain, Heating load, Cooling load, and lighting load, were monitored in this study. Researchers concluded the following:

- The solar heat gain in all cities increased by increasing the WWR.
- The cooling load in North and South orientations first decreased by moving from 0% to 10% WWR and then began to increase from 10% to 100% WWR. In East and West orientations, the cooling load stayed steady from 0% to 30% WWR and then began to increase from 40% to 100% WWR.

- The heating load exhibited a diverse pattern for each orientation. In the North, the heating load had its peak value in 20% WWR and started to decrease by increasing the WWR. In the South, the heating load had its peak value at 10% WWR and began to drastically decrease with increasing the WWR. The East and West orientation had more smooth changes with different patterns for each city.
- The lighting Load generally had a reduction pattern through increasing the WWR with a steeper slope in the North and South orientations, especially when moving from 10% to 20% WWR.

In general, the optimum WWR fell within 20%-50% in all cities. Shiraz and Bushehr, with hot climates, had closer WWR, while Tabriz, with a cold climate, had higher percentages of WWR.

4) **Effect of window-to-wall ratio on measured energy consumption in US office buildings** (Troup, Phillips, Eckelman, & Fannon, 2019.)

According to Lawrence Berkeley National Laboratory, 34% of commercial buildings' energy consumption is window-related. Moreover, the US energy information administration stated that in 2016, 19% of the total annual energy consumption was related to the commercial division, accounting for 18% of that year's CO2 emission. These results indicate the great importance of exploring the window contribution to energy consumption. Between 10% to 50% of energy could be saved in load-dominated buildings by optimization of glazed surface ratio and utilization of energy-efficient glazing types. A highly-developed fenestration system could result in 10% to 40% savings in HVAC energy consumption[16].

This article used data from the commercial building energy consumption survey (CBECS) to evaluate the effect of the window-to-wall ratio on total annual energy use along with the heating, cooling, lighting, and ventilation loads. Unlike most other studies that utilize iterative simulation methodology, this study investigated the topic by big data analytics. CBECS provided simplified characteristics of commercial buildings and correlates them with energy consumption. Linear and multi-linear regressions were used to forecast the relation of each building's characteristics with end-use energy consumption. Twenty-eight building characteristics, including exterior glazing percentage which was divided into seven range, were chosen as independent variables. A population of interest was defined to represent the original number of buildings. The characteristics of these buildings were considered as independent variables, which were then applied to the following single and multi-linear regression equations to attain the 5 dependent variables including total energy use and total end-use for heating, cooling, ventilation, and lighting.

$$Y = \beta_0 + \beta_1 X_1 + \cdots + \beta_n X_n + \epsilon$$

β_0: Intercept of the model

β_1: Coefficient of independent variable x

ϵ: Residual or errors of the mode

n: Number of independent variables

Results utilized information from 1212 buildings included in the equation, which was representative of the actual number of buildings in the survey. The average total energy consumption was suggested by the regression as 130 kBtu/ft2, which is divided into several divisions as follows:

-30% for envelope independent usage (office equipment, computers, etc.)

-11% for lighting

-14% for ventilation

-8% for cooling

-32% for heating

-5% for minor electricity usage (refrigerator, cooking, etc.)

Outcomes of the study demonstrated that the median for cooling and heating load increased as the glazed percentage increased. In contrast to expectations, by increasing the glazed percentage, the lighting median also increased. Otherwise stated, more glazed surfaces did not lead to less lighting energy consumption. The current results could slightly stand against the common belief that more window area that let in more natural light decrease the electrical lighting and energy consumption. However, it should be noted that the 2012 CBECS data, which was considered as the basis for this study, was not completely accurate. For instance, envelope performance details and characteristics such as the R-value of the walls and glazings were not included in the data. As an outcome, results are rather crippling to precisely explain the phenomenology of the numbers.

The proposed research seeks to explore an explanation for the lighting result delivered by the current study. Studying the effects of glazing percentage on energy consumption and exploring a glazing-less scenario may help to better understand the relation between energy consumption and glazing percentage[15].

2.2 Electrical and Daylight Integration

5) **Effects of Daylight Controls on Electric Lighting Energy Consumption**
(Karaguzel and Lam, 2012)

This study examined the effect of the daylight control system on lighting energy savings in open offices. Karaguzel and Lamutilized the simulation method to evaluate the lighting performance of nine office spaces with different simulation parameters. The EnergyPlus Detailed daylighting calculation method was used as the simulation engine. The geometry and building features were set up in the Design Builder which is a Graphical User Interface for EnergyPlus.

The main simulation parameters that were manipulated in the design alternatives included:

1. Lighting Power Density
2. Building enclosure
3. Ambient-Task lighting separation
4. Target illuminance

The table below shows a summary of each design alternative:

Table 2.1: Lighting simulation model alternatives

Model Name	Ambient – Task Lighting Separation	LPD Ambient (W/SF)	LPD Task (W/SF)	Daylight -Linked Controls *	Control Parameter-1 Illuminance Set-point - Lux	Control Parameter-2 DGI** Set-point	Controlled Element Against Glare	Window Type***

Baseline _Alt01	Connected	1.0		No	N/A	N/A	N/A	Single Clear R-value (IP) =1.0 SHGC= 0.861 Vt= 0.898 Vt/SHGC= 1.04
Alt_02	Connected	2.0		No	N/A	N/A	N/A	
Alt_03	Separated	0.50	0.25	No	N/A	N/A	N/A	
Alt_04	Separated	0.50	0.25	Yes	500	22	Interior Roller Shades	
Alt_05	Separated	0.50	0.25	Yes	250	22	Interior Roller Shades	
Alt_06	Radically Separated	0.25	0.25	Yes	21.5 (Moonlight)	22	Interior Roller Shades	
Alt_07	Connected	1.0		No	N/A	N/A	N/A	Dynamic Double Low-e Argon Winter R-value (IP) =4.9 SHGC =0.50 Vt= 0.745 Vt/SHGC = 1.49
Alt_08	Separated	0.50	0.25	No	N/A	N/A	N/A	
*- Daylight-linked controls are affecting ambient lighting only where task lighting operates on a fixed schedule.								
**- DGI (Discomfort Glare Index) – Each view angle for each daylight sensor is adjusted to simulate occupants view direction is to the windows.								
***-Windows of Alt_06 and Alt_07 are equipped with an external shading element (Roller Shade – Light) operated with a seasonal schedule to provide dynamic SHGC to the glazing. Sumer Time values are R-value (5.1), SHGC (0.20), Vt(0.275), Vt/SHGC (1.36)								

Since the one-Step-at-a time method (OAT) was used in the study, each alternative represented the distinct effect of one simulation parameter named above. The authors took specific result metrics to evaluate the effect of each simulation variable on the lighting energy consumption, which included Interior lighting energy consumption, Lighting energy share, Operational lighting energy, Daylight autonomy, Peak interior lighting load, Total energy consumption, Space heating energy, Space cooling energy, and space heating and cooling design load.

Karaguzel and Lam concluded that reduction in LPD and separation of task light and ambient light (Alternative 6) resulted in the largest lighting energy savings among the nine design alternatives. Generally, the reduction in LPD had the most significant effect on energy savings. Meanwhile, the incorporation of the daylight control sensors was found to save up to 19.6% lighting energy in comparison to a non-controlled alternative. Also, decreasing the target illuminance level had minor effects on lighting energy consumption. High-performance glazing materials for windows solely can lead to an 8.8% reduction of whole-building energy consumption without changing the LPD or using daylight sensors. It was also highlighted that separating the task-ambient light (with LPD of 0.25 W/ft2) with a combination of a high-performance building enclosure and daylight control sensors can save up to 57% of annual whole-building energy consumption [17].

6) **Effect of LED lighting on the cooling and heating loads in office buildings**
(Ahn, Jang, Leigh, Yoo, Jeong, 2014)

Ahn, Jang, Leigh, & Yoo proposed a strategy to effectively increase building energy performance through the integration of lighting and the HVAC system. According to Ahn and colleagues (2014), although the new generation of light sources such as LED or fluorescent lamps are energy efficient, still 75% to 85% of electrical input into these sources turned into heat. Given that 20% to 40% of the entire building energy consumption is accounted for by lighting, the heat produced by lighting sources increases the cooling load and causes more CO_2 emissions [18]. All the heat generated by LED sources is in the form of convective heat and could fully be collected in a heatsink. Ahn and colleagues (2014). suggested adding another heatsink to the light fixtures to enable them to perform in both cooling and heating periods. To elaborate the mechanism, one of the heatsinks was placed inside the returned air duct and the other inside the space. This way, the heat generated by the light source could be collected inside the return air duct and could be removed easily to cause a reduction in the cooling load. Also, the heatsink exposed to space acted as a radiant heat source in the heating periods and therefore, helped to decrease the heating load. To assess the proposal, an experiment was carried out in a green building in Korea and in a virtual none-high performance building in the United States. Results showed an overall 3.01% and 9.27% reduction in the total end energy use of green building and virtual building, respectively. The statistics and numbers presented, either in this study or sources cited in the study, demonstrated data on energy savings potential to the general body of knowledge. The methodology of categorizing various iterations and providing gradual steps to reach the results was also inspiring [6].

7) **Assessing the Effects of Glazing Type on Optimum Dimension of Windows in Office Buildings**
(Moorjani and Asadi, 2014)

Moorjani and Asadi (2014) studied the effect of three types of glazing systems including single-glazed, Double-glazed(air-filled), and Double glazed with Low-E coating (Argon-filled), along with the orientation on the layout and optimum window dimension of an office room located in Dallas, Texas. EnergyPlus engine along with Rhinoceros/Grasshopper interface was utilized to simulate the model. The Genetic and Simulated Annealing algorithm were used to optimize the size and layout of the windows.

After running the simulation and delivering the optimum values for each orientation and type of glass, it was concluded that the optimum WWR generally was very small (about 6.4% to 18%).

Table 2.2:Optimum Glazing Dimension

Orientation	Glazing Type	Optimum Dimension		
		Width (m)	Height (m)	Area (m)
South	Single-glazed	0.7	1.2	0.84
	Double-glazed	1.22	0.92	1.12
	Low-e	1.2	1.0	1.2
East	Single-glazed	0.8	1.2	0.96
	Double-glazed	1.22	1.12	1.36
	Low-e	1.4	1.1	1.54
West	Single-glazed	0.7	1.1	0.77
	Double-glazed	1.02	1.02	1.04
	Low-e	1.2	1.0	1.2
North	Single-glazed	1.1	1.2	1.32
	Double-glazed	1.53	1.22	1.86
	Low-e	1.8	1.2	2.16

In the next step, the optimum window dimension for each scenario was used to calculate the whole-building energy consumption of the office room. Results indicated that changing the glazing system had more impact on space heating energy than space cooling and lighting energy. The application of the simple double-glazed system and the low-E coating double-glazed system increased the total R-value of the room, which resulted in a reduction of the heating load both in day and night during the winter. However, it increased the cooling load at night while decreasing it in days during the summer. The results also indicated that the total energy consumption savings associated with the glazing system are not significant when using the optimum window dimensions in the model. However, by increasing the WWR, the effect of the glazing system was more noticeable[1].

8) **Low-energy LED lighting heat gain distribution in buildings, part 1: Approach and pilot test**
(Liu, Zhou, LOCHHEAD, Zhong3, Huynh, Maxwell, 2017)

Lighting heat gain is one of the main contributors to the cooling load. Thus, it is important to understand the luminaires' heat distribution pattern, which further helps to have a concise estimation of the HVAC sizing. ASHRAE handbook of fundamentals provides a table with values associated with radiative and convective heat fraction of luminaires. However, most of these data are related to fluorescent luminaires and there is a lack of information about the fraction values for LED luminaires.

This paper studied the heat distribution pattern of 14 LED luminaire types including High bay, Troffer, Linear pendant, and Downlight through a systematic experimental method to fill the information gap related to LED luminaires in the ASHRAE Handbook of fundamentals. The study has been presented in two papers; part I included the test approach and experiment set up, while part II presented the LED thermal distribution results.

Radiation and convection are the main forms of heat transfer in lighting systems. According to the ASHRAE 2013a, heat gain through conduction can be ignored in the lighting thermal calculation. The heat gain through convection is an instant addition to the cooling load while the heat gain through radiation has a time lag effect on the cooling load because it takes time for the radiative heat to be absorbed by the surfaces in the space. According to the 2013 ASHRAE Handbook, there are two methods for cooling load calculation:1. Heat Balance 2. Radiant Time series. This study took the HB method which is more accurate than RTS in many aspects.

The remainder of the paper detailed the features of the chamber, the equipment used for radiative heat calculations (radiometer), dimensions, etc. The results presented in the second part of the study were included in this chapter[19].

9) **Low-energy LED lighting heat gain distribution in buildings, part II: LED luminaire selection and test results**
(Liu, Zhou, Lochhead, Zhong3, Huynh, Maxwell, 2017)

As previously stated, the research aims to determine the split between convective and radiative heat fraction of different types of LED luminaires and the split between conditioned space and ceiling plenum heat gains.

Based on results, between 40% to 60% of the input power in recessed LED luminaires turned to heat gain in conditioned space while this fraction for high efficacy troffer luminaires ranged between 43% to 53%. The radiative heat fraction for most of the recessed luminaires was calculated between 30% to 42% of the lighting input power. This amount was 51% for high efficacy troffer and 16% for the downlight luminaires. In the suspended LED luminaires, the amount of radiative heat gain was recorded 42% to 51% of power input and for the linear pendant, it was recorded 55% to 61% of power input. Results indicated that the Recessed luminaires emitted less radiative heat than the pendant ones. It should be mentioned that the values reported above are in contrast with the chart the US Department of Energy has published on its website which considers 0 radiant heat fraction for LED sources.

After delivering the heat conversion fraction for each of the 14 luminaires, 4 of them were chosen to evaluate the effect of supply airflow, supply air temperature, dimming control, floor finish, and return air configuration on the LED heat gain.

Among all the factors above, return airflow and supply air rate had the most impact on the LED heat gain while the floor finish and dimming control had the minimum impact on the heat gain. As could be predicted, increasing the supply airflow rate and implementing the return air duct reduced the radiant and convective heat fraction emitted from LED luminaires [20].

10) **LEDs for lighting: Basic physics and prospects for energy savings**
(Gayral, 2017)

This manuscript provided a brief history of LED light developments, their physics, energy savings, and other features. The following highlights the most relevant findings.

In a brief introduction, LED is a semiconductor light source that emits light through the mean of current flow. When an electric current path through a semiconductor, the unstable electrons move from N-type semiconductors to fill a hole in P-type semiconductors, to become stable. This flow of electrons releases energy in the form of visible light.

Until 2014, one primary LED limitation was its color. LEDs were produced only in red and yellow colors. However, scientists realized that to produce a white-colored LED, they need to produce a blue LED.

In 1981, a scientist, Isamu Akasaki, and his student, Hiroshi Amano, made some progress on enhancing one of the chemicals (GaN) used in an LED semiconductor. Simultaneously, another scientist, Shuji Nakamura, built upon findings from Akasaki and Amano's by improving the GaN epitaxial layer. This work later led to the emission of the blue-violet range in LED lights. The key invention of Akasaki and Amano, along with further enhancements of Nakamura, led to low-cost production of high-quality blue GaN/InGaN, which was then surrounded by a phosphor shield to manufacture white LED sources. Since then, LED light bulbs have become commercially available at a reasonable price and have become one of the most economical light sources to provide low-energy cold and warm colors.

Despite the advantages of LED over CFL and Incandescent bulbs, they work under continuous low-voltage current, which requires buildings to be equipped with DC low voltage circuits that drive LED lamps without needing an AC to DC converter energy losses [21].

2.3 Energy Modeling and Daylight Simulation Software

11) **Challenges to Integrated Daylighting and Electric Lighting Simulation Methods in a Whole-Building Energy Simulation Context**
(Guglielmetti and Scheib, 2012)

In this study, Guglielmetti and Scheib (2012) categorized the lighting simulation algorithms, methods, and tools while proposing the technological gap in the integrated daylighting simulation. EnergyPlus and Radiance were explored as two rigorous whole-building and daylighting simulation tools.

In chronological order, several algorithms for daylighting calculation were introduced and explained, including Split-flux, Radiosity, Backward Raytracing, and Forward Raytracing. EnergyPlus proposed two methods for daylighting simulation:

1.DElight 2. Detailed

The Detailed method used the Split-flux algorithm based on reflected illuminance from the space components. In this method, the daylight transmitted by the window was divided into downward traveling flux and upward traveling flux.

DElight is a more accurate version of the detailed method with interreflected calculation enhancements. The delight method uses the Radiosity algorithm which presents the most accurate interreflected illuminance among all the other lighting simulation algorithms.

The final algorithm was backward Raytracing, in which the rays are traced from the calculation points back to the light source. Along the way, each intersection with nonlight objects resulted in more rays spawn to space until the rays intersected with the light source. Backward raytracing was used in Radiance, which is one of the world-renown engines for daylighting calculation.

In the next step, the authors introduced two new terms to explain the lighting simulation methodology:

1.Simulation Type 2. Control System Model

Simulation type described how the daylight was simulated over time through four distinct types:

- Point-in-time method, which simulated the model for specific timesteps per hour. Although it produced an accurate result, the simulation time was extremely long.

- Interpolated Design Day, which is another climate-based daylighting simulation type that solves the time issue in the point-in-time method by calculating the timesteps in some critical design days including summer solstice, equinoxes, and winter solstice.

- Single-phase Daylight Coefficient (DC), which performed in the same manner as point-in-time method but with a rigorous raytracing approach.

- 3-phase Daylight Coefficient (DC), which removed limitations of the single-phase approach by implementing the geometry changes into each timestep.

The Control system model expressed the electrical lights' response to the available daylight level. Most of the software use illuminance proxy control, which considers the illumination level in one point within the whole floor plane and adjusts the electrical loads accordingly. The sensor signal, another control system, was much more robust and accurate than the illuminance proxy system. The simulation output of three daylight calculation engines, including EnergyPlus, OpenStudio, and SPOT, were compared to one other to investigate their differences. The table below indicates the results for annual energy use.

Table 2.3:Annual Energy Use Results

	ELECTRIC LIGHTING USE (kWh)	
SIMULATION METHOD	**CLASSROOM1**	**CLASSROOM2**
Baseline	2,300	2,228
EnergyPlus	1,158	1,158
SPOT	1,390	1,618
OpenStudio	650	1,025

Based on the results, the authors concluded that there is no right or better tool when it comes to energy simulation and with all messiness it implies, there is more than one way to calculate building performance. Even highly validated tools can deliver inaccurate results due to interpolation errors [22].

Chapter 3 : **Methodology**

This chapter examines the research process and covers the general scheme and detailed steps that have been taken to achieve the results. The chapter begins with a brief introduction to the research method. Next, the set of codes and standards, based on which the initialization had been formed, are introduced, and then, the research process is explained in three discrete parts.

3.1 Introduction

A high-quality design properly addresses different criteria such as comfort, aesthetics, energy performance, and cost. The decisions about each of these criteria can significantly impact other decisions. As a result, a designer is faced with a complicated interconnected system that can be addressed successfully only by having a sufficient and comprehensive body of knowledge. This research specifically studies the impact of architectural design decisions only on building energy performance. To narrow down the study, attention has been drawn to three specific architectural design factors including:

1. Window-to-wall ratio 2. lighting system 3. Orientation

3.2 Methodology Overview

Defining the research process is a crucial step in every research project, as it outlines a clear image of study procedures and the required knowledge and tools. It highlights the possible pitfalls and brings confidence to the process by helping to identify the research requirements and specific conditions. Overall, it simplifies the project by breaking it down to several manageable and easily understandable steps.

3.2.1 Building Performance Testing Technique

Among the several techniques for building performance assessment, computer simulation was opted to monitor the effects of the research variables on the building energy performance. Some of the advantages of a simulation-based method include:

- The simulation method is less costly than the experimental method
- The research contained 40 different design alternatives, each needed to be evaluated separately. The experimental method is not feasible in studies with a high number of alternatives
- Delivering realistic results with an experimental method is very complicated and needs a high level of precision with the aid of control factors

The research implemented a quantitative approach by statistically analyzing data that were delivered from the simulation tools to find the energy consumption pattern associated with the research variables. Figure 3.1 shows each step of the research process distinctly. The research starts with initialization, which includes identifying the influential parameters in the study and providing a value based on research aims or standards. This step requires a complete review of the literature and codes available on the subject. After completing the initialization, the study divides into two main parts.

1. Lighting analysis, to make sure the lighting loads utilized in the energy modeling tool can provide sufficient illumination level for spaces
2. Whole building energy analysis, to observe the energy performance of the space based on its characteristics

Then, results of the energy simulation model were analyzed to conclude the study by confirming or rejecting the research hypothesis (see Figure 3.1).

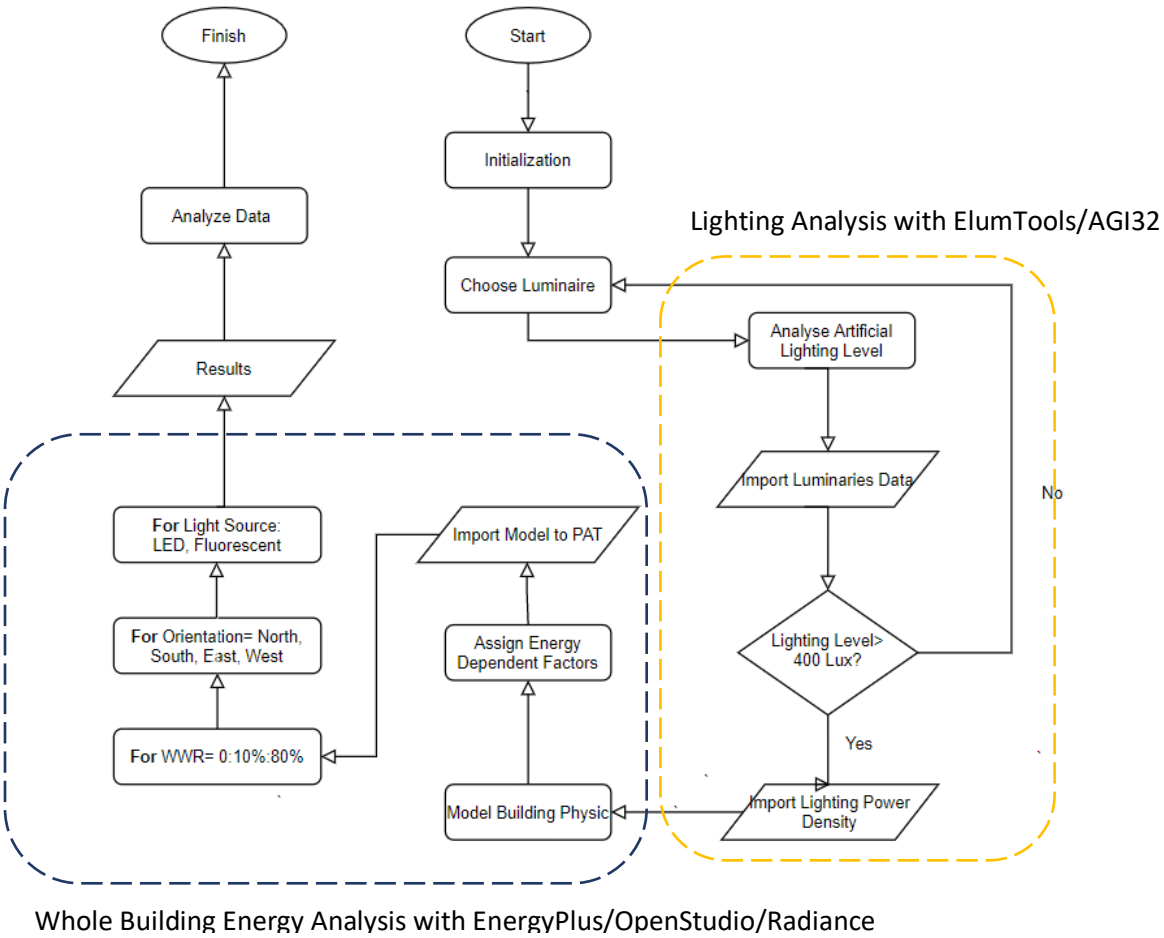


Figure 3.1:Research Flowchart

3.3 Initialization

During the initialization, various influential parameters on the building simulation were identified and organized under two main categories:

1. Explicit Parameters
2. Implicit Parameters

Explicit parameters include those that are fixed and non-adjustable, such as climate zone and location. On the other hand, implicit parameters can be manipulated and adjusted more independently. After identifying all the parameters affecting the energy results, they were given standard values based on the

research aim, and were divided into fixed and variable categories. This research shifted toward a retrofit project. The School of Architecture + Design at Virginia Tech campus in Blacksburg was considered as the simulation model and this early decision determined some of the explicit parameters associated with the site such as climate zone, exterior obstructions, and orientation. Several of the building parameters in Cowgill Hall remained the same while some such as the materials, construction layers, function, lighting system, etc. were changed to make the building comply with the most current codes and standards.

3.3.1 Building Code

Among the various standards and energy guidelines such as ASHRAE, USGBC, IECC, IGCC, and IBC, ASHRAE Standard 189.1, which is a comprehensive guideline for high-performance buildings, was used as the base guideline for compliance.

3.3.2 Simulation Parameters

To simplify the study, only the third floor of Cowgill hall was considered as the simulation model. To find the optimum WWR in presence of LED and fluorescent luminaires in four cardinal directions, WWR, type of light source, and orientation were considered as variables, and the rest of the parameters were set as fixed. Table 3.1 depicts all the influential parameters identified in the simulation based on their type.

Table 3.5 Simulation Parameters

Parameters	Explicit	Implicit	Fixed	Variable
Location (Climate Zone)	☒		☒	
Exterior Obstructions (Exterior Shadings)	☒		☒	
Geographical Orientation	☒			☒
Space Function	☒			
Mechanical System		☒	☒	
Structural System		☒	☒	
Material Composition		☒	☒	
Construction Layers		☒	☒	
Lighting System		☒		☒
WWR		☒		☒
Lighting Control Strategy		☒	☒	
Operational Schedule		☒	☒	
Furniture Location		☒	☒	
Luminaires Type		☒		☒

1. Location

Cowgill Hall is located in the town of Blacksburg in Montgomery County, Virginia. According to the 2012 International Energy Conservation Code, Virginia falls into climate zone 4A, which is defined as mixed and Humid with IP Units CDD50ºF ≤ 4500 AND 3600 < HDD65ºF ≤ 5400 and SI Units CDD10ºC ≤ 2500 AND HDD18ºC ≤ 3000. A mixed-humid climate is generally defined as a region that receives more than

20 in (50 cm) of annual precipitation and has approximately 5,400 heating degree days (65°F basis) or fewer. The average monthly outdoor temperature drops below 45°F (7°C) during the winter months.

The US climate zone map can be seen in [[23], Fig. 3.2].

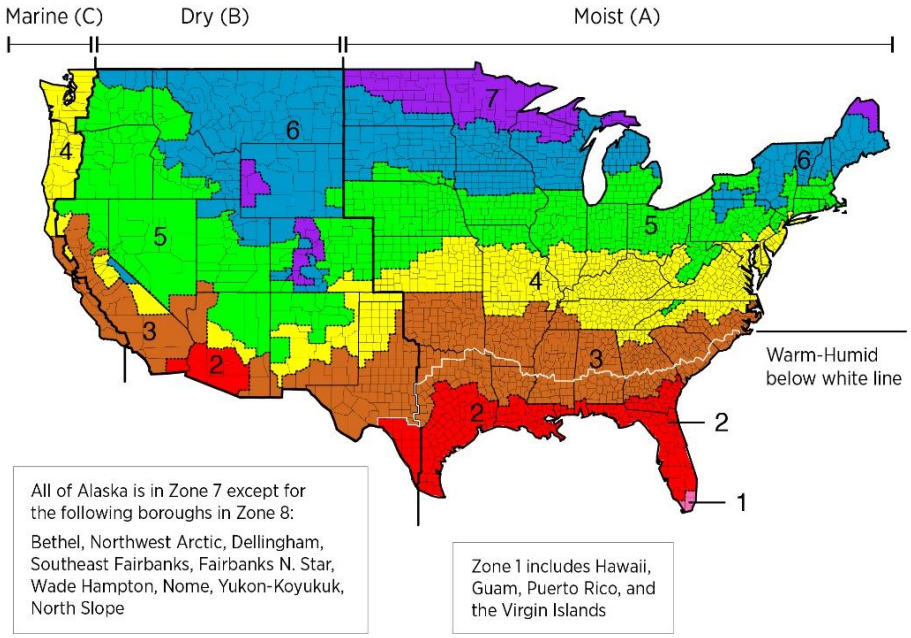


Figure 3.2 US Climate Zone Map

2. Exterior Obstructions

Cowgill Hall is located on the west side of the Drillfield on Perry street. Its construction was completed by 1996. It was the first building ever built for the architecture program and the first departure from the traditional gothic-style buildings on the campus[24]. The building is surrounded by Burrus Hall on the south side of Cowgill Plaza, Johnston Student Center on the West, Bishop Favor Hall on the North, and Hancock Hall on the East. Figure 3.3- 3.6 show the exterior obstructions of the Cowgill Hall [25].

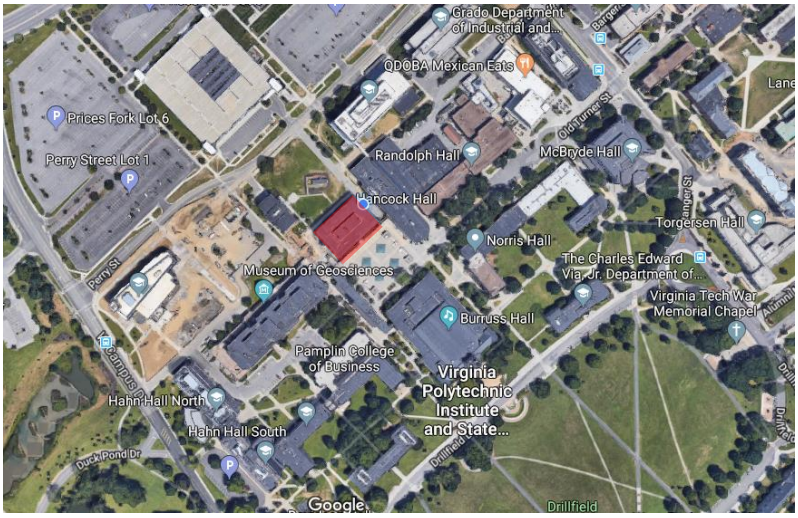


Figure 3.3 Cowgill Hall

Figure 3.4 Surrounding Buildings

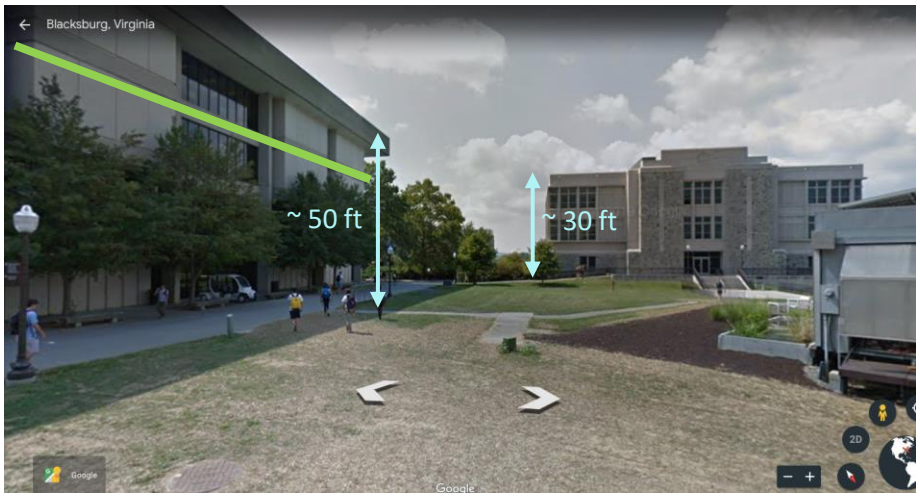


Figure 3.5 Surrounding Buildings

Figure 3.6 Surrounding Buildings

3. Cardinal Direction

The North orientation was Rotated 45 degrees to the west, so that each of the sides in the rectangular plan would be perpendicular to each cardinal direction. The current consideration makes it easier to track the changes in different alternatives. The research specifically tends to observe the changes in the wider portion of the plan near the window openings (Perimeter zones) in four orientations.

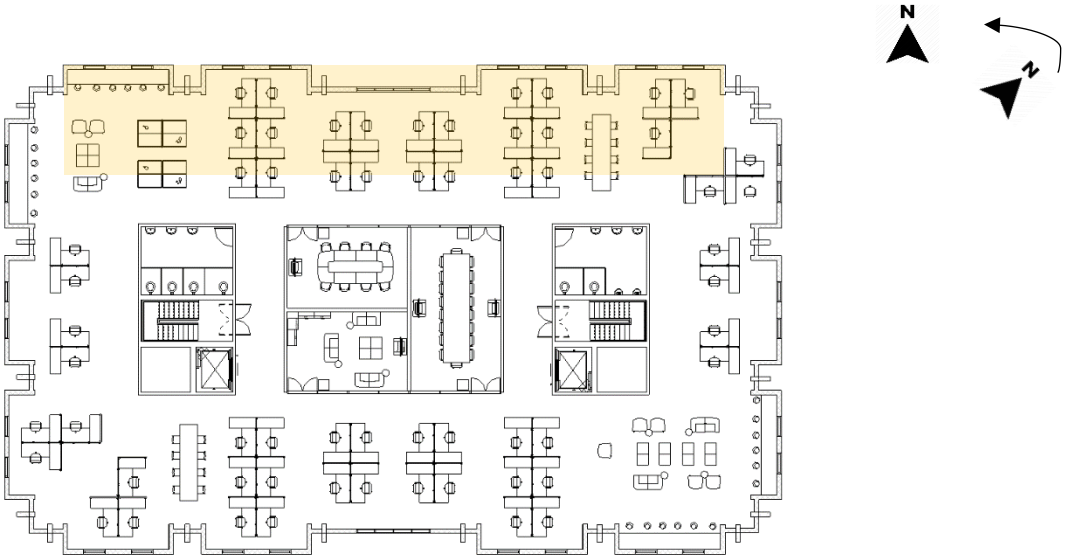
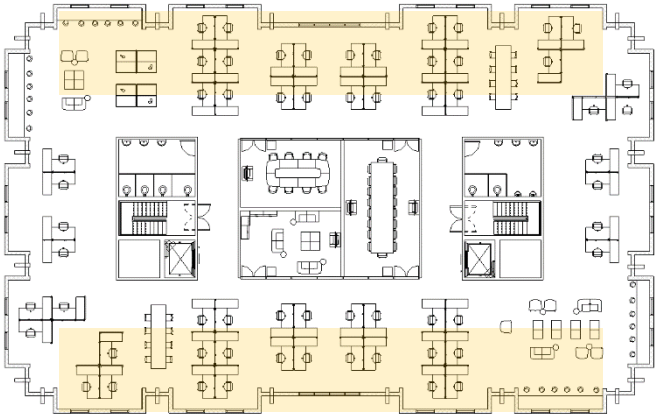


Figure 3.7 Cowgill Floor Plan

To track the changes of energy consumption in East and West directions, the building was rotated 90 degrees so that the wider perimeter would be exposed to the East and West.



Third floor Area: 11885 sqft or 1104 sqm

Figure 3.8 Floor Plan along North-South Axis

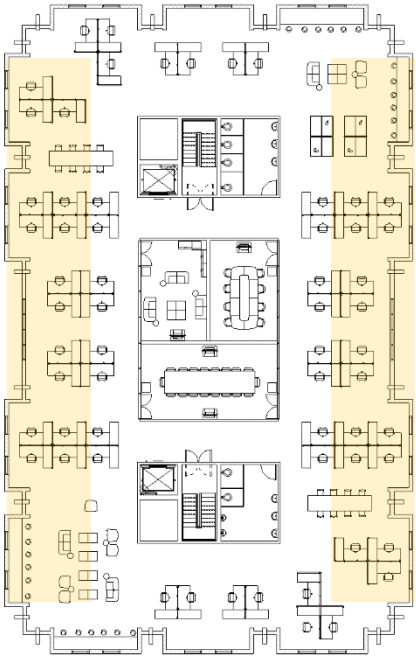


Figure 3.9 Floor Plan East-West Axis

4. Space Function

Cowgill Hall in Virginia Tech houses the School of Architecture+Design and serves multiple educational purposes. According to the US Department of Energy, commercial buildings consume more energy than the transportation or industry sectors, accounting for a total of 40% of US energy use[26]. Due to this great share of energy, the function of the building was changed to an open office.

5. Structural System

Cowgill Hall was built with a beam-column concrete structure and the structural system remained the same for this study.

6. Materials

Many of the building materials have been preserved while some, such as flooring material, were changed. The materials were chosen based on their Light Reflectance Value (LRV). LRV is the portion of the light that is reflected from the surface compared to the amount of light that is received by the surface. LRV can depict how dark or light colors may look on a scale of 0 to 100. The closer the number to 100 the more reflective and lighter the color is and vice versa. A mean value has been identified in a range of values for the building's primary material finishes based on[21, Tab3.2][21, Fig3.10].

Table 3.11 Color Reflection Factors

Medium Value Colors	%
White	80–85
Light gray	45–70
Dark gray	20–25
Ivory white	70–80
Ivory	60–70
Pearl gray	70–75
Buff	40–70
Tan	30–50
Brown	20–40
Green	25–50
Olive	20–30
Azure blue	50–60
Sky blue	35–40
Pink	50–70
Cardinal red	20–25
Red	20–40

Approximate Reflection Factors

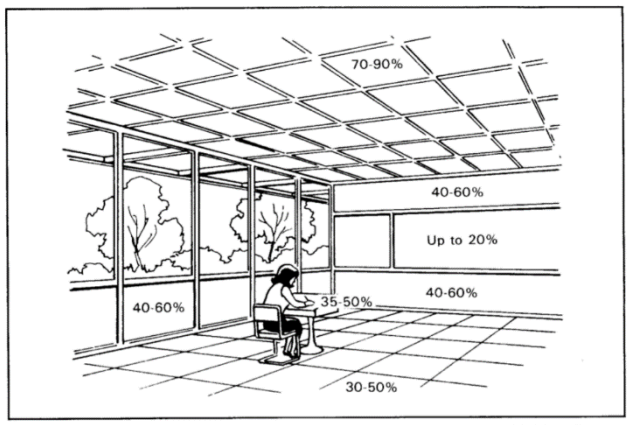


Figure 3-11: Distribution of Surface Reflectances. As a general rule, use highly reflective surfaces to distribute light, and to use darker colors on surfaces where light distribution is not as important, such as the floor.

Figure 3.10 Distribution of Surface Reflectance

Table 3.3 shows the finish materials for the ceiling, floor, interior walls, and task surfaces along with their associated Light Reflectance Value (LRV).

Table 3.16 Materials light reflectance value

Surface	Finish Material	LRV
Floor	Vinyl sheets	42
Ceiling	White paint on the exposed concrete ceiling	80
Interior Walls	Light grey paint on masonry	50
Task	Laminate (wood core+plastic finish)	45

Given that the selected luminaires for the office space draw 30% of their light up to the ceiling, a highly reflective finish was chosen to help scatter the light and provide an appropriate ambient light level for space. The reflected light will boost the lighting quality and prevents contrast.

7. Occupant load

According to the Building International Code, the occupant load for commercial buildings is 100 sqft. However, the 2018 edition of the National Fire Protection Association (NFPA) changed it to 150 sqft. Also, a new factor of 30 square feet per person for collaboration spaces with areas less than or equal to 450 square feet can now be used. For collaboration spaces with areas greater than 450 square feet, the rate is 15 square feet per person [28].

Concerning the interior furniture, the open office can house 80 desks which allow for 80 employees to officially work in the space. Based on the floor area and the number of employees, the occupant load was calculated as 185 sqft per person, which is slightly more than the minimum allowed Occupant load.

8. Construction Layers

The current construction materials and layers in the building were changed to enhance the thermal properties of the exterior layers. Due to Cowgill's old construction, many of the climate-based energy codes and standards including the R-values of the construction layers are not met. As a result, new construction layers were proposed based on the ASHRAE standard guidelines, and International Code Council. [22, Tab. 3.2] highlights the ASHRAE 189.1-2014 Standard and ICC thermal property requirements of the building envelope.

Table 3.17 Building Envelope Requirements for Climate Zone 4(A, B, C)(SI)

	Nonresidential		*Residential*		**Semiheated**	
Opaque Elements	**Assembly Maximum**	**Insulation Min R-Value**	**Assembly Maximum**	**Insulation Min R-Value**	**Assembly Maximum**	**Insulation Min R-Value**
Roofs						
Insulation entirely above deck	U-0.164	R-6.2 c.i.	U-0.164	R-6.2 c.i.	U-0.475	R-2.1 c.i.
Metal building[a]	U-0.189	R-2.3 + R-4.4 c.i.	U-0.189	R-2.3 + R-4.4 c.i.	U-0.419	R-0 + R-2.3 c.i.
Attic and other	U-0.107	R-10.6	U-0.107	R-10.6	U-0.174	R-6.7

Walls, above grade									
Mass	U-0.532	R-2.01		U-0.460	R-2.29		U-3.293	NR	
Metal building	U-0.307	R-1.9+ R-2.3 c.i.		U-0.256	R-2.8 + R-2.8 c.i.		U-0.828	R-0 + R-1.1 c.i.	
Steel framed	U-0.327	R-2.3 + R-2.2 c.i.		U-0.327	R-2.3 + R-2.2 c.i.		U-0.634	R-2.3 + R-0.7 c.i.	
Wood framed and other	U-0.327	R-2.3 + R-1.3 c.i.		U-0.327	R-2.3 + R-1.3 c.i.		U-0.455	R-2.3 + R-0.7 c.i.	
Walls, below grade									
Below grade *wall*	C-0.608	R-1.8 c.i.		C-0.4703	R-2.2 c.i.		C-6.473	NR	
Floors									
Mass	U-0.291	R-2.9 c.i.		U-0.2607	R-3.3 c.i.		U-0.547	R-1.5 c.i.	
Steel joist	U-0.194	R-6.7		U-0.194	R-6.7		U-0.266	R-5.3	
Wood framed and other	U-0.169	R-6.7		U-0.169	R-6.7		U-0.261	R-5.3	
Slab-on-grade floors									
Unheated	F-2.658	R-3.5 for 1200 mm		F-2.658	R-3.5 for 1200 mm		F-1.264	NR	
Heated	F-4.309	R-3.5 for 1200 mm		F-3.5171	R-2.6 full slab		F-4.601	R-3.5 for 1200 mm	
Opaque doors									
Swinging	U-2.556			U-2.556			U-3.578		
Nonswinging	U-2.556			U-2.556			U-7.412		
Fenestration	**Assembly Max. U**	**Assembly Max. *SHGC***	**Assembly Min. VT/*SHGC***	**Assembly Max. U**	**Assembly Max. *SHGC***	**Assembly Min. VT/*SHGC***	**Assembly Max. U**	**Assembly Max. *SHGC***	**Assembly Min. VT/*SHGC***
Vertical fenestration, 0% to 40% of *wall*		(For all frame types)			(For all frame types)			(For all frame types)	
Nonmetal framing, all	U-1.79	S-0.40 E&W-0.36 N-0.50	1.10	U-1.79	S-0.40 E&W-0.36 N-0.50	1.10	U-2.61	NR	NR
Metal framing, fixed	U-2.15			U-2.15			U-3.73		
Metal framing, operable	U-2.56			U-2.56			U-4.14		
Metal framing, entrance door	U-3.94			U-3.48			U-3.94		
Skylight, 0% to 3% of *roof*									
All types	U-2.84	0.40	NR	U-2.84	0.40	NR	U-6.53	NR	NR

* The following definitions apply: c.i. = continuous insulation (see ANSI/ASHRAE/IES Standard 90.1-2013, Section 3.2), FC = filled cavity (see ANSI/ASHRAE/IES Standard 90.1-2013, Section A2.3.2.5), *Ls = liner system* (see ANSI/ASHRAE/IES Standard 90.1-2013, Section A2.3.2.4), NR = no (insulation) requirement.

a. When using the R-value compliance method for metal building *roofs*, a thermal spacer block is required (see ANSI/ASHRAE/IES Standard 90.1-2013, Section A2.3.2).

Based on the highlighted values new construction layers have been proposed as follows:

- Wall Above Grade

The calculated U-value for the exterior wall is 0.49 which is below the maximum 0.59 allowable value in the ASHRAE 189.1. The R value for each layer has been brought below.

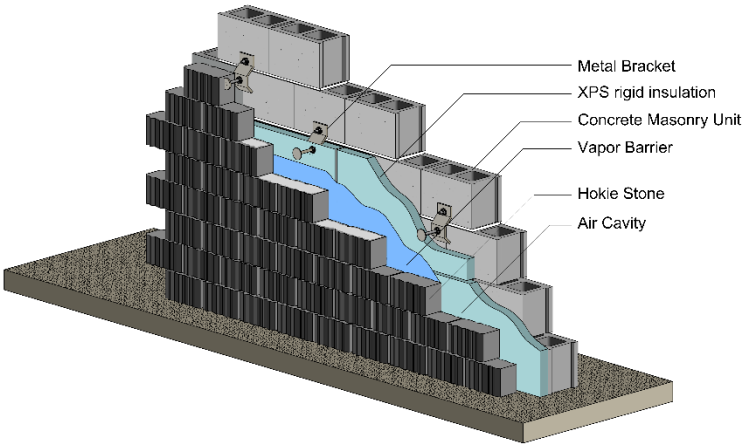


Figure 3.11 Exterior Wall Section

Layer:

Outside

Poured Limstone Concrete 4 in - 120 lb/ft3	R value: 0.089 Thickness: 4''	Thermal conductivity: 1.14 W/m K
Wall air space	R value: 0.17 Thickness: 2''	Thermal resistance: 0.17
Wall Insulation	R value: 1.57 Thickness: 2.68''	Thermal conductivity: 0.043 W/ m K
Concrete Block 6 in lb/ft3- Partly Grouted Cells empty	R value: 0.18 Thickness: 6''	Thermal conductivity: 0.84

R value: 2.009
U value: 0.45

The order shows the way the layers had been inserted into energy simulation software as construction data.

The materials and the R-values associated with them have been extracted from the BCL material library linked to the NREL website.

- Floor Above Grade

The floor in third story of Cowgill Hall is not exposed to the outside, as a result it was defined with adiabatic surface boundary condition in the energy modeling software.

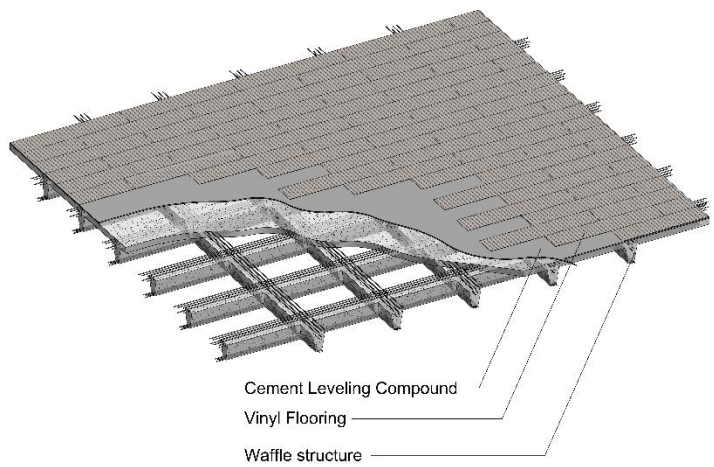


Figure 3.12 Floor Section

Slate or Tile ½ in

M11 100mm Lightweight concrete

Lightweight Concrete- 8 in- 80 lb/ft3

- Interior Wall

G01a- 19mm gypsum board

Air gap

G01a- 19mm gypsum board

- Glazing Type

A window wall glazed system with a metal frame was selected from the windows directory on the National Fenestration Rating Council website[30]. Table 3.5 exhibits different characteristics of the glazed material used in the study. Note that all factors comply with the fenestration requirements mandated by ASHRAE standard 189.1 2014(See table 3.6).

Table 3.25 Glazing Features

CPD #	U-factor	SHGC	VT	Condensation Resistance	Air Leakage	Ventilation Rating (Standard Screen)	Ventilation Rating (Enhanced Screen)
ARA-K-53-00001-00001	0.37	0.35	0.62	47	≤ 0.3		

Close

Group ID	Manufacturer Product Code	Frame/Sash Type	Glazing Layers	Low-E	Gap Widths	Spacer	Gap Fill	Grid	Divider	Tint
1	Dual Thermal Break: SB60 / AIR / CLR (6MM/6MM) - 1" IG	AT/NA	2	0.035(2)	0.5	A1-D	Fill 1: AIR (100)	N	-	CL

U factor: 0.37

Visible transmittance: 0.62

Condensation resistance: 32

Solar heat gain coefficient: 0.35

Table 3.29 Fenestration Requirements

ASHRAE 189.1-2014 Prescriptive Fenestration Requirements								
Climate Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Vertical Fenestration								
Maximum U-factor								
Non-metal frame, all	0.45	0.36	0.32	0.32	0.29	0.29	0.29	0.29
Metal frame, fixed	0.51	0.51	0.45	0.38	0.38	0.38	0.34	0.34
Metal frame, operable	0.59	0.59	0.54	0.45	0.45	0.45	0.36	0.36
Metal frame, entrance door	0.99	0.75	0.69	0.69	0.69	0.69	0.69	0.69
Maximum SHGC								
Non-metal frame, all	S&E&W-0.25, N-0.35	S&E&W-0.25, N-0.35	S&E&W-0.25, N-0.35	S-0.40, E&W-0.36, N-0.50	S-0.40, E&W-0.36, N-0.50	S-0.40, E&W-0.36, N-0.50	S-0.45, E&W-0.41, N-0.55	S-0.45, E&W-0.41, N-0.55
Metal frame, fixed	S&E&W-0.25, N-0.35	S&E&W-0.25, N-0.35	S&E&W-0.25, N-0.35	S-0.40, E&W-0.36, N-0.50	S-0.40, E&W-0.36, N-0.50	S-0.40, E&W-0.36, N-0.50	S-0.45, E&W-0.41, N-0.55	S-0.45, E&W-0.41, N-0.55
Metal frame, operable	S&E&W-0.25, N-0.35	S&E&W-0.25, N-0.35	S&E&W-0.25, N-0.35	S-0.40, E&W-0.36, N-0.50	S-0.40, E&W-0.36, N-0.50	S-0.40, E&W-0.36, N-0.50	S-0.45, E&W-0.41, N-0.55	S-0.45, E&W-0.41, N-0.55
Metal frame, entrance door	S&E&W-0.25, N-0.35	S&E&W-0.25, N-0.35	S&E&W-0.25, N-0.35	S-0.40, E&W-0.36, N-0.50	S-0.40, E&W-0.36, N-0.50	S-0.40, E&W-0.36, N-0.50	S-0.45, E&W-0.41, N-0.55	S-0.45, E&W-0.41, N-0.55
Skylights with Glass								
Maximum U-factor								
All types	0.75	0.65	0.55	0.50	0.50	0.50	0.50	0.50
Maximum SHGC								
All types	0.35	0.35	0.35	0.40	0.40	0.40	Any	Any

9. HVAC System

The mechanical system remained the same in the building. A four-pipe air handling unit with Variable air volume already provides heating, cooling, and ventilation in the Cowgill Hall. The hot water is supplied by a central plant outside the building at the Virginia Tech campus. The plant distributes steam to the different buildings on the campus and the mechanical equipment in each building transforms it into a liquid phase. In this study, the supply system was considered local with a boiler providing hot water and a chiller providing cold water.

10. Window-to-Wall Ratio

The percentage of window openings in the building is one important factor in energy performance. A glazed wall usually has a lower R-value than a solid wall. Therefore, more energy can be transferred through the glazed surface. Standards limit the vertical fenestration area to 40% of the gross above-grade wall area. With exceptions for some buildings, the area of west-oriented and east-oriented vertical fenestration must each not exceed the area of south-oriented vertical fenestration.

In this study, nine different WWR percentages, starting from 0 to 80 percent with a 10 percent increment, were considered for different design alternatives. A fixed 22-inch (70cm) distance was placed from the upper edge of the windows to the ceiling in all scenarios and the lower edge would be moved down to increase the window area. A horizontal window geometry was chosen over a vertical one since it provides a more even light distribution. Vertical window geometry creates very dark or very light spots and causes illuminance contrasts in the spaces.

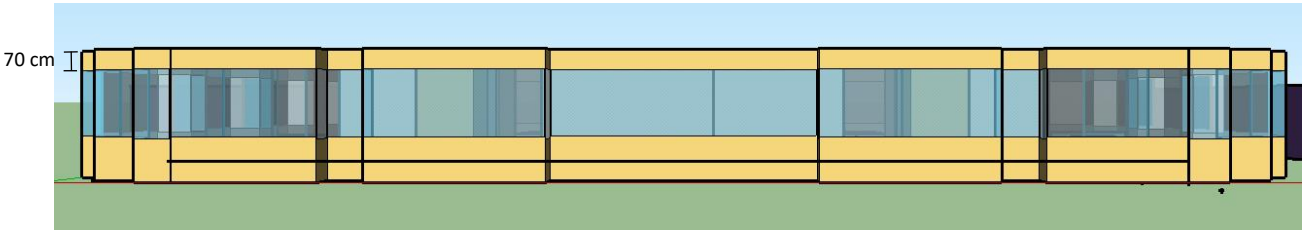


Figure 3.13 North Facade

11. Operational Schedule

The office operational schedule is important given that the mechanical and electrical systems are reliant on it. In this study, the energy plus default set of operational schedules for office buildings was used, which contained schedules for lighting, office equipment (mostly plug loads), and infiltration.

12. Furniture

The location, geometry, material, dimensions, and height of desks and other furniture pieces are important because they highly affect the lighting distribution. Interior furniture, especially with dividers

such as office work stations, act as interior obstructions. They can absorb, block, or reflect the daylight or electrical light illumination, and change the quality of light inside the spaces.

-Floor to floor height = 14 ft

-Floor to ceiling height = 12 ft

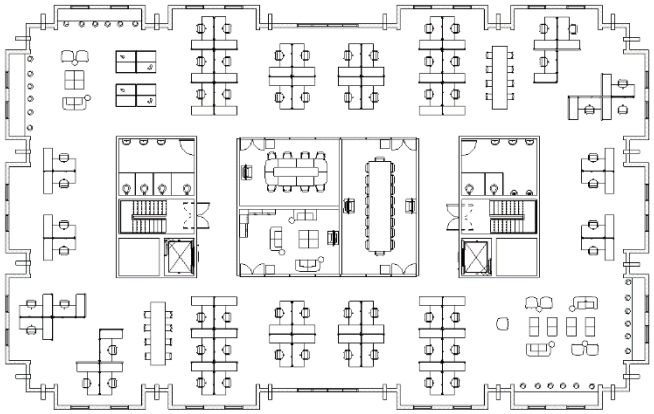


Figure 3.14 Furniture Plan

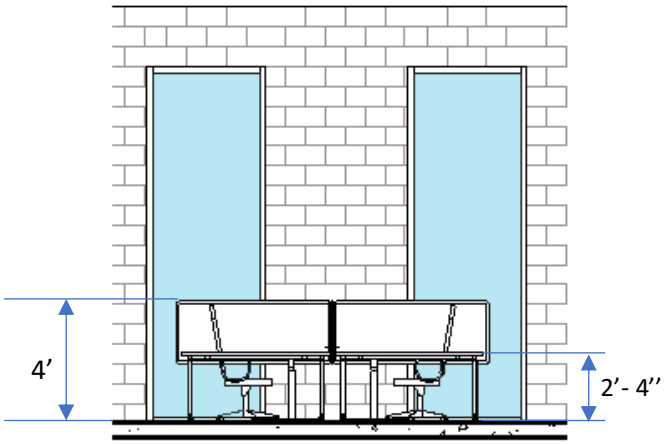


Figure 3.15 Task Height

13. Reflected ceiling plan

The location of luminaires, suspended ceiling, air ducts, and return air ducts affect the simulation results. Since the study is not tracking the effects of these parameters, a reflected ceiling plan has been proposed to fix the location of each of these elements. Note that changes in the luminaires do not change the location or height of them in the plan.

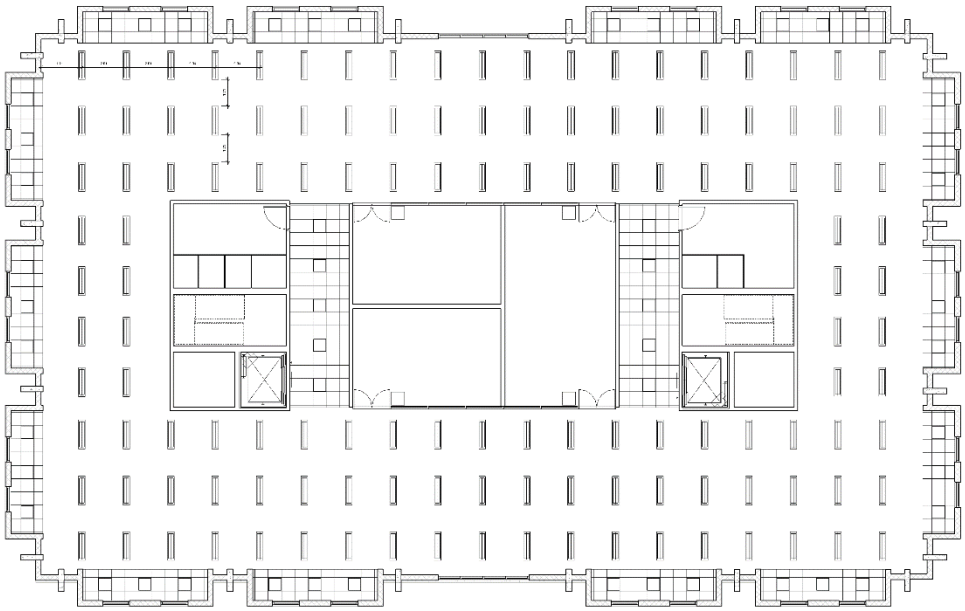


Figure 3.16 Reflected Ceiling Plan

14. Light Source

Fluorescent, Compact Fluorescent, and LED lamps are some of the most common light sources that are often used in open offices. The difference in features of light sources such as efficiency or light output, directly and indirectly affect the whole building energy consumption. In the beginning, it was decided to set the luminaires as fixed elements and only change the light sources inside them. However, the following reasons led to change the luminaires for different light sources:

1) Luminaires designed for a specific source of light are more energy-efficient
   - Change of luminaires prevents waste and significantly enhances energy performance.
2) Lack of luminaires that can work with LED and fluorescent light sources
   - Recent lighting products are mostly manufactured in a kit with specific luminaire equipment and light source.
3) Different light emittance pattern between the LED and fluorescent sources
   - The difference in light sources' emittance pattern requires distinct luminaires with specific lenses and other equipment to distribute the light in the desired direction.

The space target illumination level was set according to the range provided in the Illuminating Engineering Society of North America (IESNA). [24, Tab 3.7] indicates the range for each space function.

Table 3.43 Standard Illumination Level

ROOM TYPE	LIGHT LEVEL (FOOT CANDLES)	LIGHT LEVEL (LUX)	IECC 2015 LIGHTING POWER DENSITY (WATTS PER SF)
Bedroom - Dormitory	20-30 FC	200-300 lux	0.38
Cafeteria - Eating	20-30 FC	200-300 lux	0.65
Classroom - General	30-50 FC	300-500 lux	1.24
Conference Room	30-50 FC	300-500 lux	1.23
Corridor	5-10 FC	50-100 lux	0.66
Exhibit Space	30-50 FC	300-500 lux	1.45
Gymnasium - Exercise / Workout	20-30 FC	200-300 lux	0.72
Gymnasium - Sports / Games	30-50 FC	300-500 lux	1.20
Kitchen / Food Prep	30-75 FC	300-750 lux	1.21
Laboratory (Classroom)	50-75 FC	500-750 lux	1.43
Laboratory (Professional)	75-120 FC	750-1200 lux	1.81
Library - Stacks	20-50 FC	200-500 lux	1.71
Library - Reading / Studying	30-50 FC	300-500 lux	1.06
Loading Dock	10-30 FC	100-300 lux	0.47
Lobby - Office/General	20-30 FC	200-300 lux	0.90
Locker Room	10-30 FC	100-300 lux	0.75
Lounge / Breakroom	10-30 FC	100-300 lux	0.73

According to table 3.7, the standard light level for open offices falls within 300 to 500 lux. In this study, 400 lux was considered as the target illumination level. Meanwhile, all the desks and tables were equipped with task lights to ensure sufficient illumination levels on the task surfaces while reducing energy consumption because:

- Not all employees have similar light level preferences and task lights allow for individual control over the illumination level. Thus, many of the task lights may remain off during the day or be on but with a low power level (when using dimmable fixtures).
- Employees' working hours may differ from each other and with task lights, it is possible to reduce the energy consumption when one does not need light.

Luminaire types were selected based on the status quo in Cowgill Hall. The main area of the ceiling has an exposed waffle structure and is covered with suspended luminaires. All the nooks in the plan have drop ceilings and are covered by recessed luminaires. Also, each of the desks is equipped with an individual operable task light.

The following factors limited the range of proper luminaires for the study:

- Not all the lighting manufacturers provide the luminaires IES file, Revit family, and other required data. As a result, only the products of a few manufactures, which had the required data, could be considered.
- The proper luminaires should draw 30% of the light up and 70% down. Thus, the light distribution map limited the options. Initial simulations provided a good estimation regarding the light distribution and lumen output of the selected luminaires and narrowed down the luminaire choices.

The selected luminaires, their photometric features, and other information can be found in the lighting result section of the results chapter in this book.

15. Thermal properties of light sources

[25, Tab 3.8] shows the general thermal properties of different light sources. Each type of light source has distinct heat and visible light fraction. Note that the type of lighting fixture also has a profound impact on the heat and visible light fraction. Figure 3.17 depicts different types of luminaires and their position on the ceiling.

Table 3.51 Heating Properties of Light Sources

	Incandescent (%)	Fluorescent (%)	LED (%)
Visible light	8	21	15–25
Radiant heat	73	37	–
Convective heat	19	42	75–85

Although the ASHRAE Handbook of fundamentals provided the heat properties of different fluorescent lighting fixtures, there is a lack of information regarding the LED lighting fixtures. Liu et al. (2017)

proposed the heat distribution pattern in various LED light fixtures through an experimental research. However, results of the study have not been confirmed by ASHRAE and therefore have not been used in this study. Change of the luminaire type or light source alters the thermal properties of the lighting system and affect the results to a great extent.

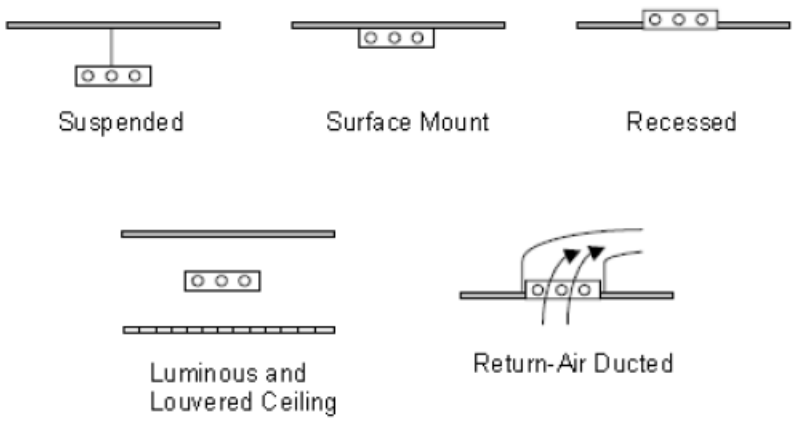


Figure 3.17 Different luminaire types [11]

16. Lighting Schedule

After running the daylight simulation, Radiance provided EnergyPlus with a new lighting schedule. In this study, the sum of ambient and task lights were dimmed together based on the daylight availability and there was no distinction in their dimming settings. Because of this, the task lights do not have a specific schedule and do not follow the building occupancy schedule.

17. Lighting Control Strategy

Continuous dimming with daylighting control sensors was selected as the lighting control strategy. The sensors are also linked to the operational schedule set, which contains the sub schedules such as lighting schedule and activity level.

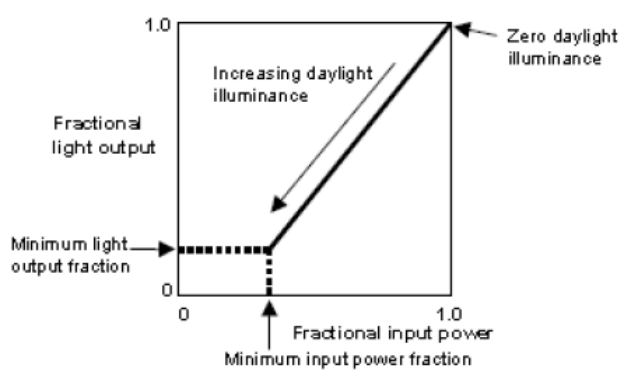


Figure 3.18 Illustration of continuous dimming relationship

Light sensors gauge the condition and change the light level as necessary. As a result, finding the right locations for the sensors is important. The red marks shown in figure 3.19 were considered as daylight control points based on the location of luminaires and OpenStudio limitations.

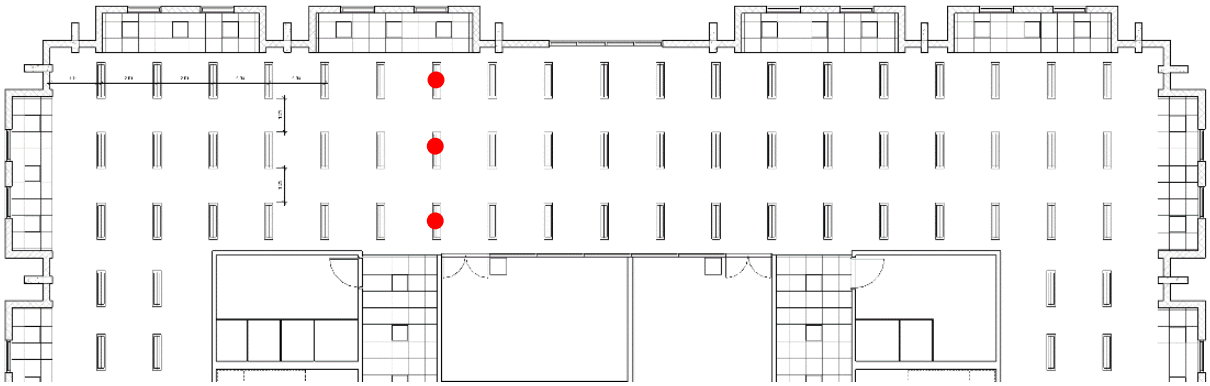


Figure 19 Daylight Control Points' Location

Three rows of luminaires created three lighting zones in the order of proximity to the windows. One daylight control sensor was allocated to each row of luminaires in each lighting zone. This arrangement simplified the dimming by starting from the light zone 1, which is closer to the windows, and received more sunlight and continuing inward to light zone 2 and 3 respectively.

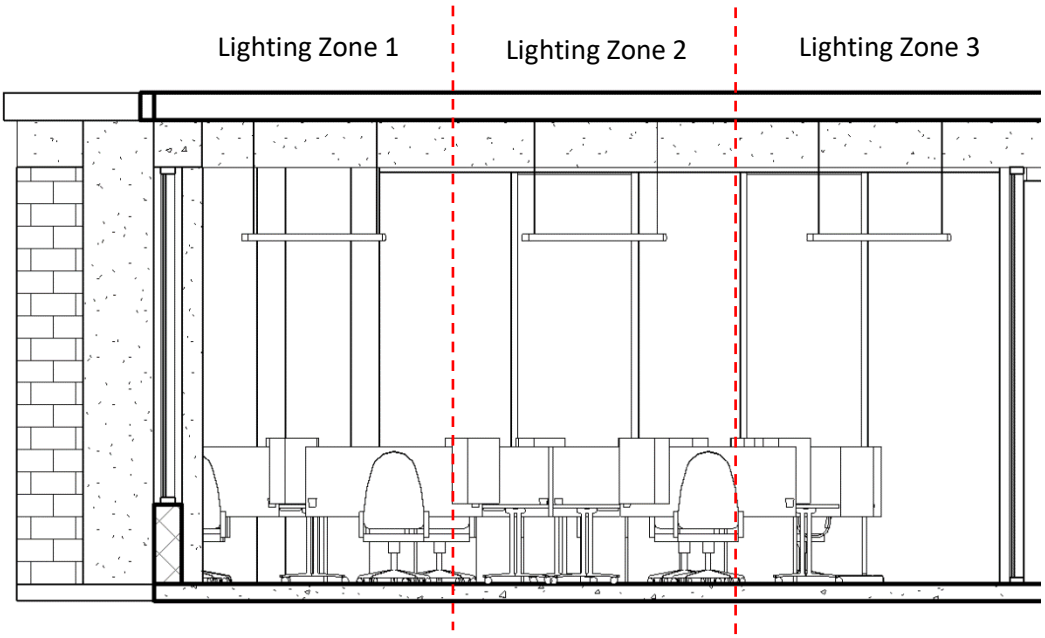


Figure 3.20 Lighting Zone Divisions

3.4 Simulation Overview

After the building parameters had been identified and given an appropriate value, they were inputted into the energy modeling software. As previously stated, the study aimed to explore the effect of research variables on the whole building energy consumption pattern. The range of values for each variable are as follows:

- WWR: nine scenarios starting from 0% to 80% with 10% increment
- Type of light source: two light sources including LED and fluorescent
- Orientation: four cardinal directions (North, East, West, South)

A combination of different values of each variable provided a total of 72 design alternatives to be simulated.

3.4.1 Design Alternatives:

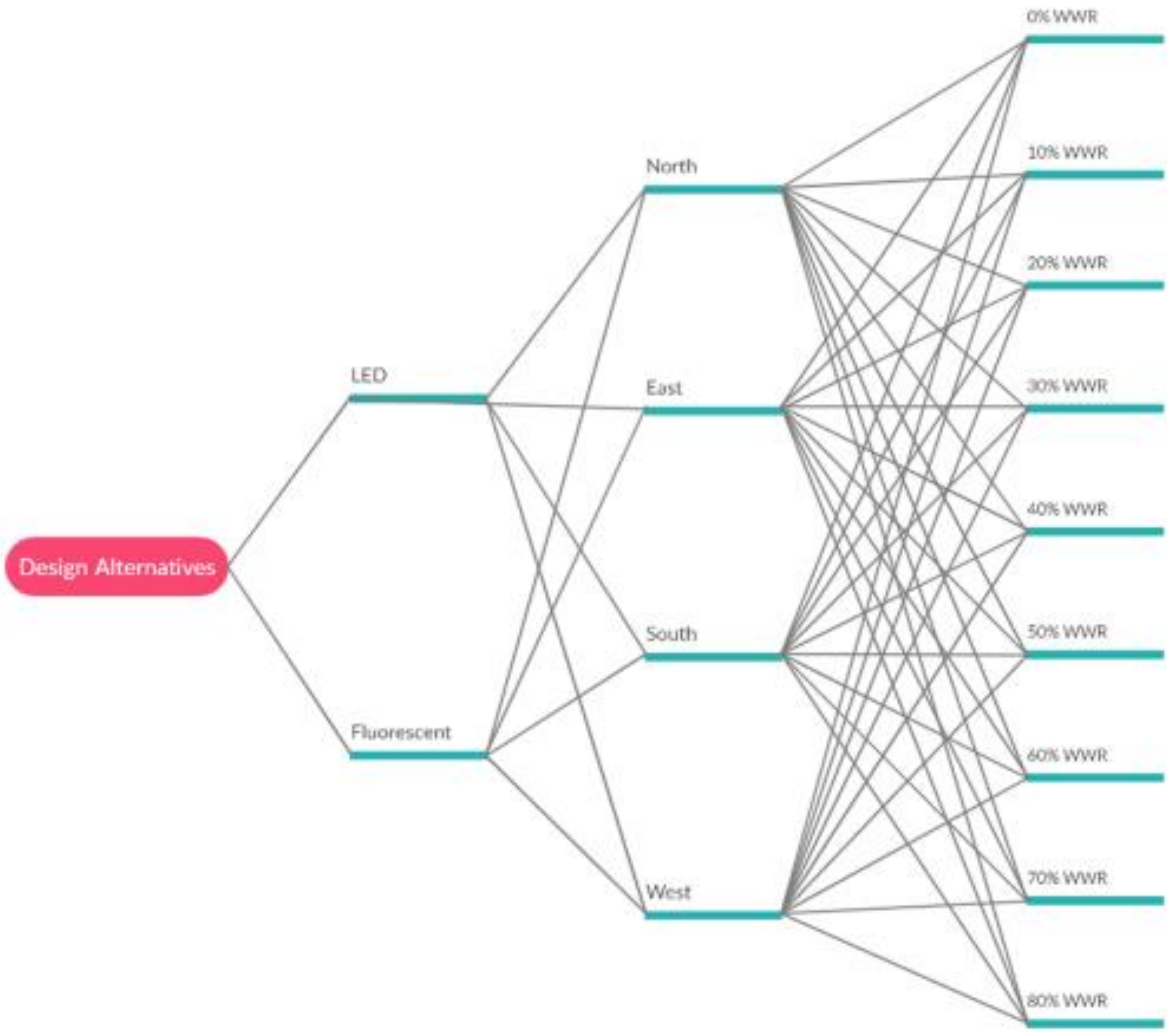


Figure 3.21 Design Alternatives Diagram

3.5 Simulation Tools

A simulation technique was selected to conduct the study and assess the building energy performance. Technological developments in recent years have introduced many advanced computer programs that can simulate the building energy and lighting performance with acceptable precision. However, the large variety of simulation programs make it difficult to choose the right application that fits the study objectives. After carefully reviewing the features, advantages, and disadvantages of different software programs, AGI32 was selected for the lighting analysis and OpenStudio/EnergyPlus for whole-building energy modeling.

The primary reason for using a combination of two different programs included the inability of the majority of building performance simulation (BPS) software to evaluate the spatial illumination level and lighting quality. On the other hand, many lighting computation tools can analyze the electrical lighting performance but disabled to evaluate the lamps' thermal behavior. Due to the lack of a stand-alone software that can combine these distinct functions, two programs were used to accomplish the results.

3.5.1 Lighting Analysis Tools

A lighting simulation software was required to find the desired LED and fluorescent luminaires that could provide a sufficient light level in the open office. It was important to keep the LED and fluorescent scenarios' light level very close to one other to provide comparable conditions for the simulations.

To identify the proper software, the features of several lighting simulation products such as AGi32, Dialux Evo, Relux, and SPOT were reviewed. Then, the AGi32's add-on for Revit (ElumTools) was selected, which uses the full Radiosity calculation method. For more information about the Radiosity Method, see [33]. The followings indicate the justification for choosing AGi32 over other lighting simulation software:

- AGi32 has been developed by a USA-based company and has a complete directory of IES files and luminaires of American lighting products.
- AGi32 has powerful graphic visualization and realistic renders which show the lighting condition inside and outside of a building.
- It can work through the Revit user interface, which is an architectural drawing software. This will drastically accelerate the lighting simulation initializing process since there is no need to model the building geometry from scratch.

Tools Introduction

AGi32

AGi32 is a lighting calculation tool developed by the Colorado-based Lighting Analysts Illumination Engineering Software company. It was designed to compute the exterior and interior illumination, and assist in determining the luminaires placement. AGi32 and ElumTools are known for their powerful visualization and can provide both numeric and rendered output [34]. AGi32 provides the user with two lighting calculation options, each with its merits and disadvantages.

- Direct Calculation method
- Full Radiosity method

The direct calculation method only considers the light directly coming from luminaires and is mostly used for exterior applications. The full radiosity method, on the other hand, takes into account the interreflected light, which is very important in the interior lighting. The full radiosity method leads to a more accurate lighting simulation but requires additional time for computation.

AGi32 utilizes the point by point calculation method, which allows the user to include as many calculation points as required. It then provides various outputs in each calculation point including Illuminance, Luminance (defuse), Daylight factor, Unified Glare Rating, Roadway Luminance, Veiling Luminance, Small Target Visibility, and Glare Rating. To predict the photometric features of a space, it is necessary to model the space in the AGi32 interface, assign the calculation points, set their height, choose a calculation method, and run the simulation.

Software Limitations

- Despite being stated in the software manual, AGi32 is unable to import 3D file formats. The program crashes and closes when a slightly large file is imported. As a result, the 3D model import function is somewhat useless.
- Although the daylight calculation is possible through AGi32, the possibility of importing weather files to the software has not been addressed. Thus, it does not allow for a climate-based calculation.
- AGi32 does not have an option for photosensor control. As a result, it cannot dim the electrical luminaires with respect to the available daylight.
- The software is not free.

ElumTools

ElumTools is a lighting calculation tool designed as a plugin for Autodesk Revit. It was developed by the Lighting Analysts IIllumination Engineering Software company and shares the same features with AGi32. Unlike AGi32, which is a stand-alone software, ElumTools is an add-on for Autodesk Revit and uses the Radiosity method to compute the light level [35]. By installing ElumTools, a ribbon tab is created in the Revit environment, through which it is possible to import IES files for different luminaires, change the material properties through the material library, create calculation points, change features associated with points, drop and locate luminaires, select the results output, and take advantage of ElumTools's other functions.

A great advantage of ElumTools over AGi32 is that there is no need to draw a separate model for lighting analysis and all the operations can be done in the Revit model. Like AGi32, it provides a walkthrough option to navigate inside and outside the building and evaluate the light quality.

Software Limitations

- The software is not able to import weather files, which results in less precision in daylight computation.

- ElumTools does not address photosensor control. As a result, it does not dim the electrical lamps in response to daylight.
- The software is not free.

3.5.2 Energy Performance Analysis Tools

There are several candidates for whole-building energy simulation software, including DesignBuilder, OpenStudio, Equest, Grasshoppers' plugins such as DIVA, Honeybee, and Ladybug. Although many of these programs share the same simulation engine (EnergyPlus), their user interface and general program features are different. After reviewing the features and capabilities of each software program, Openstudio, which works with a combination of EnergyPlus and Radiance engines, was selected over other programs due to the following reasons:

- Unlike DesignBuilder, OpenStudio is an open-source application with free access.
- In addition to the EnergyPlus engine, OpenStudio utilizes Radiance for daylight analysis.
- OpenStudio comes in a kit with various tools which aid in energy modeling and energy modelers with any level of proficiency can use the software.
- It is a more comprehensive tool compared to other energy simulation tools.
- It is linked to SketchUp which is an architectural environment for 3D modeling.

Tools Introduction

OpenStudio

OpenStudio is a collection of tools to support whole-building energy modeling with EnergyPlus and Radiance engines. It has been developed by the National Renewable Energy Laboratory in the US Department of Energy. It is an open-source software that was first developed as a simple plugin for SketchUp to edit the geometry and model using EnergyPlus simulation. It contains several graphical interfaces such as OpenStudio application, Sketchup Plugin, Dviewer, Results Viewer, and Parametric Analysis Tool (PAT).

SketchUp- OpenStudio: The initial model geometry can be drawn in SketchUp and building parameters are given values through the OpenStudio application.

Parametric Analysis Tool: PAT can simultaneously run simulations for various design alternatives that have been created by applying different measures to a base model. It also has a built-in directory for mathematical algorithms that can be used to simplify the optimization procedure.

Result Viewer-Dview: Results Viewer and Dviewer provide charts, maps, and other graphical documents base on the simulation results.

Ruby: Open Studio also utilizes Ruby, C++, and C# to write more commands that cannot be applied through the OpenStudio application. The above programming languages can be used to create new measures, which can apply changes to the base model.

BCL Library: All the premade measures, materials, HVAC systems, constructions, and many other building data are collected in the online Building Component Library (BCL). Users are also encouraged to share the measures they write on the BCL to further complete the library data.

Unmet Hours: Another advantage of OpenStudio is its strong user support through Unmet hours, an online platform, where people can ask questions or share ideas and get responses by a group of NREL experts or other users from all parts of the world.

EnergyPlus

EnergyPlus is a console-based and open-source whole building energy simulation program that has been developed by NREL. EnergyPlus works with text input and provides text output. It is an integrated tool to simulate heating, cooling, ventilation, water consumption, lighting illumination, and plug load in a building.

EnergyPlus utilizes Idf editor as a basic interface to simplify inserting input values to the program. It also uses EP-launch to manage the input and output and run several simulations. EP-compare is another tool that assists EnergyPlus to graphically compare the results of various simulations. Since the Idf editor environment is not user friendly, many developers have introduced an intermediary tool for creating EnerguPlus input files. Software such as OpenStudio and DesignBuilder can be named as the Graphical

User Interface (GUI) for EnergyPlus. OpenStudio creates a text input file for EnergyPlus by providing the user with a more friendly environment to insert the desired values for building parameters. Then it hands the text file to the simulation engine and after the simulation is completed, translates the text output file to understandable tables and charts.

Radiance

Radiance, developed by Greg Ward and his team, is one of the most powerful programs for lighting simulation. It is an open-source tool that is used by engineers and architects for lighting, daylighting and solar control design. Radiance, which utilizes the Ray Tracing method, is recognized as the most useful software package for architectural lighting analysis. Like EnergyPlus, Radiance is a command-line program, which requires text input and creates text output. Since the command-line interface is not user-friendly, several GUIs such as SPOT, Daysim, and OpenStudio have been developed to facilitate working with the Radiance engine[36].

Software Limitations:

- OpenStudio does not support simulation of curved geometry and surfaces.
- Many of the BCL measures, including the WWR measure, have trouble implementing the changes in the model.
- The number of software bugs after each release is comparatively more than other programs in the market.
- Since they are load-based programs, neither EnergyPlus nor OpenStudio can evaluate the quality of interior light and illumination level provided by electrical sources.
- Illuminance map in Radiance and OpenStudio are presented only in a rectangular shape. As a result, complicated floorplan geometry can hardly be supported by these tools.
- In Radiance, only one and in EnergyPlus, maximum two daylight control points can be used in each thermal zone. In some conditions, this limitation can reduce the precision of lighting results.
- There is a problem with zone areas in the EnergyPlus report. Rather than the space area, EnergyPlus takes the total area of each distinct zone (which can be made of several spaces) to report the metrics such as HVAC and lighting loads. In other words, some of the reports are based on the wrong areas.

Daylight Analysis with a combination of OpenStudio, Radiance, and EnergyPlus

Daylight illumination and glare can be calculated both with EnergyPlus and Radiance through OpenStudio GUI. OpenStudio Plugin in SketchUp provides specific objects such as illuminance map, daylight control point, glare sensor, airwall, and interior partitions, which prepare the model and enable the lighting calculations.

- An **illuminance map** visually reports the calculated light level or Illuminance all over its boundary.

- **Daylight control points** change the electrical lighting schedule according to the available daylight and reduce the lighting power consumption. Note that two daylight control points are allowed for each thermal zone in EnergyPlus simulation.
- **Glare sensors** can report the glare index where they are located.
- **Air walls** construction has no architectural counterpart and is used to divide spaces and define thermal zone boundaries. To avoid blocking the sunlight, surfaces with air wall construction are ignored by the Radiance Translator.
- **Interior Partitions** are used to model interior obstructions such as columns, furniture, etc.

After setting up the objects required for daylight calculation, OpenStudio can transfer the input file either to EnergyPlus or Radiance. By activating the Radiance measure in OpenStudio, instead of EnergyPlus, Radiance will be used for daylight calculation. Radiance uses the backward Raytracing method while EnergyPlus uses Radiosity in DELight method and Split-flux in Detailed method. [17, Tab 3.9] shows the lighting simulation algorithms, methods, and types.

Table 3.59 Summary of Simulation Tool Components

PROGRAM	SIMULATION ALGORITHM (TYPES)	CONTROL SYSTEM MODEL (ELECTRIC LIGHTING)
EnergyPlus - Detailed	Split-flux (interpolated design day)	Illuminance proxy (load based)
EnergyPlus - DELight	Radiosity (interpolated design day)	Illuminance proxy (load based)
OpenStudio	Raytracing, (point-in-time, single- or 3-phase DC)	Illuminance proxy or Sensor signal (load based)

3.6 Energy Modelling Process

The following figures present the steps that were taken to run the simulation and yield the results.

1. Modeling the building geometry and exterior shadings in SketchUp

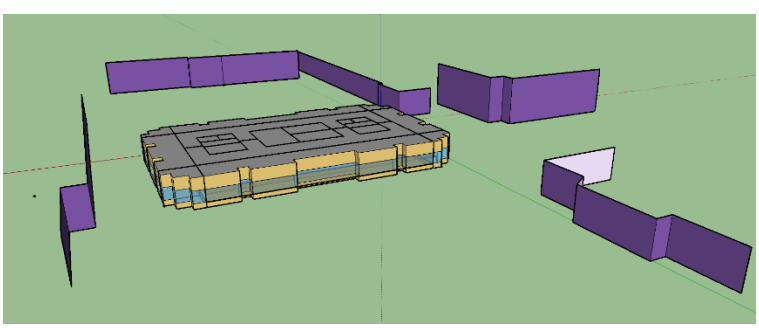


Figure 3.22 Exterior Shades

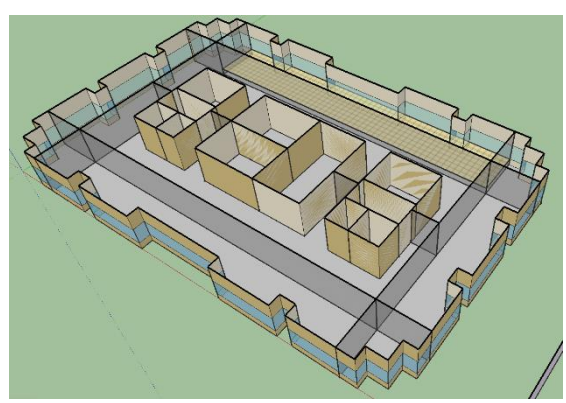


Figure 3.23 Interior Walls

2. Assigning thermal zones, constructions, and lighting calculation objects

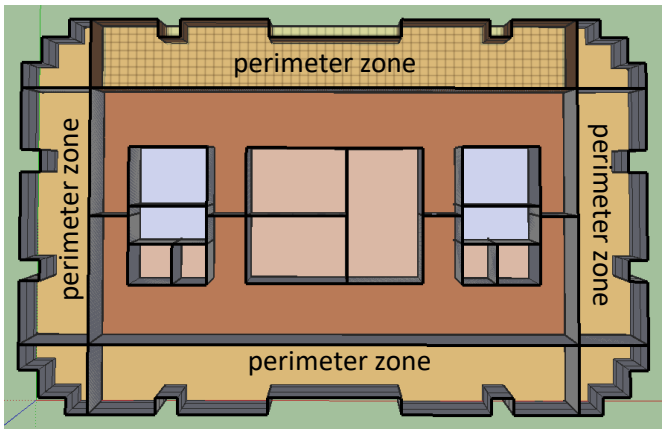


Figure 3.24 Thermal Zones

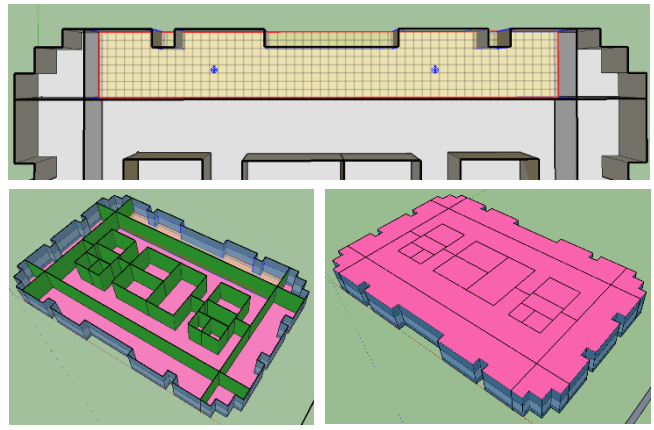


Figure 3.25 Surface Boundary Condition

Figure 3.26 Illumination Map

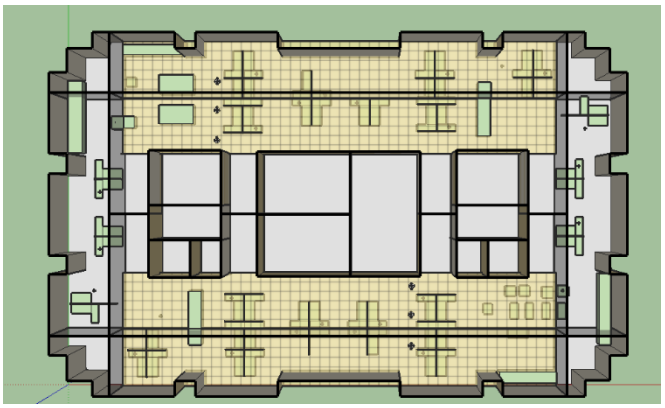


Figure 3.27 Interior Obstructions

Interior obstructions such as furniture and dividers were modeled with Interior partitions and given appropriate reflection values through OpenStudio application.

3. Assigning building parameters in OpenStudio Application

Figure 3.28 shows the OpenStudio application Interface. There are 15 tabs in the ribbon to the left of the screen, each allocated to one building category.

Site
Schedual
Construction
Loads
Space Types
Geometry
Facility
Spaces
Thermal Zones
HVAC Systems
Output Variables
Simulation Settings
Measures
Run Simulation
Results Summary

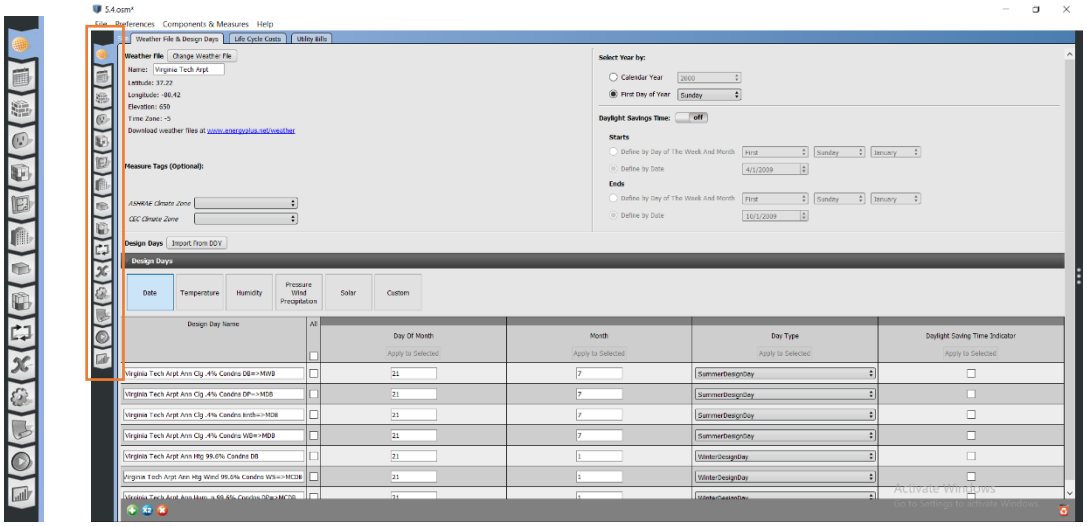
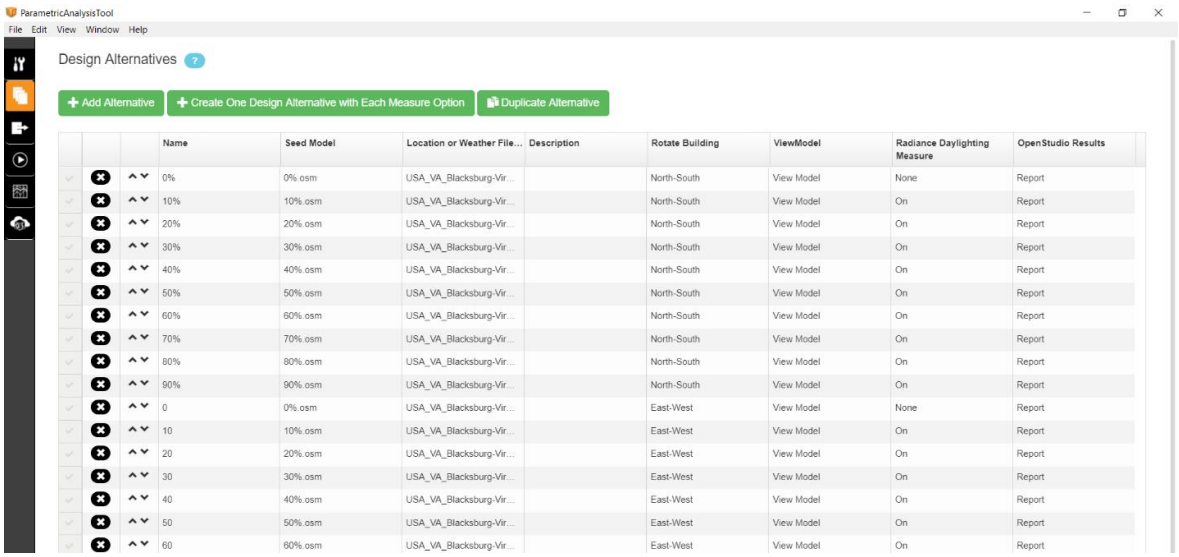


Figure 3.28 OpenStudio Workflow

4. Completing the model and importing it to the PAT

PAT provides a platform to make design alternatives through the combination of research variables. BCL measures are useful components that help to create design alternatives in OpenStudio. This study used Building Rotation, Radiance, OpenStudio Result, and View Model measures to create design alternatives. Instead of using WWR measure in OpenStudio, 9 seed models each with distinct WWR were imported to the PAT to represent the variable. Also, rather than using a lighting measure, lighting loads for LED and fluorescent scenarios have been addressed in the distinct seed models.



Name	Seed Model	Location or Weather File...	Description	Rotate Building	ViewModel	Radiance Daylighting Measure	OpenStudio Results
0%	0%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	None	Report
10%	10%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	On	Report
20%	20%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	On	Report
30%	30%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	On	Report
40%	40%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	On	Report
50%	50%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	On	Report
60%	60%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	On	Report
70%	70%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	On	Report
80%	80%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	On	Report
90%	90%.osm	USA_VA_Blacksburg-Vir...		North-South	View Model	On	Report
0	0%.osm	USA_VA_Blacksburg-Vir...		East-West	View Model	None	Report
10	10%.osm	USA_VA_Blacksburg-Vir...		East-West	View Model	On	Report
20	20%.osm	USA_VA_Blacksburg-Vir...		East-West	View Model	On	Report
30	30%.osm	USA_VA_Blacksburg-Vir...		East-West	View Model	On	Report
40	40%.osm	USA_VA_Blacksburg-Vir...		East-West	View Model	On	Report
50	50%.osm	USA_VA_Blacksburg-Vir...		East-West	View Model	On	Report
60	60%.osm	USA_VA_Blacksburg-Vir...		East-West	View Model	On	Report

Figure 3.29 PAT Workflow

5. Running the simulation and analyzing the results

The simulation was run in batch and the desired metrics from EnergyPlus and OpenStudio reports were extracted for further analysis. To better understand the results, they have been visualized into graphs and tables using MATLAB and Flourish online tool[37].

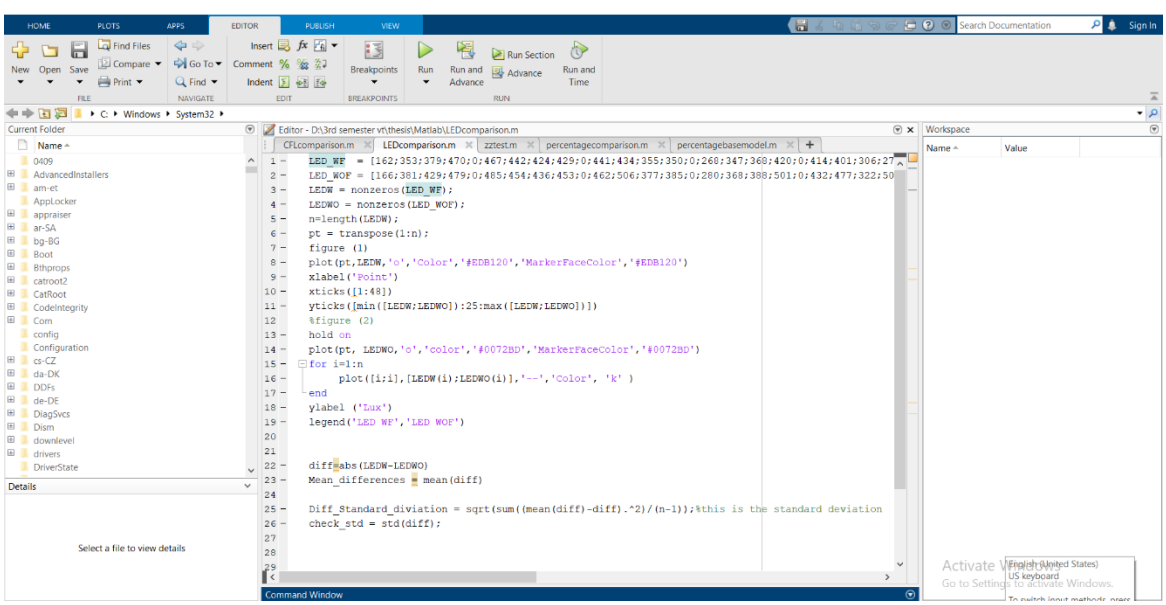


Figure 3.30 MATLAB Workflow

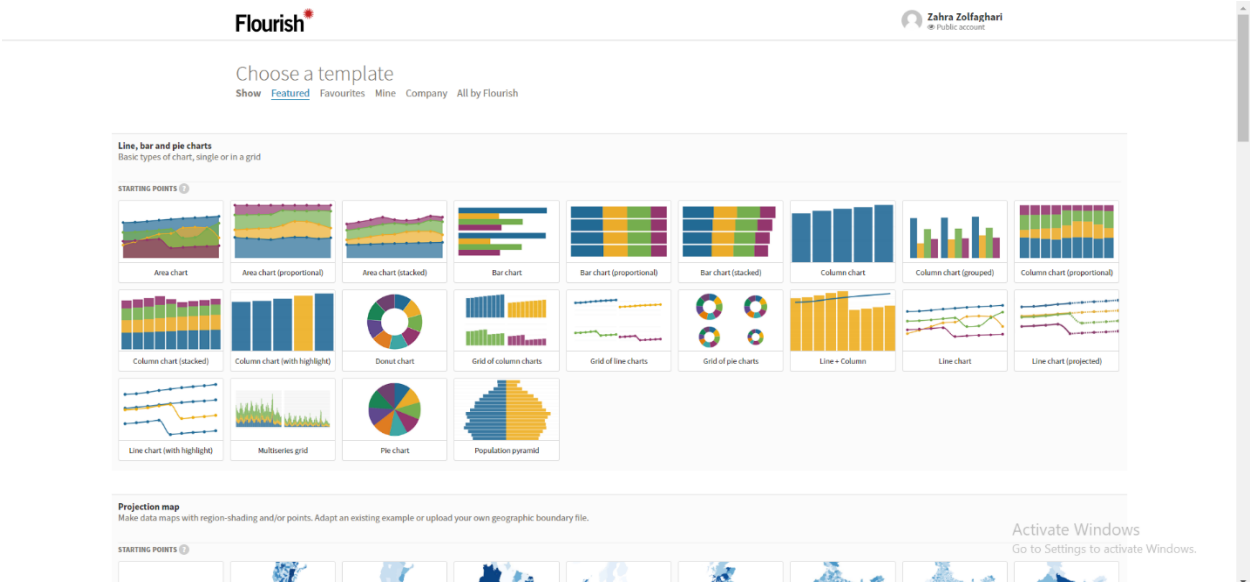


Figure 3.31 Flourish Data Visualization and Storytelling [26]

Chapter 4 : **Data Analysis and Results**

4.1 Simulation Results

In the following chapter, results of the study are presented in two sections:

1. Lighting analysis
2. Energy Performance and daylight analysis

To understand the relationship between research variables and the whole building energy consumption, in each section, the simulation outputs are presented through readable graphics.

4.2 Lighting Analysis:

As mentioned in the previous chapter, OpenStudio and EnergyPlus which are load-based programs, are not able to measure the sufficiency of interior light levels. To address this issue, AGi32 and its Revit extension, ElumTools, were used for the photometric prediction and interior lighting calculation. Figure 4.1 depicts the reflected ceiling plan proposed for the open office in which location and type of the luminaires are the same for LED and fluorescent scenarios.

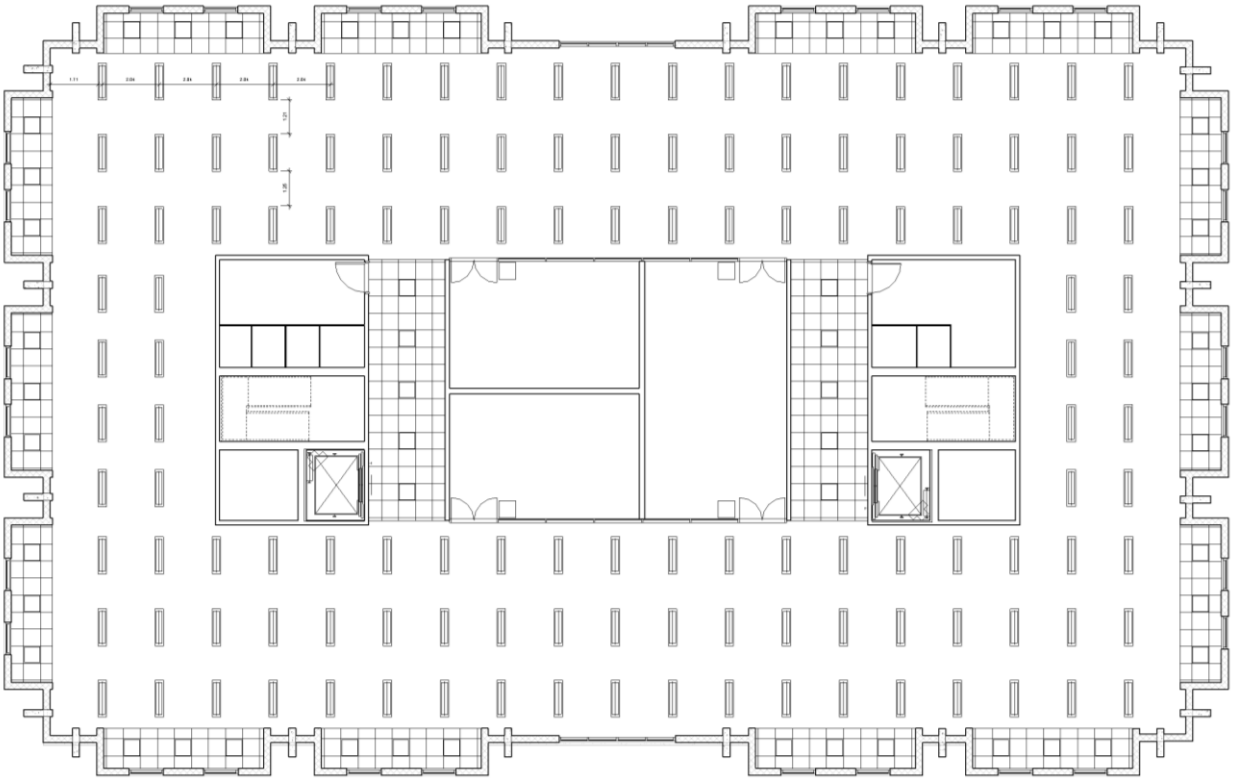


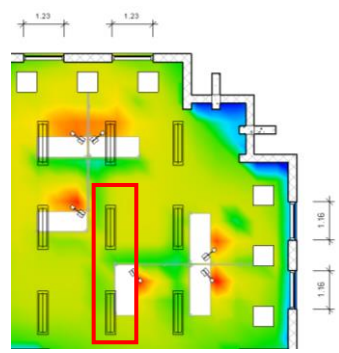
Figure 4.1 Luminaires Type and Location

Running the lighting simulation with different luminaires eventually led to finding the handful of LED and fluorescent luminaires with rather a close illumination output. In the last run, six types of luminaires (three for LED and three for fluorescent) were selected for inclusion in the study with the following lighting information:

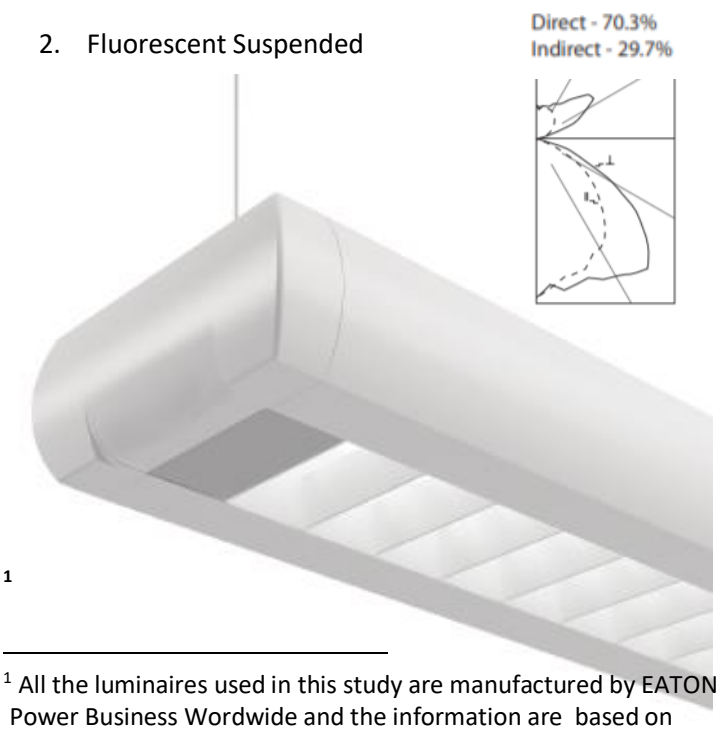
1. LED Suspended

CCT: 3500K

Lamp Count	308
Lumens per Lamp	Absolute
Proration Factor	1.00
Total Lamp Lumens	Absolute
Luminaire Lumens	2096
Efficiency (%)	NaN
Luminaire Watts	15
Ballast Factor	1.00
Total Light Loss Factor	1.00



2. Fluorescent Suspended



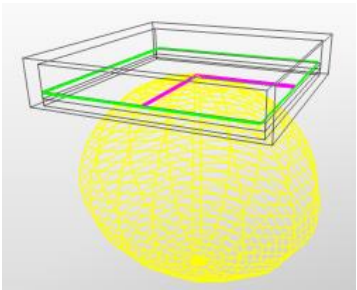
CCT: 3500K

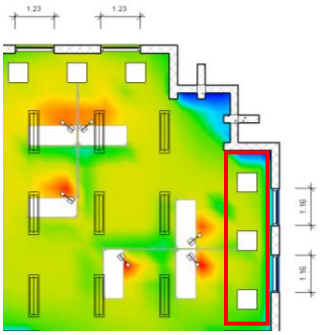
Lamp Count	1
Lumens per Lamp	2900
Proration Factor	1.00
Total Lamp Lumens	2900
Luminaire Lumens	2343
Efficiency (%)	81
Luminaire Watts	39
Ballast Factor	1.00
Total Light Loss Factor	1.00

[1]

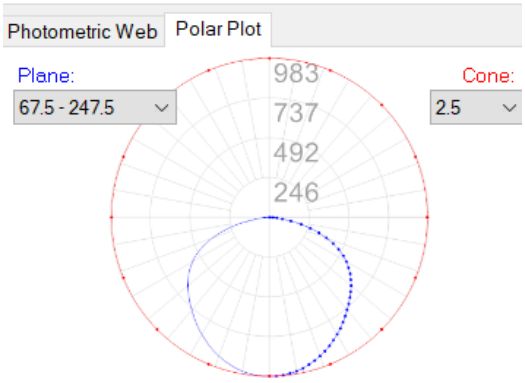
[1] All the luminaires used in this study are manufactured by EATON Power Business Wordwide and the information are based on EATON website[38]

3. LED Recessed

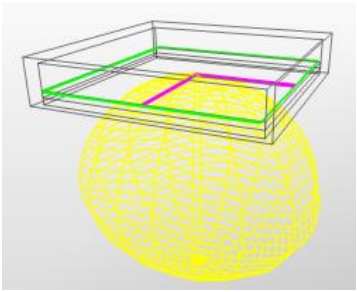




	Modified
Lamp Count	168
Lumens per Lamp	Absolute
Proration Factor	1.00
Total Lamp Lumens	Absolute
Luminaire Lumens	2987
Efficiency (%)	NaN
Luminaire Watts	29
Ballast Factor	1.00
Total Light Loss Factor	1.00

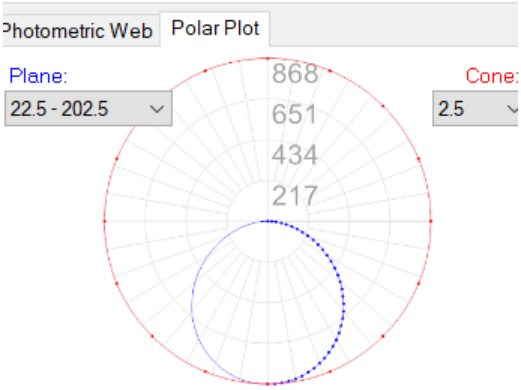


4. Fluorescent Recessed



Lamp Count	2
Lumens per Lamp	1750
Proration Factor	1.00
Total Lamp Lumens	3500
Luminaire Lumens	2710
Efficiency (%)	77
Luminaire Watts	50
Ballast Factor	1.00
Total Light Loss Factor	1.00

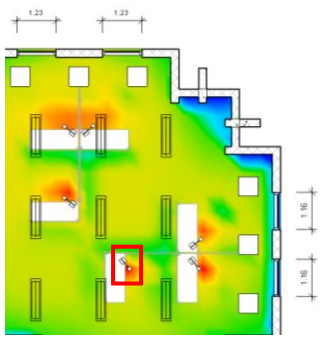
[2]

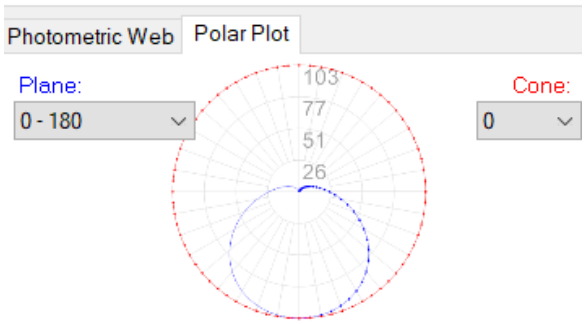


5. LED Task Light

[2] All the luminaires used in this study are manufactured by EATON Power Business Wordwide and the information are based on EATON website[38]

	Modified	F
Lamp Count	1	
Lumens per Lamp	450	
Proration Factor	1.00	
Total Lamp Lumens	450	
Luminaire Lumens	450	
Efficiency (%)	100	
Luminaire Watts	5	
Ballast Factor	1.00	
Total Light Loss Factor	1.00	

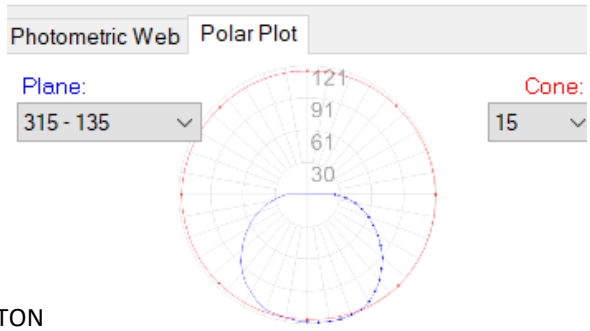




6. Fluorescent Task Light

	Modified	I
Lamp Count	1	
Lumens per Lamp	450	
Proration Factor	1.00	
Total Lamp Lumens	450	
Luminaire Lumens	450	
Efficiency (%)	100	
Luminaire Watts	15	
Ballast Factor	1.00	
Total Light Loss Factor	1.00	

[3]



[3] All the luminaires used in this study are manufactured by EATON Power Business Wordwide and the information are based on EATON website[38]

All luminaires were selected based on the following properties: wattage, lumens per lamp, number of lamps, luminaire lumens, and total lamp lumens. Suspended luminaires were selected for the main ceiling area and recessed luminaires were selected for the nooks. Note that in suspended luminaires, about 30% of the light is drawn up to the ceiling to provide the space with ambient light and 70% of the light is drawn down to the floor to directly illuminate the task areas and corridors.

4.2.1 Important Observation

To ensure that the process was more efficient and less time-consuming, each set of the selected luminaires was first tested in the model without furniture because the furniture complicates the model's geometry and drastically increases the time of lighting computation. After observing rather close results to the target illuminance in most of the areas in the floorplan, the furniture was then added to deliver more precise results. When selecting the luminaires, it is helpful to obtain an approximation regarding the lamps' performance before running the complete simulation. This method revealed an interesting point about the difference in LED and fluorescent illumination patterns.

Following the above method and in the initial run, a set of fluorescent luminaires was selected after confirming the proximity of their lighting output with the target illuminance. However, in the second run with furniture in the model, illuminance reduction of about 90 lux was reported in almost all the calculation points. Adding furniture to the model led to illuminance reduction in the LED scenario as well, but the average of reported reduction in each point was about half of the fluorescent case (50 lux). Figure 4.2 demonstrates the ElumTools' numerical output along with the randomly-selected calculation points for comparing illuminance in the models with and without furniture. Figures 4.3 and 4.4 depict the illuminance difference in the selected calculation points in models with and without furniture.

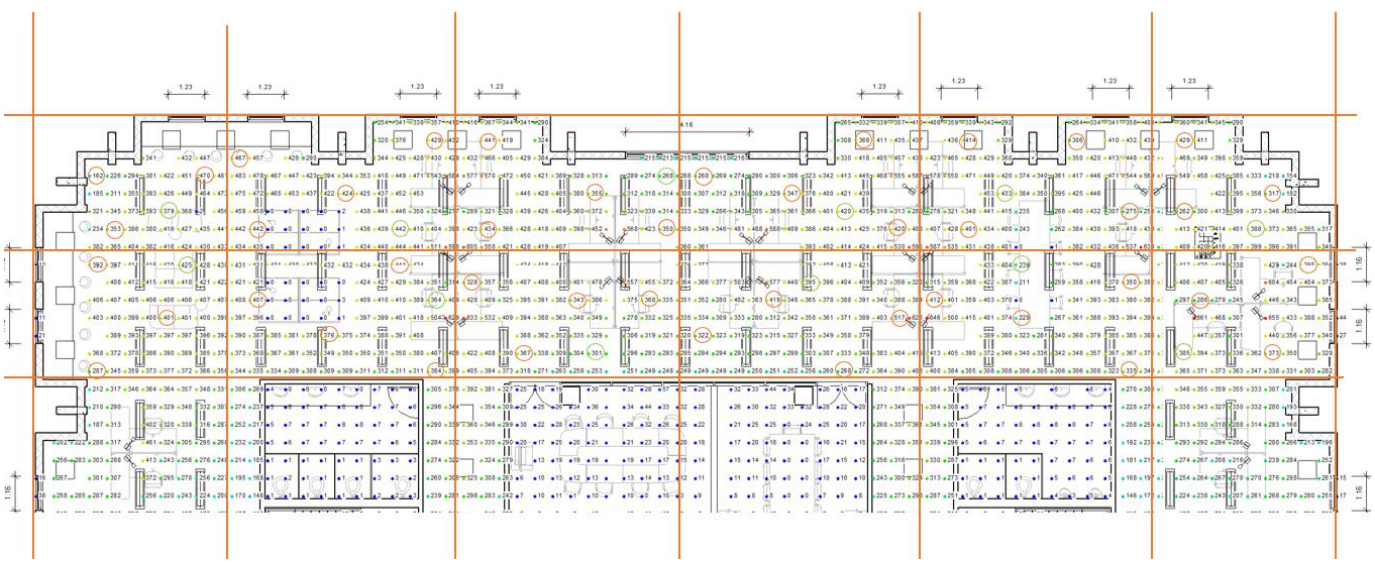


Figure 4.2 Representative Sample

Comparison of the fluorescent scenario's illuminance values with and without furniture

Standard Deviation fluorescent: 69.85

Mean difference = 91.37

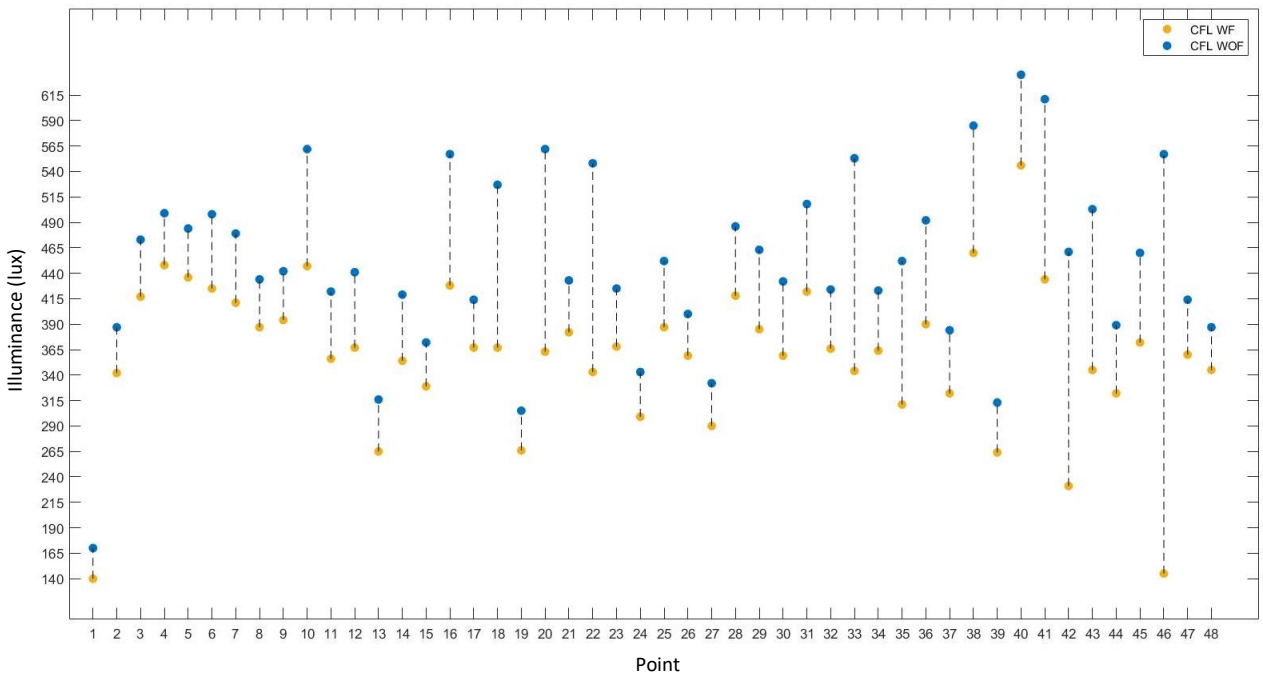


Figure 4.3 Fluorescent Illumination Difference with and Without Furniture

Comparison of the LED scenario's illuminance values with and without furniture

Mean difference = 49.68

Standard Deviation LED: 61.35

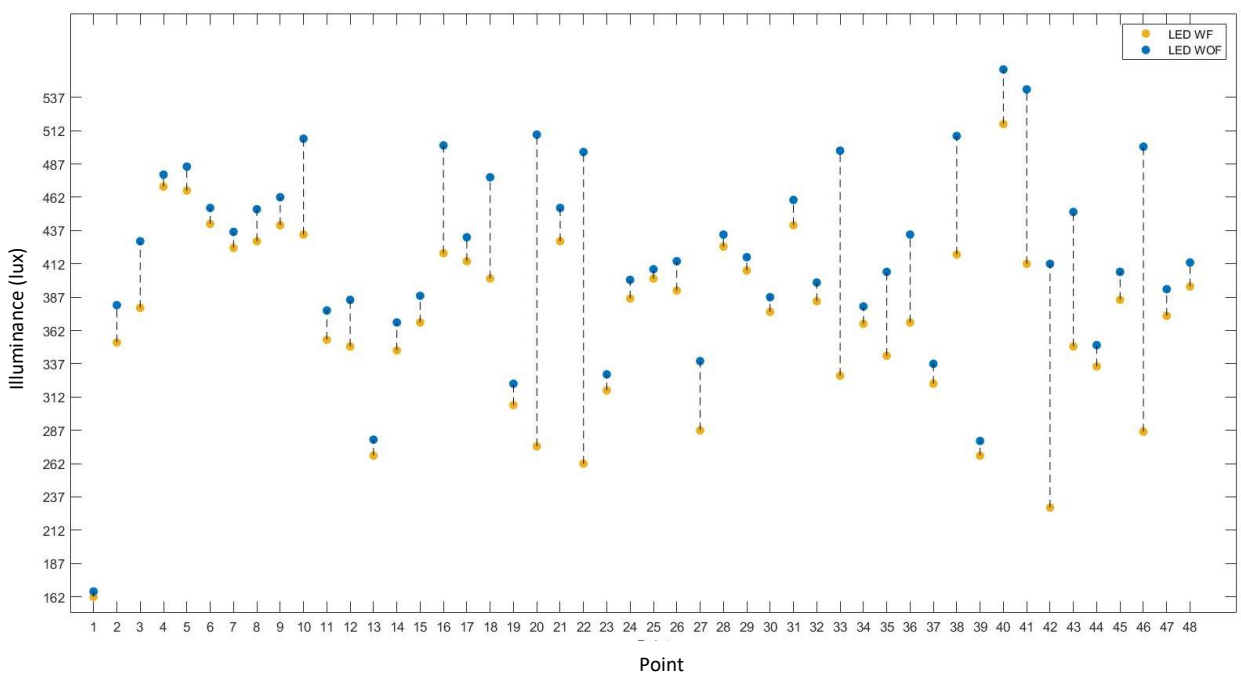


Figure 4.4 LED Illumination Difference With and Without Furniture

LED and fluorescent percentage differences with and without furniture
Mean difference fluorescent= 12.17%
Mean difference LED= 4.55%

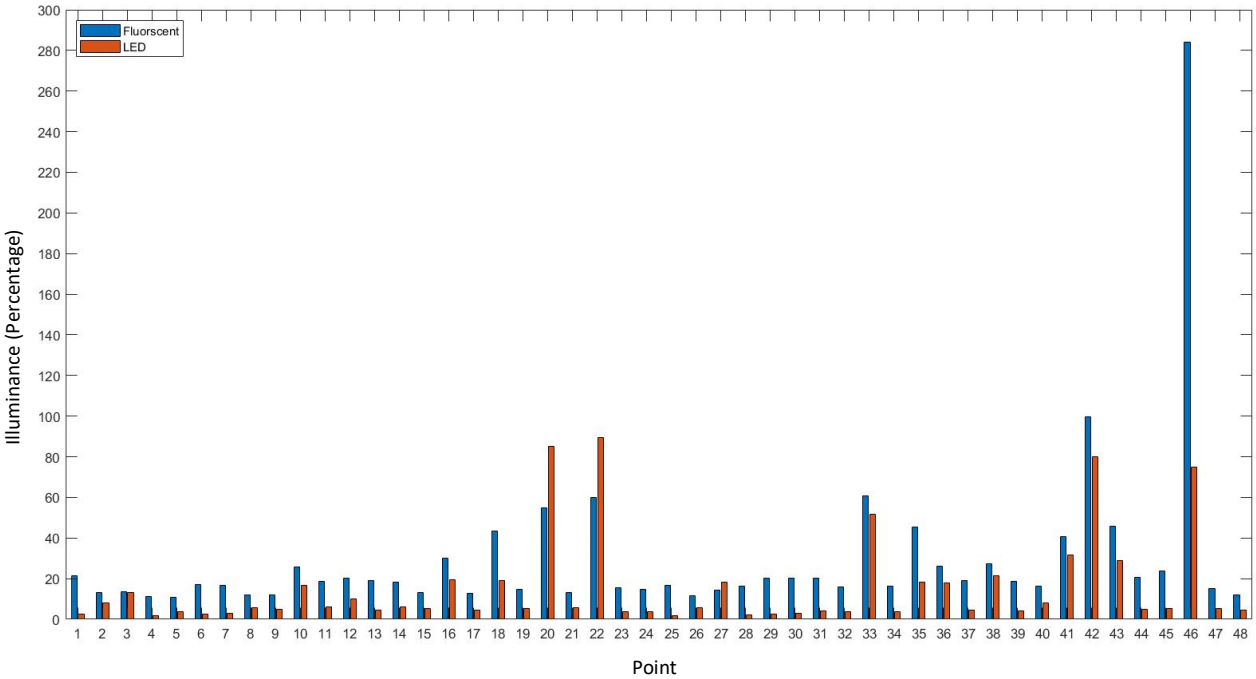


Figure 4.5 LED and Fluorescent Difference Percentage

More reduction in the fluorescent case stems from the difference in light distribution patterns between the two light sources. Fluorescent light sources emit light in an omnidirectional pattern. This means that they radiate light 360 degrees around the tube which illuminate its surroundings in all directions. As a result, only a small percentage of the light will be received by a specific target and the rest will be directed toward all directions. To solve this problem, reflectors and other utilities can be used in a fluorescent luminaire to direct the light to a specific target. In contrast, LED light sources emit light in a directional pattern. In other words, they radiate light within a 110-degree arch which helps them to direct the light toward specific targets and prevent wasting electricity energy by scattering the light toward useless directions. This feature in LED light sources removes the need for bulky and advance reflectors. Thus, it can be assumed that compared to LED scenarios, the percentage of light reaching the task surfaces is smaller in the fluorescent scenarios even with the presence of reflectors in their luminaires. This smaller percentage of illuminance further will be absorbed and reflected by furniture surfaces, which causes even more reduction in the light level.

4.2.2 AGi32:

AGi32 is one of the main products of the Colorado-based Lighting Analyst software developers for photometric prediction. It is a standalone software that has a distinct user interface and requires modeling geometries in its environment. Although 2D file formats such as DWG can be imported to the program without any problem, it is unable to import 3D files and calculate the models with complicated geometries. All of these problems led to using ElumTools, which is AGi32 ‘ plugin for Revit.

4.2.3 ElumTools:

Elumtool is the only fully integrated lighting calculation plugin for Revit Autodesk. It provides Revit with a tab for lighting analysis through which one can change and edit the reflectance values in the material library, import the Revit lighting families and IES files, and locate the luminaires in the spaces. Compared to other lighting analysis tools, AGI32 and ElumTools have the advantage of producing realistic renders and strong visualizations that can perfectly depict the lighting quality in and outside the building. The following figures depict some of the Elumools and AGi32's graphical outputs including the illumination maps, Pseudo renders, pseudo maps, and lighting reports of the photometric simulation in this study.

1. Realistic Renders

Both ElumTools and AGi32 are Radiosity based software, well-known for their high visualization power. Figure 4.2 to figure 4.6 show samples of realistic renders, which detail the furniture, materials, and precise lighting outlook of the space.

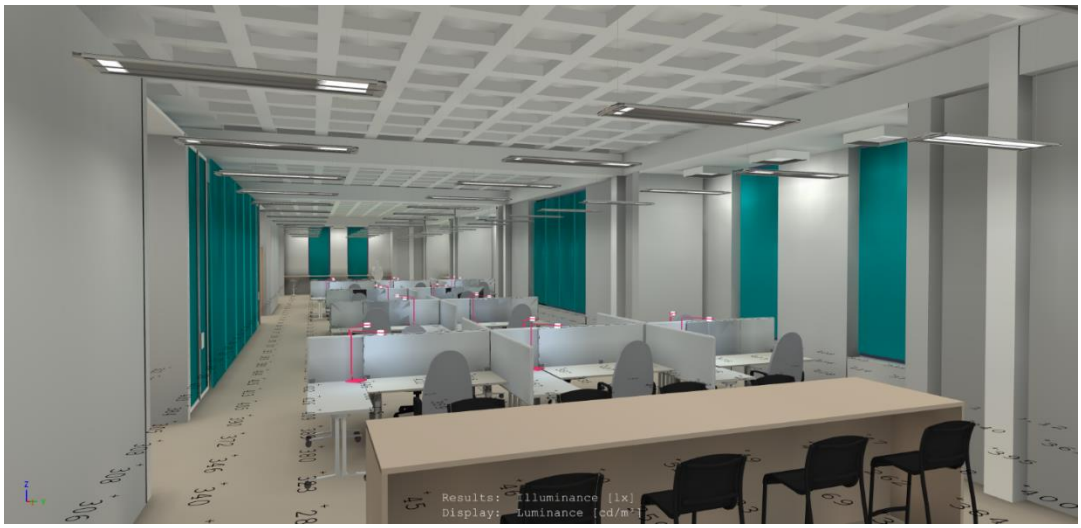


Figure 4.6 ElumTools Render output

Direct and Inter-reflected Light

Figure 4.7 Direct and Inter-reflected Render

Direct Only Light

Figure 4.8 Direct Only Render

Inter-reflected Only Light

Figure 4.9 Inter-reflected render

2. Contour and Spatial Maps

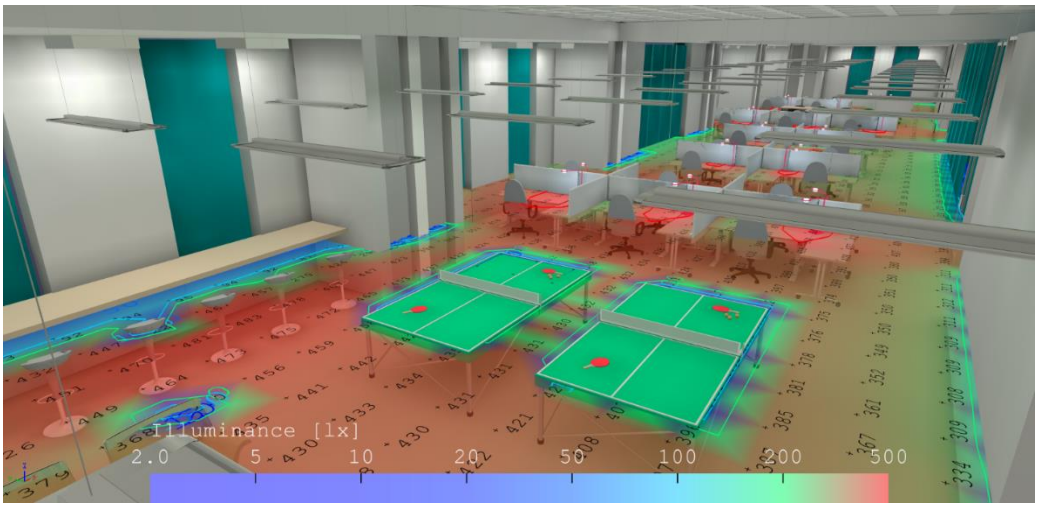


Figure 4.10 Contour Render

3. Pseudo Renders

ElumTools and AGi32 create “Illuminance” and “Luminance” Pseudo color 3D and 2D graphics along with showing the calculation points with their numerical values.

Luminance Pseudo Renders

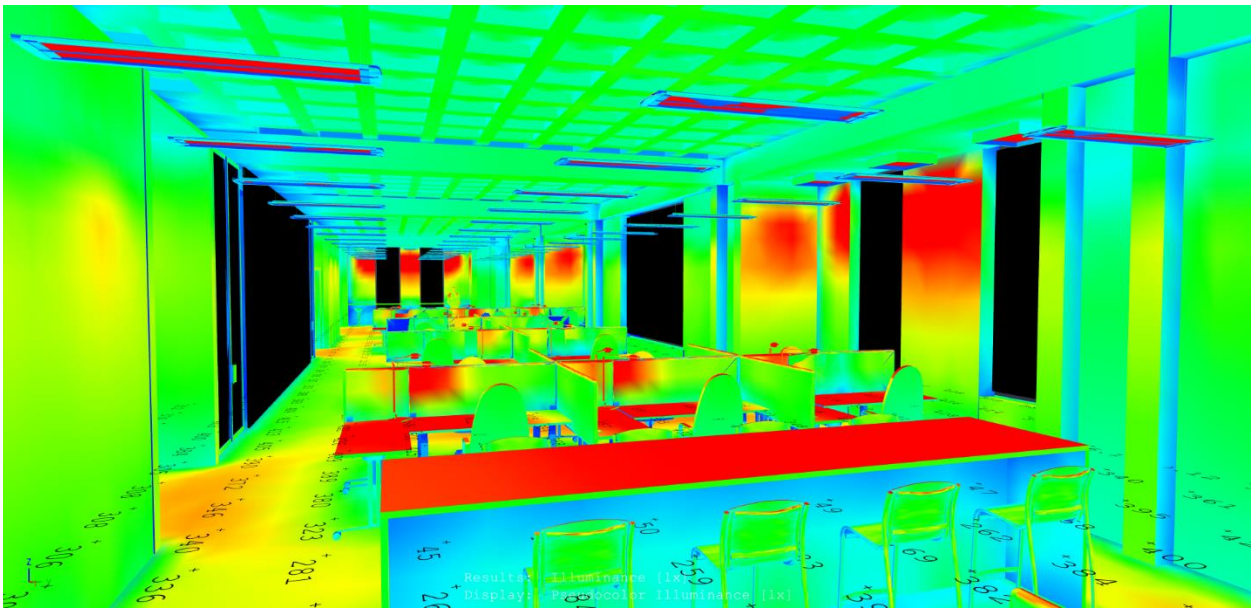


Figure 4.11 Luminance Pseudo Renders

Illuminance Pseudo Renders

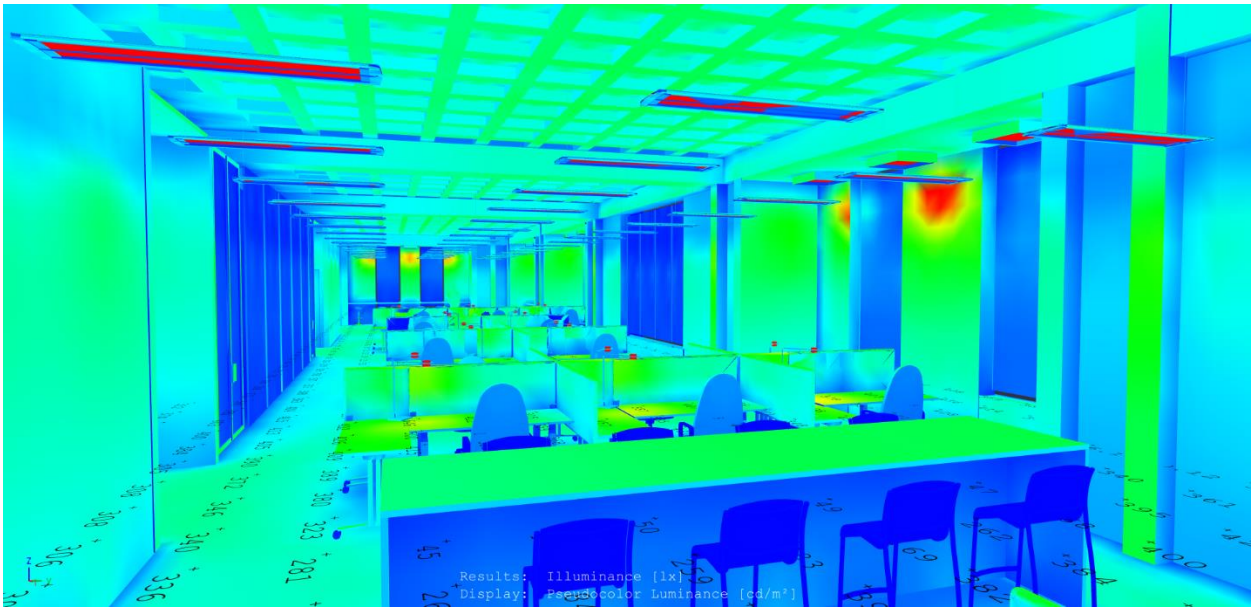


Figure 4.12 Illuminance Pseudo Renders

4.2.4 ElumTools Results:

Several steps were taken to prepare the model for lighting simulation. In the first step, appropriate surface reflection values were assigned to the materials. Next, the location of calculation points, their

quantity, their distance from each other, and their heights were set up. Afterward, the IES files of the selected luminaires were inserted into the software, and the simulation was set to run. By statistically analyzing the illuminance in the calculation points, proximity of results in the LED and the fluorescent versions was verified. Figure 4.9 and Figure 4.10 show the numerical output of ElumTools with associated illuminance values in each calculation point.

Average illuminance

Average illuminance, the illuminance averaged over a specific area, is one of the important measures to compare the proximity of light levels in two spaces. Average illuminance is derived from an average of the illuminances of a representative number of points on a surface. In this study, the total average illuminance in the task height reported by ElumTools was 142 lux for the LED scenario, and 139 lux for the fluorescent scenario. Note that the low average illuminance of both scenarios compared to IESNA's required illuminance (300-500lux) is due to the many calculation points located inside the smaller rooms, which do not receive any light (0 lux).

Illumination in LED scenario

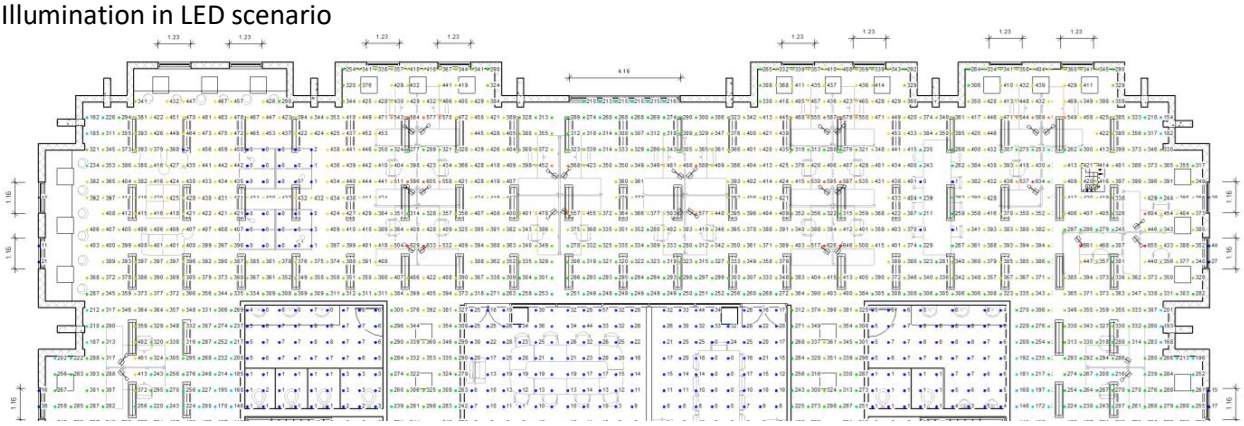


Figure 4.13 LED Lighting Result

A	B	C	D	E	F	G
Calculation Points	Average	Maximum	Minimum	Avg/Min	Max/Min	Max/Avg
Room 1	142 lx	661 lx	0 lx	25707736265.5	119397074691.0	4.6

Illumination in Fluorescent Scenario

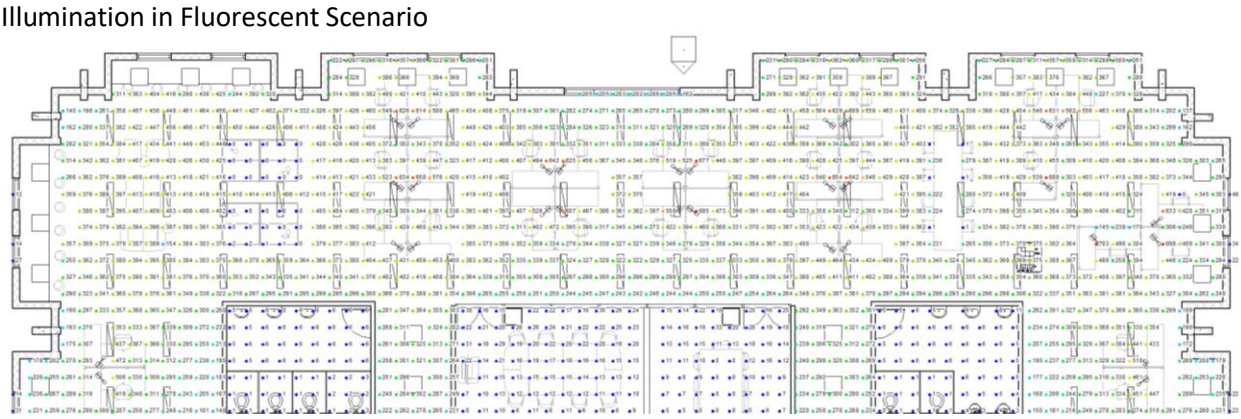


Figure 4.14 Fluorescent Lighting Result

A	B	C	D	E	F	G
Calculation Points	Average	Maximum	Minimum	Avg/Min	Max/Min	Max/Avg
Room 1	139 lx	703 lx	0 lx	4646669332.8	23578127772.6	5.1

LED Pseudo Map

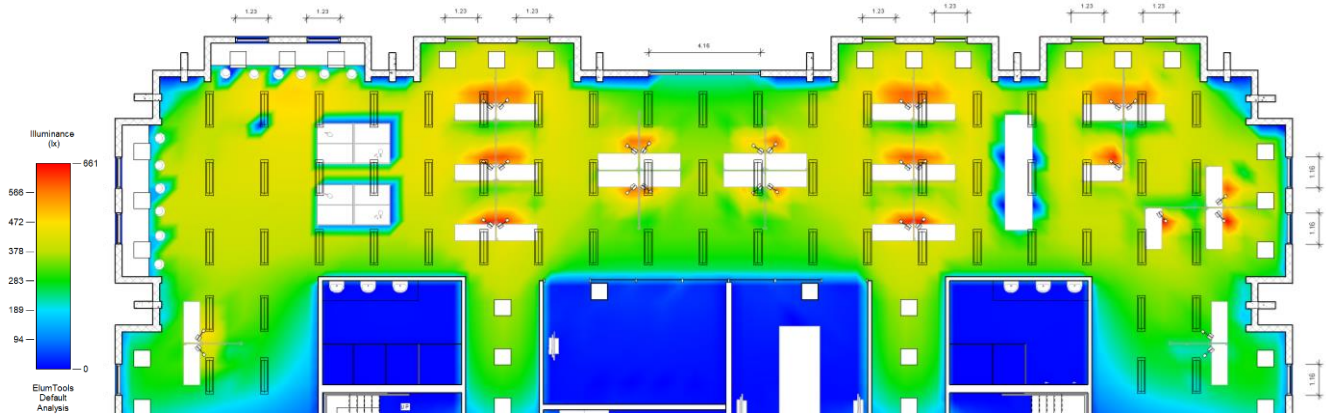


Figure 4.15 LED Pseudo Map

Fluorescent Pseudo Map

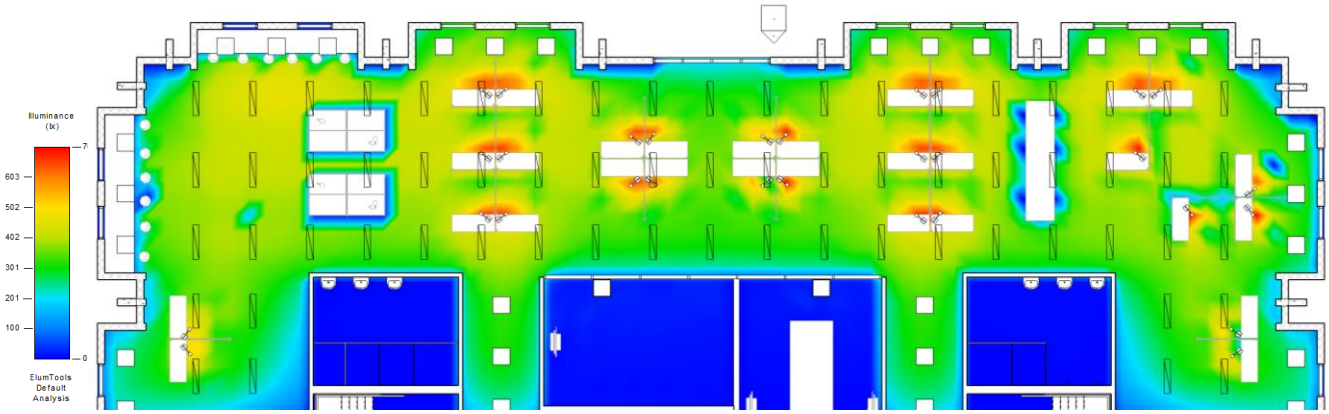


Figure 4.16 Fluorescent Pseudo Map

Since the plan is symmetrical, only half of the building was simulated to reduce the computation time. Also, the model does not have any windows and consequently, daylight cannot affect the interior lighting. As a result, the other half of the plan facing South shares the same values. Note that the spaces with functions other than open offices were excluded from the simulation in order to focus only on open office function. According to the Illuminating Engineering Society of North America (IESNA), the recommended illumination level in open offices falls within 300 to 500 lux. As a common strategy to reduce the lighting energy consumption, the ambient light level in the open office was set to 400 lux and separate task lights were considered for each workstation (desk).

Table 4.6 Standard Illumination Level [24]

ROOM TYPE	LIGHT LEVEL (FOOT CANDLES)	LIGHT LEVEL (LUX)	IECC 2015 LIGHTING POWER DENSITY (WATTS PER SF)
Conference Room	30-50 FC	300-500 lux	1.23
Lobby - Office/General	20-30 FC	200-300 lux	0.90
Locker Room	10-30 FC	100-300 lux	0.75
Lounge / Breakroom	10-30 FC	100-300 lux	0.73
Mechanical / Electrical Room	20-50 FC	200-500 lux	0.95
Office - Open	30-50 FC	300-500 lux	0.98
Office - Private / Closed	30-50 FC	300-500 lux	1.11
Parking - Interior	5-10 FC	50-100 lux	0.19
Restroom / Toilet	10-30 FC	100-300 lux	0.98

After achieving the results, to verify the similarity of illuminance in LED and fluorescent calculation points, a statistical comparison was performed by dividing the plan into twelve clusters and randomly picking three or four calculation points from each cluster. The values for all the selected calculation points were gathered and organized in excel sheets to be served as a representative sample. This sample was then inputted into MATLAB for statistical operation.

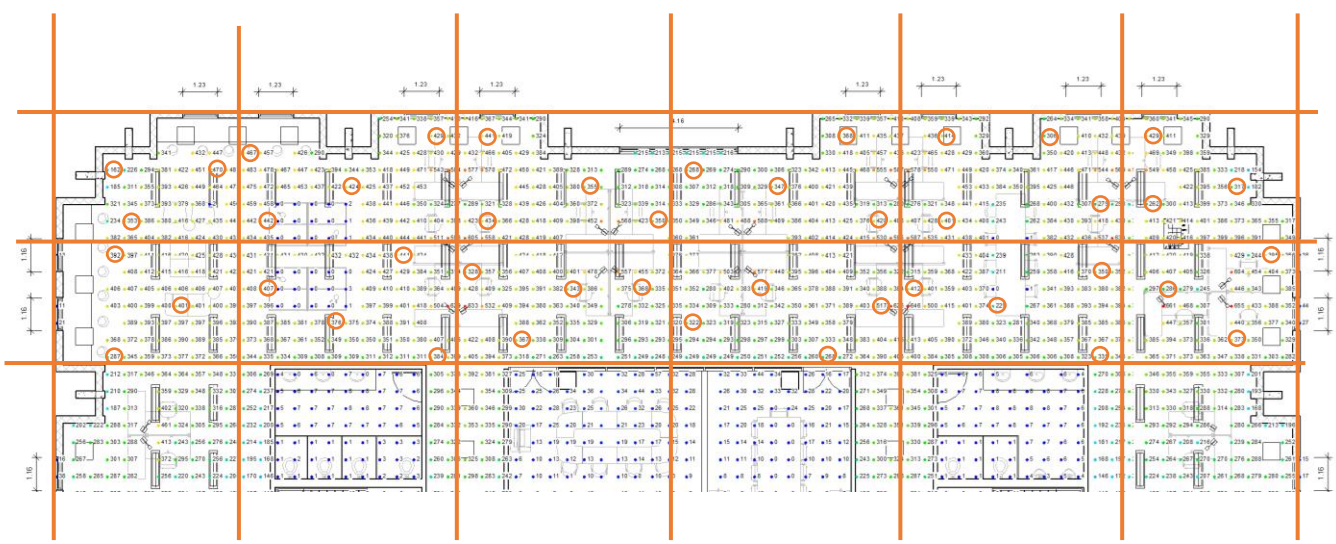


Figure 4.17 Clustered Map

MATLAB, which is a programming software developed by Math Works, was used to process data and produce graphs in a less time-consuming manner. The following figures show the MATLAB outputs visualizing the lighting results:

1. Difference between LED and fluorescent's illuminance in each point
   Mean difference: 26.5227

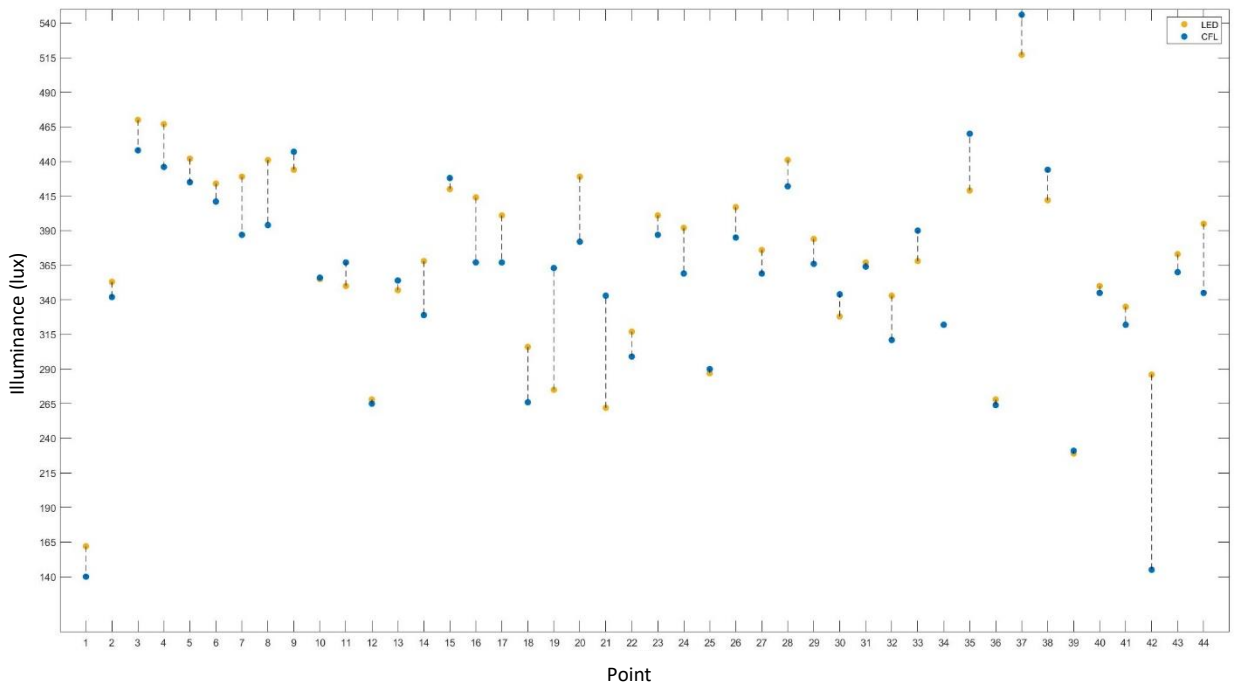


Figure 4.18 Illumination Difference

2. Difference between LED and fluorescent's illuminance in each point
   Max difference: 141
   Min difference: 0
   Standard Deviation: 26.29

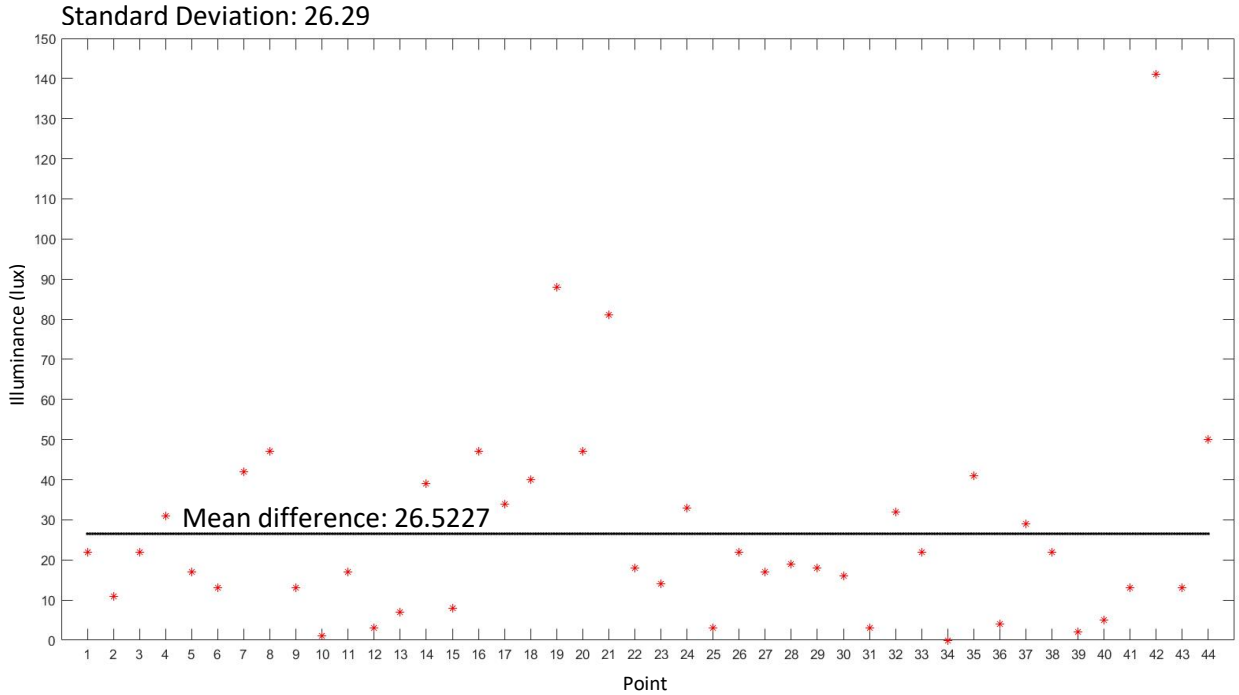


Figure 4.19 Deviations from Mean Difference

3. Percentage difference between LED and fluorescent's illuminance in each point

   Mean difference = 12.65%

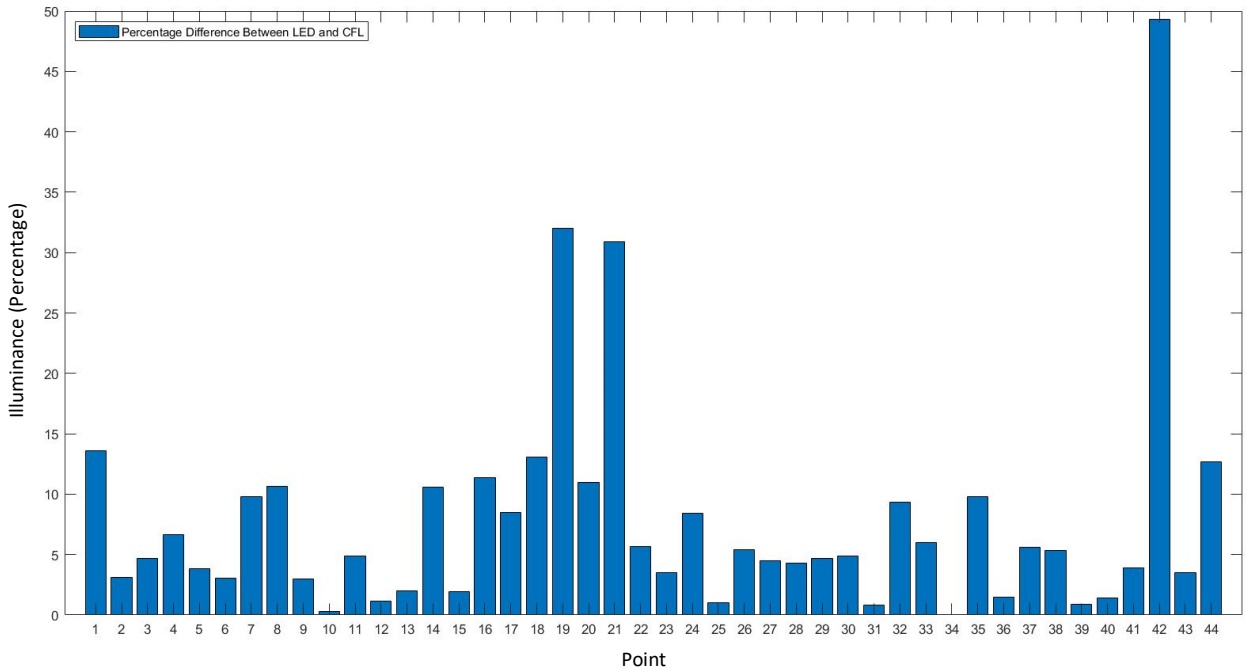


Figure 4.20 Difference Percentage

4. Lighting Power Density:

After verifying the adequacy and proximity of the illuminance level in LED and fluorescent cases, lighting power density (LPD) was calculated via the space-by-space method. LPD for each light source was then compared with the codes to check for compliance[39].

Total Area = 11885 sqft

LED:

(24 * 29) + (130*15) + (60*5) =2946W

2946/ 11885 = 0.24 W/sqft

2946/ 1104 = 2.66 W/sqm

Fluorescent:

(24 * 50) + (130*39) + (60*10) =6870W

6870/ 11885 = 0.57 W/sqft

6870/ 1104 = 6.22 W/sqm

According to the ASHRAE Standard 90.1, version 2010, the LPD for an open office should be below 0.98 w/sqft. The calculated lighting power densities for both light sources are below 0.98w/sqft. So, the LPDs comply with codes.

Table 4.10 Lighting Power Densities Using Space-by-Space Method [28]

TABLE 9.6.1 Lighting Power Densities Using the Space-by-Space Method
ANSI/ASHRAE/IESNA Standard 90.1-2010

In cases where both a common space type and a building-specific type are listed, the building specific space type shall apply.

Common Space Types	LPD, watts/sf
Atrium – First 40 ft. in height	0.03 per ft.
Height above 40 ft.	0.02 per ft.
Audience/Seating Area-Permanent:	
For auditorium	0.79
For Performing Arts Theater	2.43
For Motion Picture Theater	1.14
Classroom/Lecture/Training	1.24
Conference/Meeting/Multipurpose	1.23
Corridor/Transition	0.66
Dining Area	0.65
For Bar Lounge/Leisure Dining	1.31
For Family Dining	0.89
Dressing/Fitting Room for Performing Arts Theater	0.40
Electrical/Mechanical	0.95
Food Preparation	0.99
Laboratory: For Classrooms	1.28
For Medical/Industrial/Research	1.81
Lobby	0.90
For Elevator	0.64
For Performing Arts Theater	2.00
For Motion Picture Theater	0.52
Locker Room	0.75
Lounge/Recreation	0.73
Office: Enclosed	1.11
Open Plan	0.98
Restrooms	0.98
Sales Area	1.68
Stairway	0.69
Storage	0.63
Workshop	1.59

Building-Specific Space Types	LPD, watts/sf
Automotive: Service/Repair	0.67
Bank/Office: Banking Activity Area	1.38
Convention Center: Audience Seating	0.82
Exhibit Space	1.45
Courthouse/Police Station/Penitentiary:	
Courtroom	1.72
Confinement Cells	1.10
Judges Chambers	1.17
Penitentiary Audience Seating	0.43
Penitentiary Classroom	1.34
Penitentiary Dining	1.07
Dormitory: Living Quarters	0.38
Fire Station: Engine Room	0.56
Sleeping Quarters	0.25
Gymnasium/Fitness Center: Fitness Area	0.72
Gymnasium Audience Seating	0.43
Playing Area	1.20
Hospital: Corridor/Transition	0.89
Emergency	2.26
Exam/Treatment	1.66
Laundry/Washing	0.60
Lounge/Recreation	1.07
Medical Supply	1.27
Nursery	0.88
Nurses Station	0.87
Operating Room	1.89
Patient Room	0.62
Pharmacy	1.14
Physical Therapy	0.91
Radiology/Imaging	1.32
Recovery	1.15
Hotel/Highway Lodging: Hotel Dining	0.82
Hotel Guest Rooms	1.11
Hotel Lobby	1.06
Highway Lodging Dining	0.88
Highway Lodging Guest Rooms	0.75
Library: Card File and Cataloging	0.72
Reading Area	0.93
Stacks	1.71
Manufacturing: Corridor/Transition	0.41
Detailed Manufacturing	1.29
Equipment Room	0.95
Extra High Bay (>50 ft. Floor to Ceiling Height)	1.05
High Bay (25-50 ft. Floor to Ceiling Height)	1.23
Low Bay (<25 ft. Floor to Ceiling Height)	1.19
Museum: General Exhibition	1.05
Restoration	1.02
Parking Garage: Garage Area	0.19
Post Office: Sorting Area	0.94
Religious Buildings: Audience Seating	1.53
Fellowship Hall	0.64
Worship Pulpit, Choir	1.53
Retail: Dressing/Fitting Room	0.87
Mall Concourse	1.10
Sales Area	1.68
Sports Arena: Audience Seating	0.43
Court Sports Arena – Class 4	0.72
Court Sports Arena – Class 3	1.20
Court Sports Arena – Class 2	1.92
Court Sports Arena – Class 1	3.01
Ring Sports Arena	2.68
Transportation: Air/Train/Bus-Baggage Area	0.76
Airport-Concourse	0.36
Audience Seating	0.54
Terminal-Ticket Counter	1.08
Warehouse: Fine Material Storage	0.95
Medium/Bulky Material Storage	0.58

For energy modeling purposes, the open office plan needed to be divided into various thermal zones. As a result, the LPD for each of the thermal zones was calculated separately as follows:

1. Perimeter Zone

Zone Area for each corner =1547 sqft

=143.7sqm

LED

(10 * 29) + (17*15) + (10*5) =595W

595/1547=0.38 W/sqft

595/144=4.13 W/sqm

Fluorescent

(10 * 50) + (17*39) + (10*10) =1263W

1263/1547=0.81 W/sqft

1263/144=8.77 W/sqm

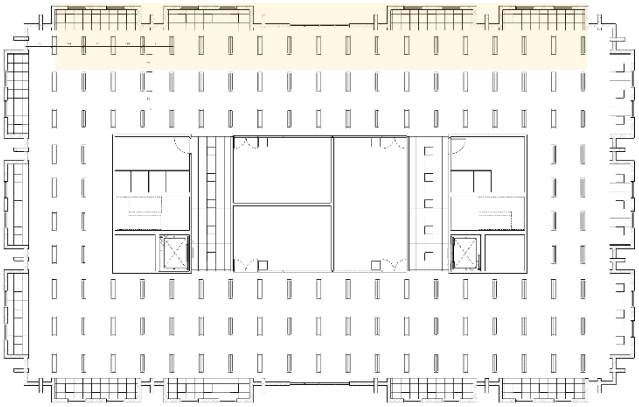


Figure 4.21 North-South Perimeter Zone LPD

2. Core Zone

Zone Area =2245 sqft

Fluorescent

(38 * 39) + (14* 10) + (5 * 50) =1872

1872/2245=0.83 W/sqft

1872/208=9 W/sqm

LED

(38 * 15) + (14* 5) + (5 * 29) =785

785/2245=0.34 sq ft

785/208=3.77 sq m

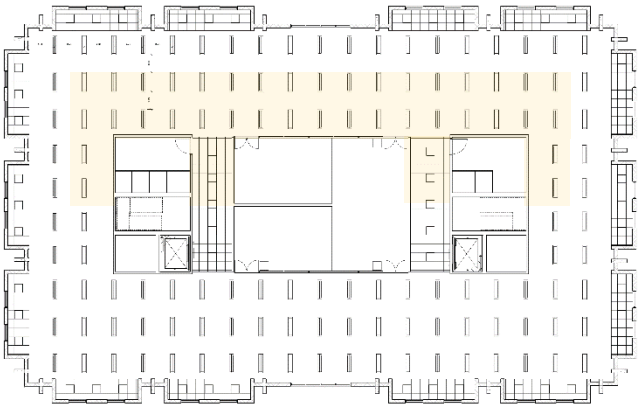


Figure 4.22 Core North Perimeter Zone LPD

3. Corner Zone

Zone Area for perimeter =153 sqft

=14 sqm

LED

(2 * 29) + (1*15) =73W

73/153=0.47 W/sqft

73/14=5.23 W/sqm

Fluorescent

(2 * 50) + (1*39) =139W

139/153=0.90 W/sqft

139/14=9.92 W/sqm

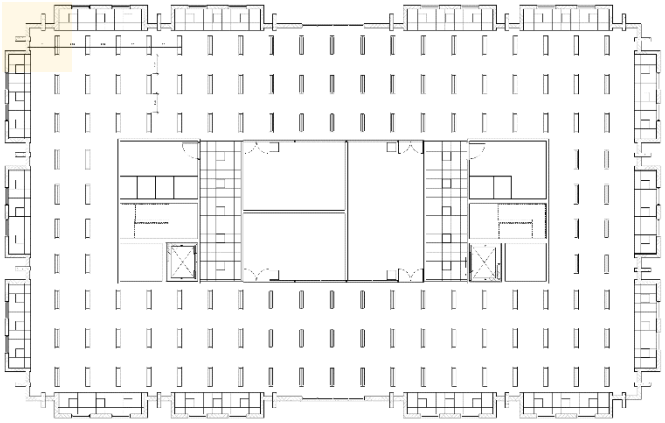


Figure 4.23 Corner Perimeter Zone LPD

4. East-West Perimeter Zone

Zone Area =826 sqft

Fluorescent

(8 * 39) + (6* 10) + (7 * 50) = 722

722/826= 0.87 W/sqft

722/76.7= 9.41W/sqm

LED

(8 * 15) + (6* 5) + (7 * 29) = 353

353/826= 0.42 sq ft

353/76.7= 4.60 sq m

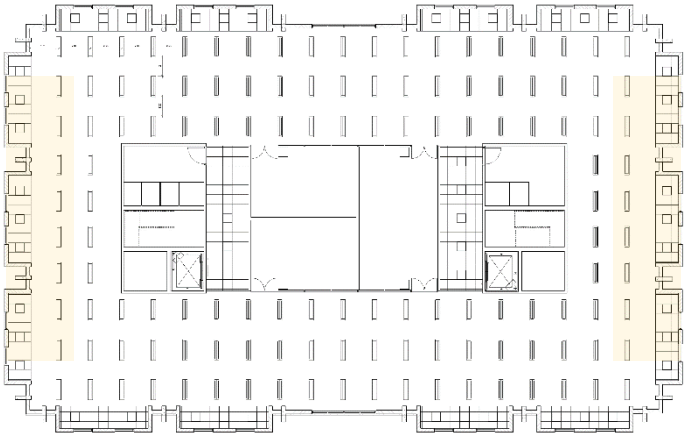


Figure 4.24 East-West Perimeter Zone LPD

4.3 Energy Performance and daylight integration Results

After completing all necessary steps to prepare the model for energy simulation, which was thoroughly described in chapter 3, the simulation was carried through the PAT platform and the general EnergyPlus report was generated. Due to the use of OpenStudio Result measure, extra results including pie charts and EnergyPlus reports in the Imperial system have also been created. Graphical representations of some of the results such as illumination maps can be viewed through results viewer or Dview. EnergyPlus results are plotted mostly in tables, columns, and bar charts under the following categories:

1. Annual Building Utility Performance Summary
2. Input Verification and Results Summary
3. Demand End-Use Components Summary
4. Source Energy End-Use Components Summary
5. Component Sizing Summary
6. Surface Shadowing Summary
7. Adaptive Comfort Summary
8. Initialization Summary
9. Annual Heat Emissions Summary
10. Climatic Data Summary
11. Envelope Summar
12. Shading Summary
13. Lighting Summary
14. Equipment Summary
15. HVAC Sizing Summary
16. Coil Sizing Details
17. System Summary
18. Outdoor Air Summary
19. Object Count Summary
20. Energy Meters
21. Sensible Heat Gain Summary
22. Standard 62.1 Summary
23. LEED Summary

To understand the effect of lighting system on WWR, relevant data indicated in figure 4.24 was extracted from the EnergyPlus report for each of the distinct design alternatives. The information was then imported to the excel sheets and organized to simplify the analysis process. The focus of the study was on the perimeter zones because of their proximity to the window openings and being affected more by solar energy. However, not all the metrics were available for perimeter zones in the EnergyPlus report. For instance, neither EnergyPlus nor OpenStudio reports the space heating or space cooling energy in individual zones. Therefore, to calculate the zonal heating and cooling energy consumption, the district heating and cooling intensities were multiplied by zone areas and the outcome provided an approximate number for heating and cooling energy consumption in each zone. This information then was added to each zone's electrical consumption and unified to Kbtu to make it possible to compare the annual HVAC + Lighting energy consumption in each zone separately. To validate the calculated Zonal Heating and Cooling energy consumption, these metrics were calculated differently by creating a ratio between volume and total heating and cooling energy. Results were close to the numbers achieved by the previous strategy. Figure 4.24 is a Performance Indicator that shows the specific data extracted from EnergyPlus and OpenStudio reports in different spatial and temporal levels of aggregation.

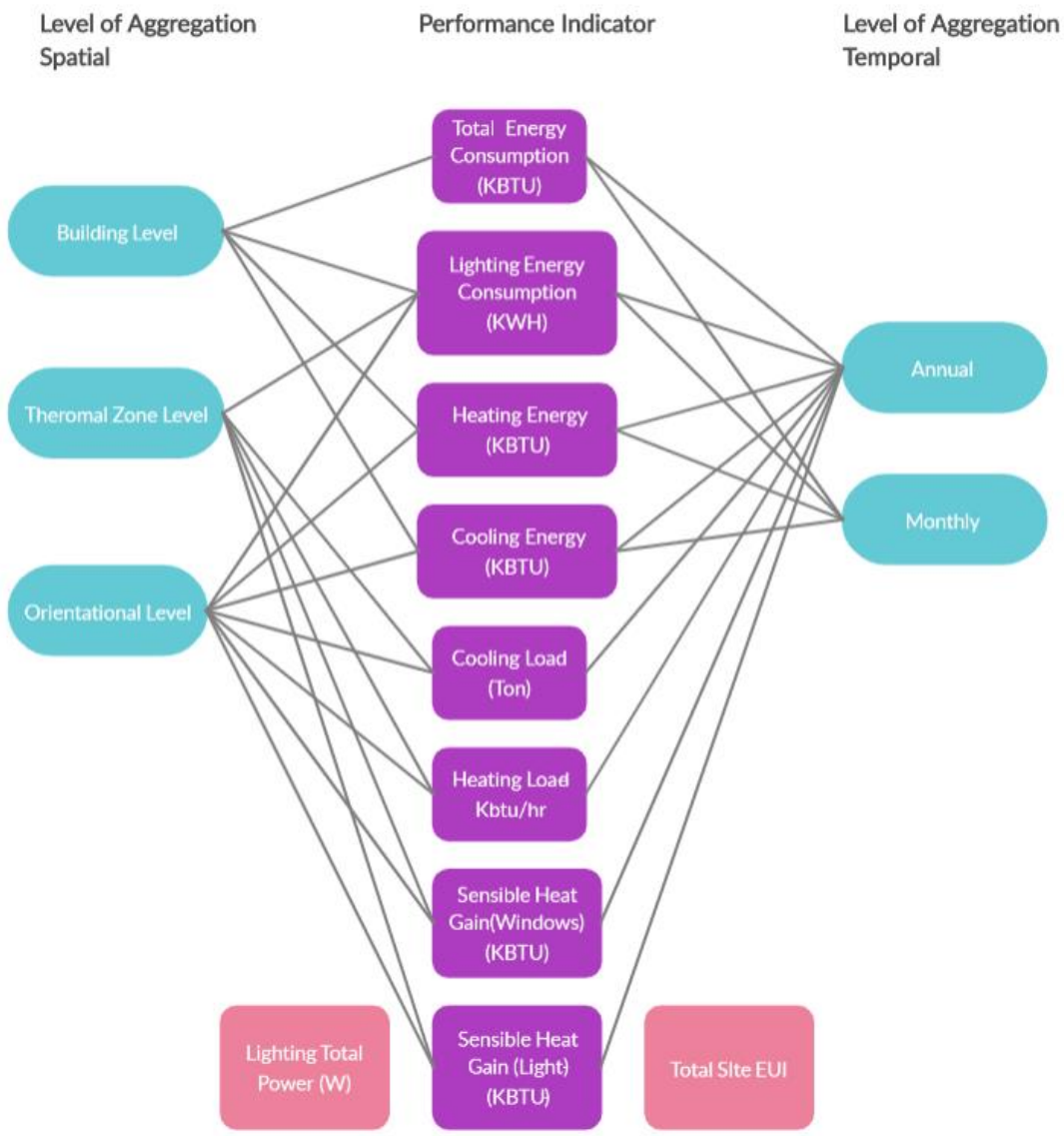


Figure 4.25 Performance Indicator Diagram

After extracting the required information from the report, they were organized in the excel sheets and slightly processed to be ready for visualization and statistical analysis through MATLAB and other visualization tools.

4.3.1 Total Site Energy (KBTU)

The total site energy in LED scenarios is lower than the fluorescent scenarios but except for the 0% WWR plot, the difference between LED's and Fluorescent's total site energy remained almost the same in various WWR alternatives. Also, the total site energy in the North-South axis is slightly less than the East-West axis, but in general, the values are very similar in the two axes.

By increasing the WWR, the total site energy increased in both LED and fluorescent scenarios. In LED plots, the total site energy in 0% and 10% WWR was very close to one another and started rising linearly

after 30% WWR. In contrast, in fluorescent plots, the total site energy was high in 0% WWR and drastically decreased in the 10% WWR plot, and then started rising linearly after 20% WWR. These changes indicate that when there are no openings, and therefore no means of light and heat transfer, the fluorescent alternatives consumed more energy than LED alternatives. By adding a low percentage of window openings, the energy consumption in both cases decreased, which is due to the reduced lighting and heating load, but this drop in the fluorescent plot was more significant. In summary, the energy reduction caused by adding window openings to the LED scenario was much less than the reduction in the fluorescent scenario.

- North-South Axis

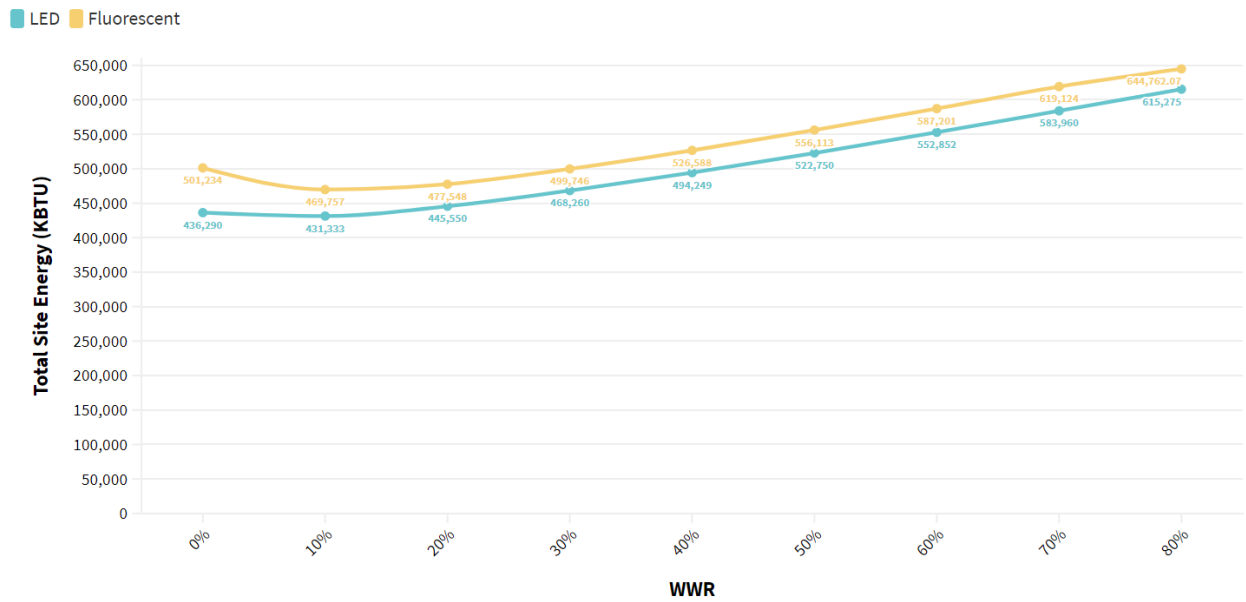


Figure 4.26 Total Site Energy (NS)

- East-West Axis

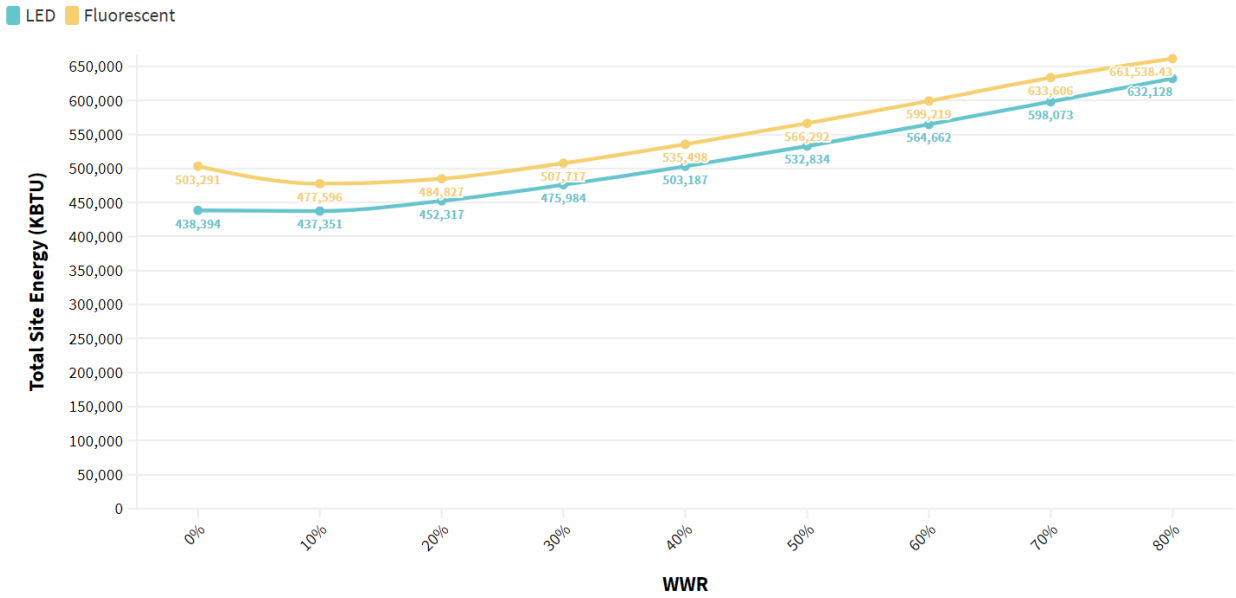


Figure 4.27 Total Site Energy (EW)

4.3.2 Annual Lighting + Space heating+ Space cooling Energy Consumption (KBTU)

Due to the more lighting energy consumption, the primary energy consumption in fluorescent scenarios was higher than that of LED scenarios. With an increase in WWR in both scenarios, the cooling load increased while the heating and lighting loads decreased. However, the reduction in lighting energy started to become negligible from 30% to 80% WWR.

In LED cases, the annual primary energy consumption in the 0% WWR was lower than that of 30% and more WWR. Thus, it can be assumed that in a building with an LED lighting system, more than 30% window area causes a dramatic increase in the space cooling energy with a slight reduction in the lighting and space heating energy. Therefore, energy savings in lighting and space heating categories do not compensate for the increase in space cooling energy.

In fluorescent cases, the annual energy consumption in the 0% WWR was more than that of 20% to 50% WWR and less than that of 50% to 80% WWR. In the fluorescent cases, from 10% to 50% WWR, the lighting energy had a noticeable reduction, which resulted in lower primary energy consumption. However, after a certain point (50% WWR), the reduction in lighting energy almost ceased as the increase in the space cooling energy continued, which in turn led to an increase in whole-building energy consumption.

- North-South Axis

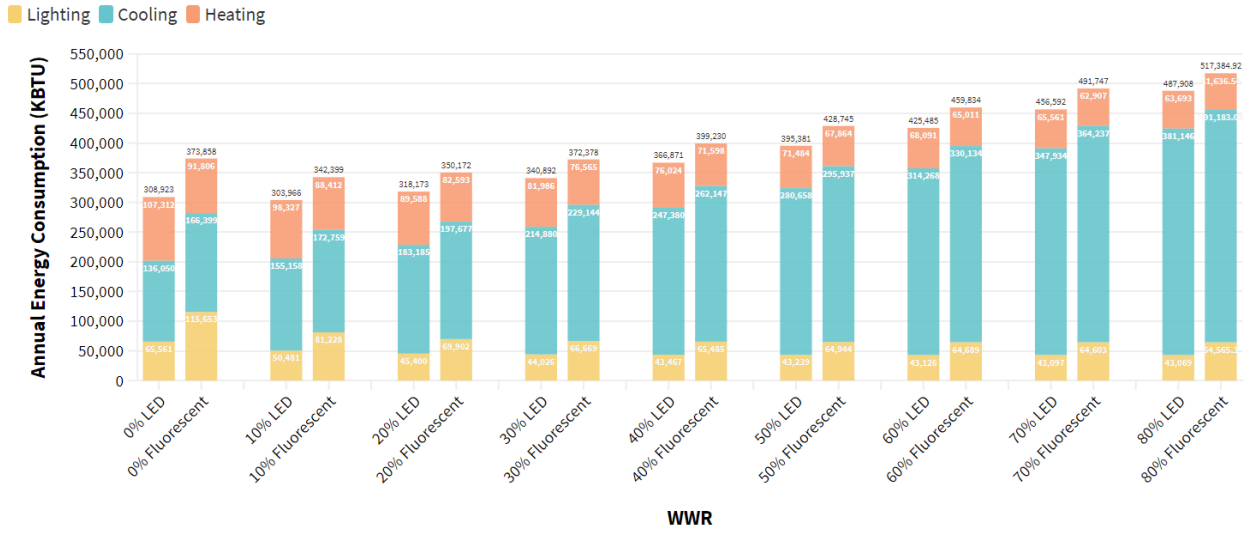


Figure 4.28 Annual Primary Energy Consumption (NS)

- East-West Axis

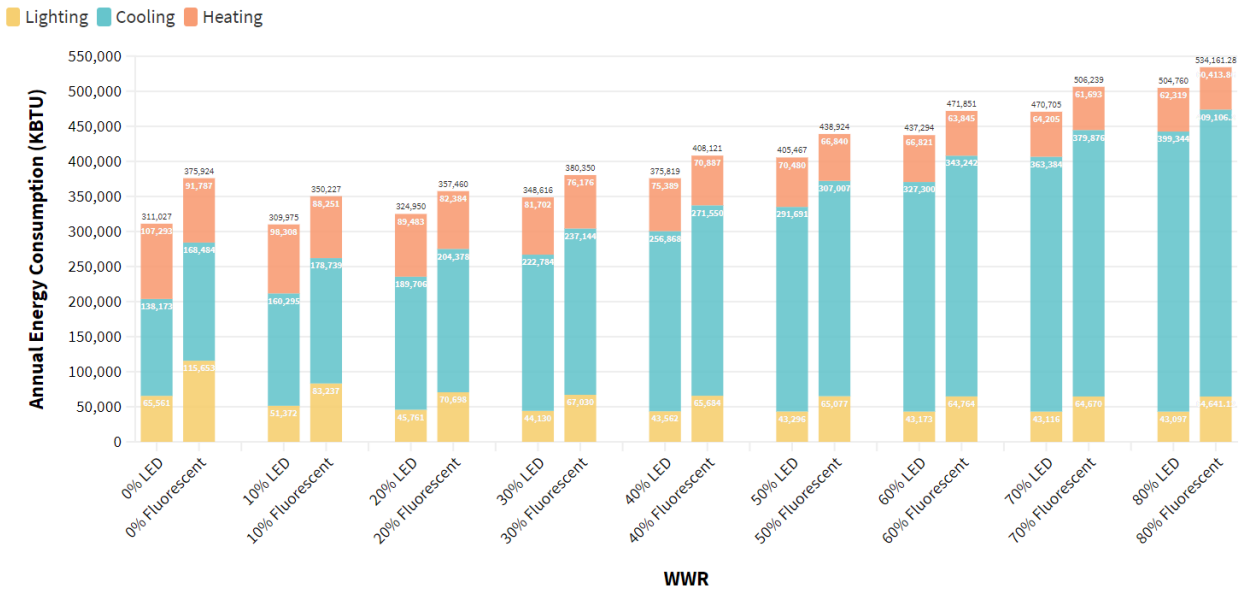


Figure 4.29 Annual Primary Energy Consumption (EW)

4.3.3 Annual Cooling Energy Consumption (KBTU)

- North-South Axis

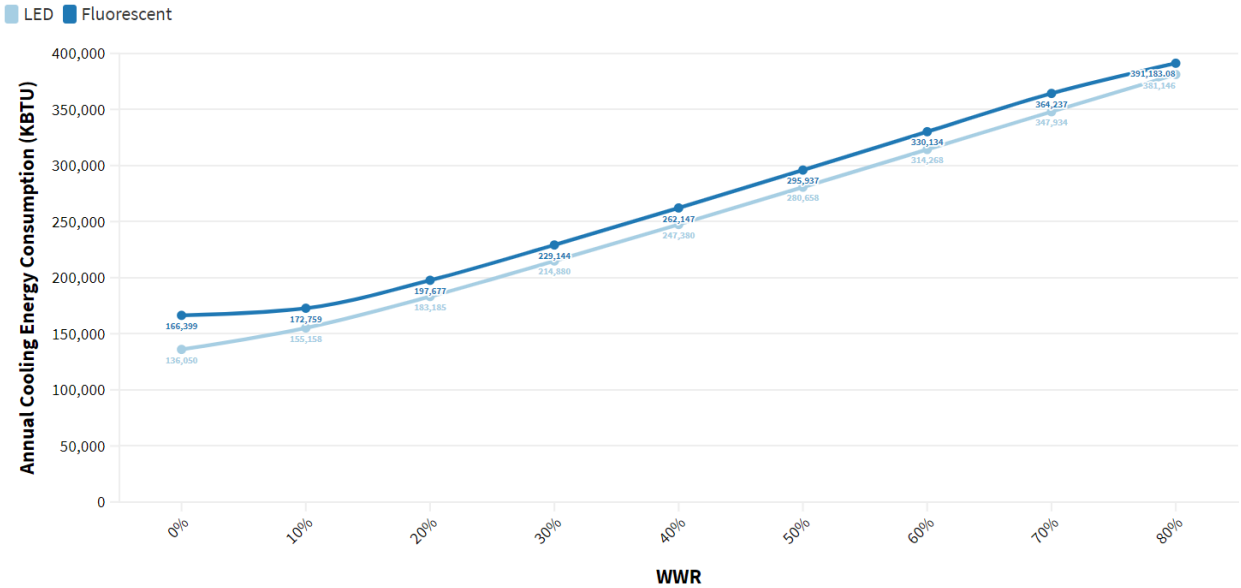


Figure 4.30 Annual Cooling Energy Consumption (NS)

- East-West Axis

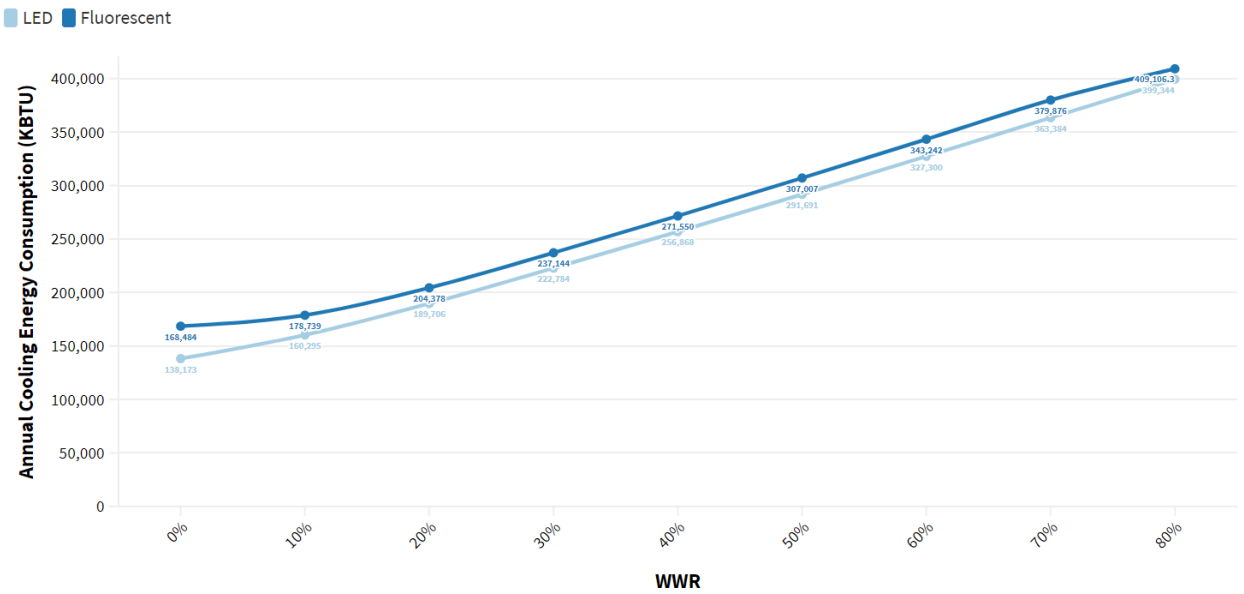


Figure 4.31 Annual Cooling Energy Consumption (EW)

4.3.4 Annual Heating Energy Consumption (KBTU)

- North-South Axis

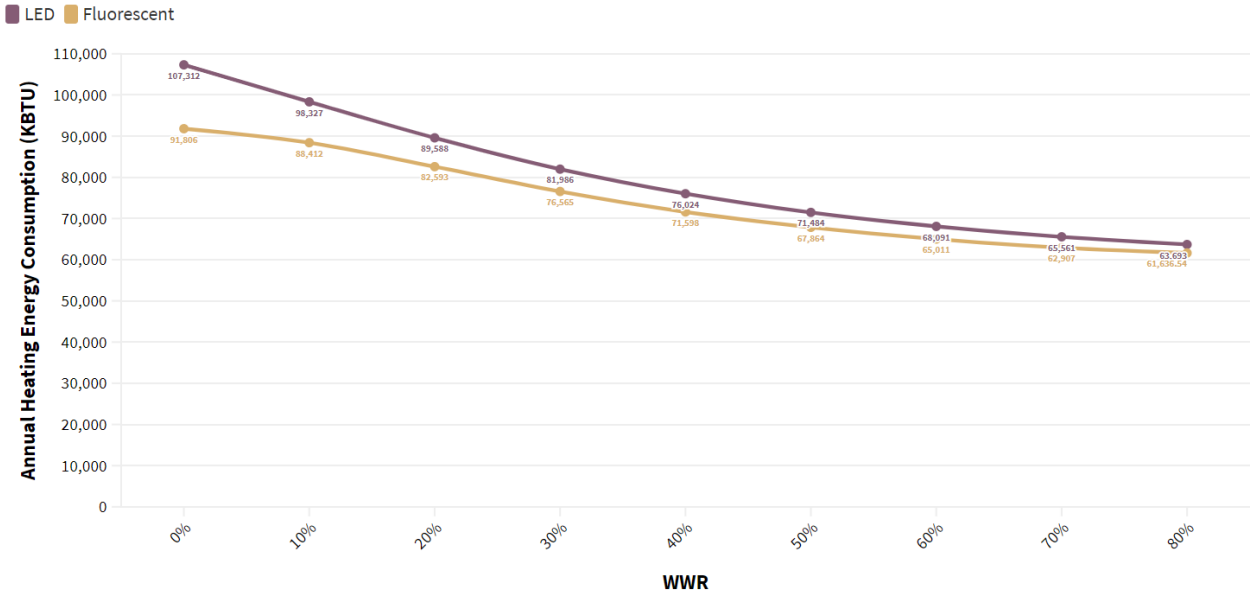


Figure 4.32 Annual Heating Energy Consumption (NS)

- East-West Axis

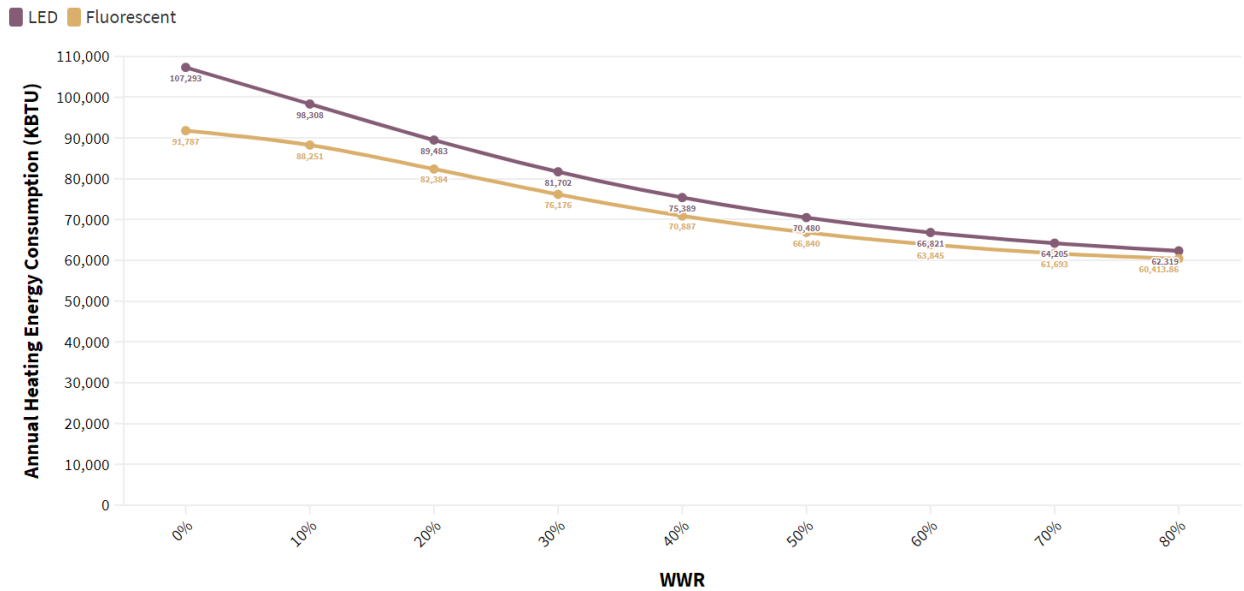


Figure 4.33 Annual Heating Energy Consumption (EW)

4.3.5 Annual Lighting Energy Consumption (KBTU)

- North-South Axis

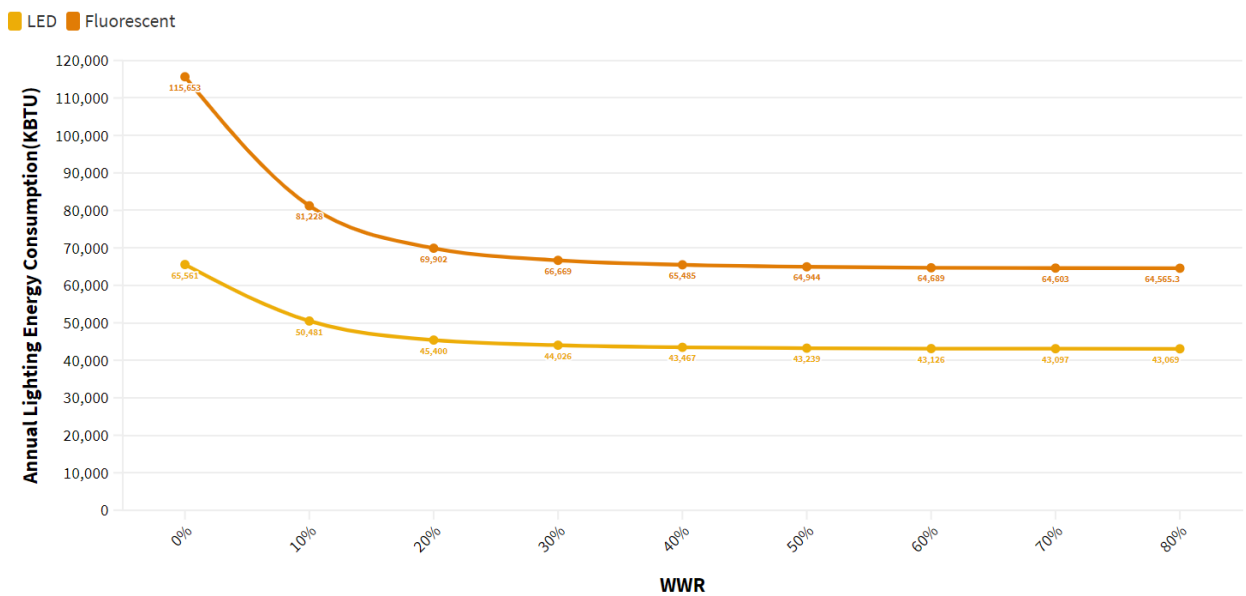


Figure 4.34 Annual Lighting Energy Consumption (NS)

- East-West Axis

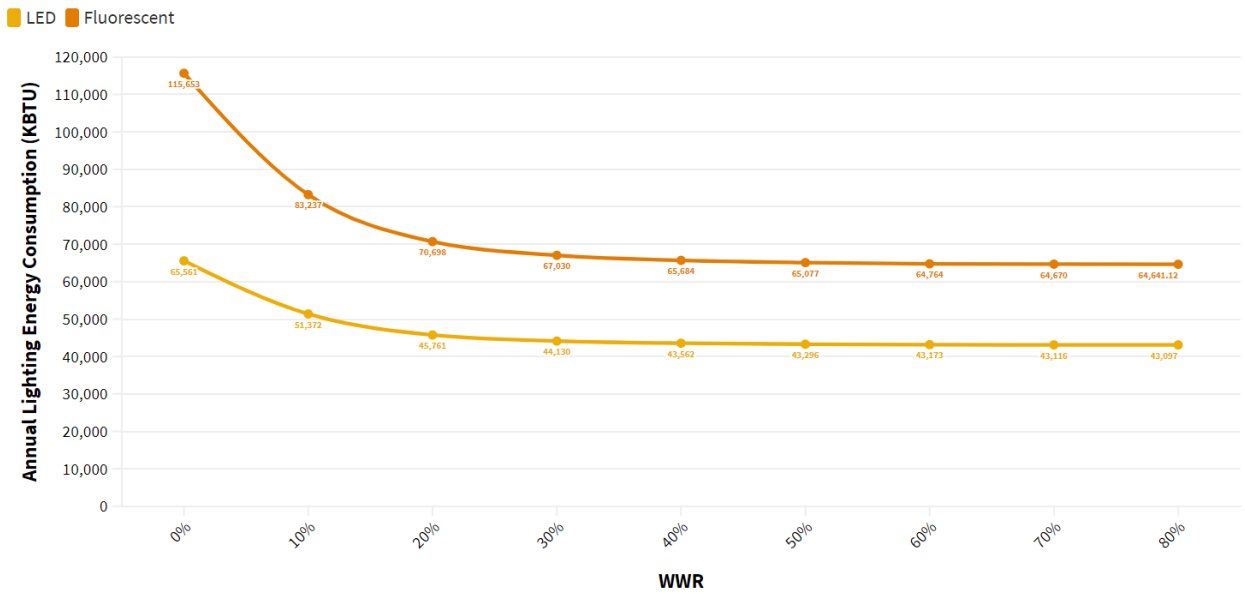


Figure 4.35 Annual Lighting Energy Consumption (EW)

4.3.6 Annual Lighting + HVAC Energy Consumption (KBTU) in Perimeter Zone

The energy consumption pattern in perimeter zones is very similar to that of the whole floor. As outlined above, with increased WWR, lighting and space heating energy decreased while space cooling energy increased. It was evident that the space cooling energy displayed more significant change compared to heating and lighting energy, with the most significant change seen when moving from 0% to 80% WWR. On the other hand, the changes in lighting energy were only significant when moving from 0% to 20% WWR, but then remained steady for the rest of the cases.

The results in the perimeter zones reject the research hypothesis which assumes that an open office with LED lighting system consumes less energy in absence of windows, compared to the scenario with presence of them. However, since the primary energy consumption in 10% and 20% WWR plots was less than 0% WWR plot, the assumption was contradicted by evidence. In fact, adding windows up to 20% caused a slight increase in cooling load while a significant reduction specifically in lighting load, which weighed more in the final energy balance. In other words, the lighting energy consumption reduction was so significant that it would result in lower whole-building energy consumption compared to 0% WWR. Although the research hypothesis was not supported for the 10% and 20% WWR plots, it was supported in the cases with more than 20% WWR. From 30% to 80% WWR, LED cases consumed more energy than the windowless scenario. This indicated that even with a highly efficient lighting system, daylight's effects on energy consumption was remarkable.

In fluorescent cases, the findings were different. Since the lighting energy consumption was very high in 0% WWR, the addition of windows to space provided it with daylight illumination which drastically decreased the lighting energy and whole-building energy consumption. Having up to 40% WWR in the open offices with fluorescent luminaires reduced the whole building energy consumption through the

daylight harvesting strategy. However, going above 40% WWR adversely affected the whole-building energy consumption because more than 40% of window openings not only did not further reduce the lighting load (compared to the lower WWR) but also increased the cooling load so greatly that resulted in more energy consumption compared to the windowless scenario.

- North-South Axis

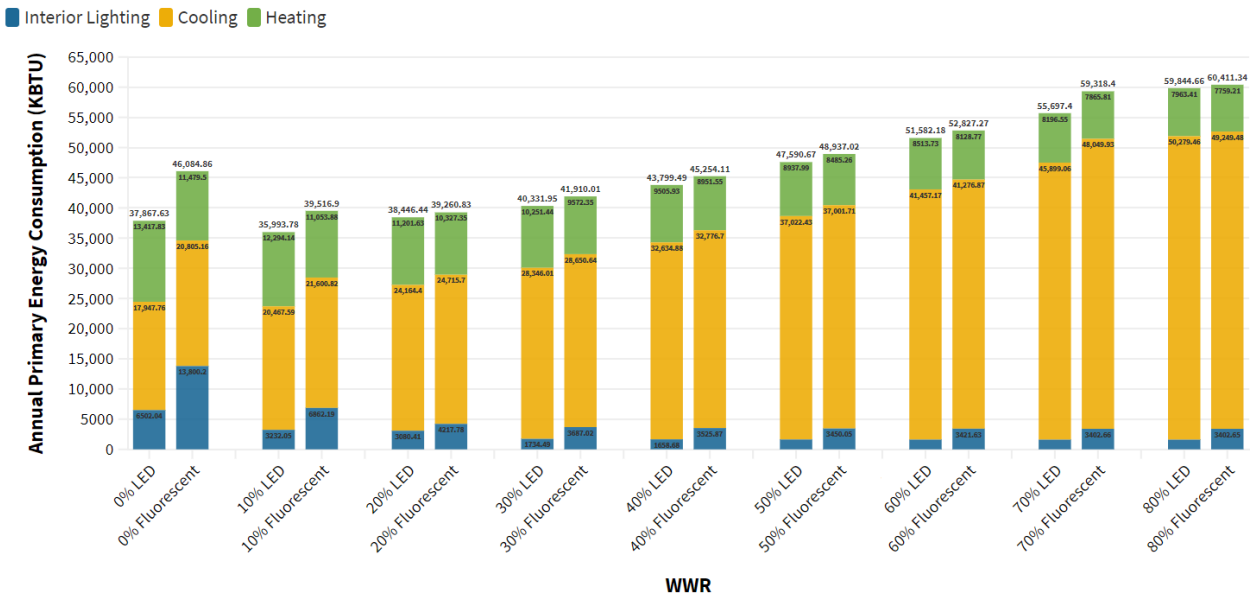


Figure 4.36 Annual Primary Energy Consumption in North Perimeter Zone

- East-West Axis

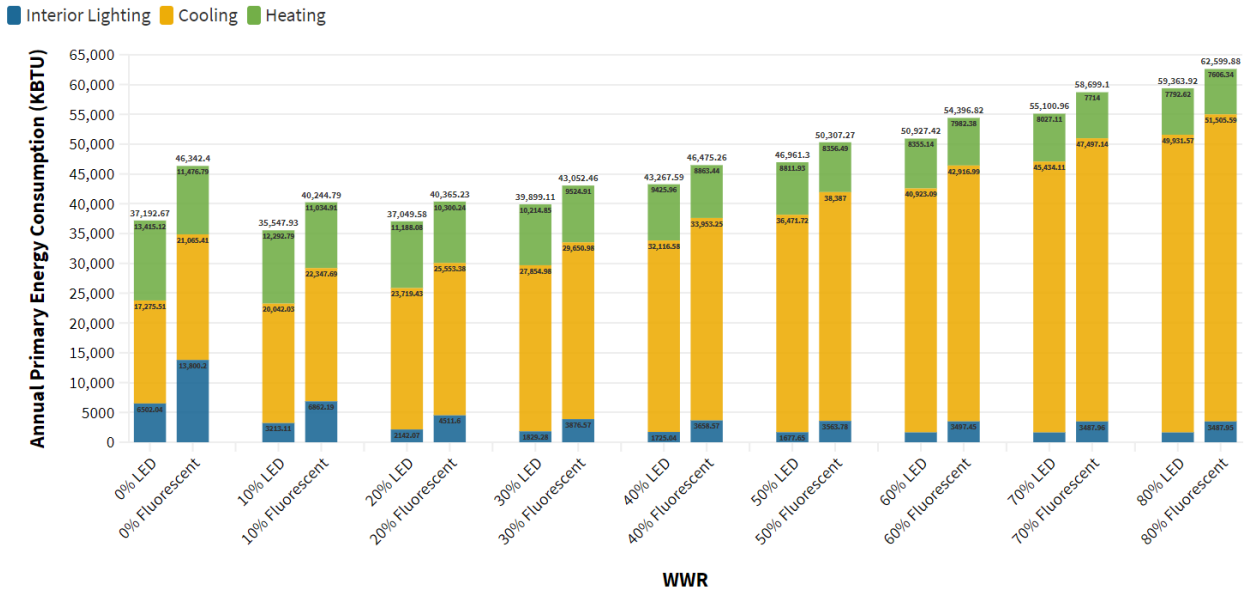


Figure 4.37 Annual Primary Energy Consumption in East Perimeter Zone

4.3.7 Annual Lighting + HVAC Energy Consumption (KBTU) in Perimeter Zone

- North

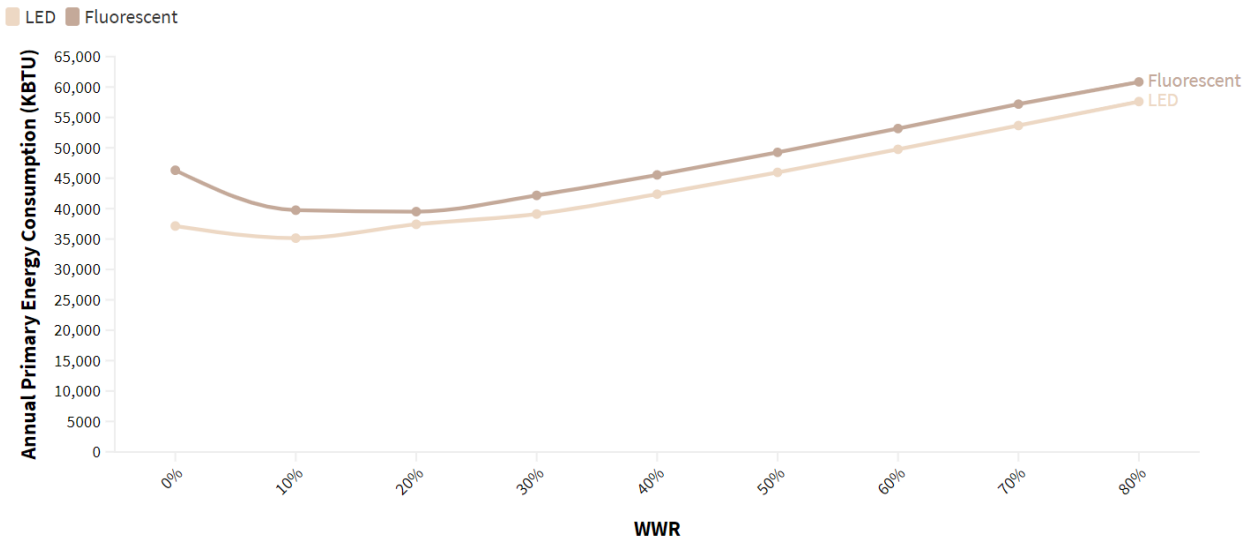


Figure 4.38 Annual Primary Energy Consumption in North Perimeter Zone

- South

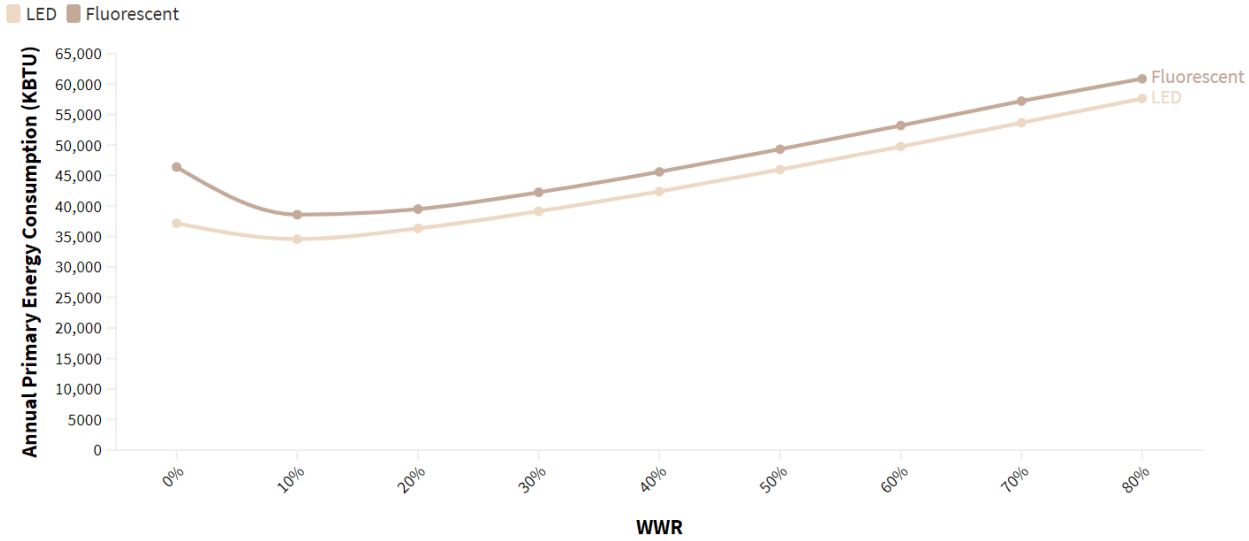


Figure 4.39 Annual Primary Energy Consumption in South Perimeter Zone

- East

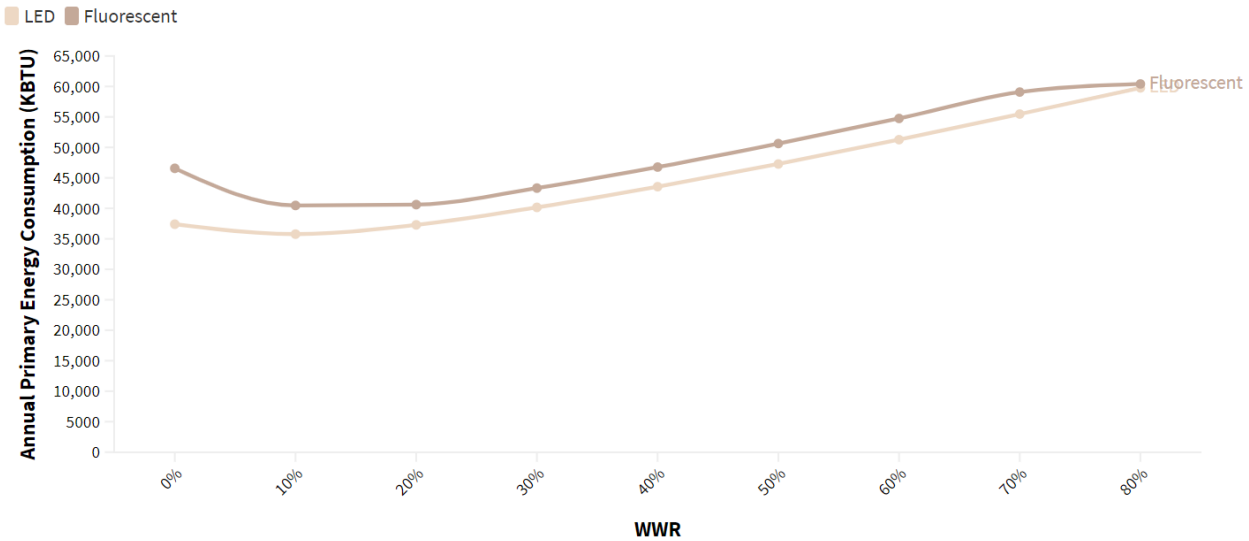


Figure 4.40 Annual Primary Energy Consumption in East Perimeter Zone

- West

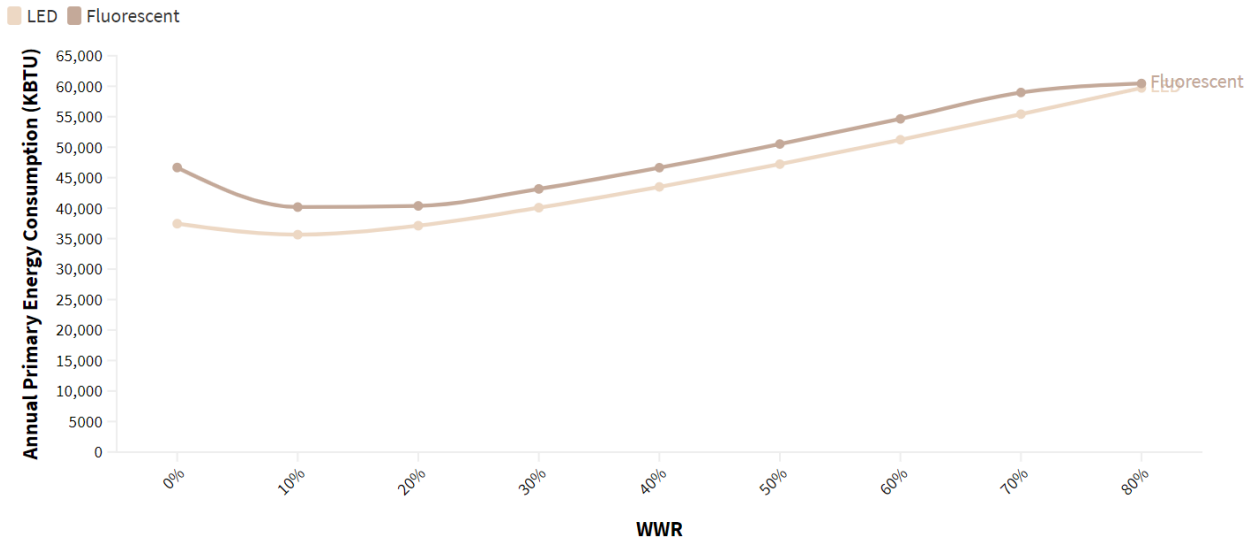


Figure 4.41 Annual Primary Energy Consumption in West Perimeter Zone

4.3.8 Electricity Consumption (KWH) in the Perimeter Zone

Fluorescent alternatives use about twice the electricity of LED scenarios, with the highest energy difference seen in the 0% WWR plot. This difference decreased as the WWR increased but with very slight changes after 30% WWR. In both light sources, the electricity consumption dropped by half, going from 0% to 10% WWR. Based on these findings, it can be concluded that window openings even as small as 10% can reduce lighting energy consumption significantly. However, from 40% to 80% WWR, the reduction in electricity energy became very steady and insignificant in both light sources. The reduction pattern in LED and fluorescent cases was very similar, with the exception that the fluorescent cases plunged more sharply when jumping from 0 to 10 percent WWR.

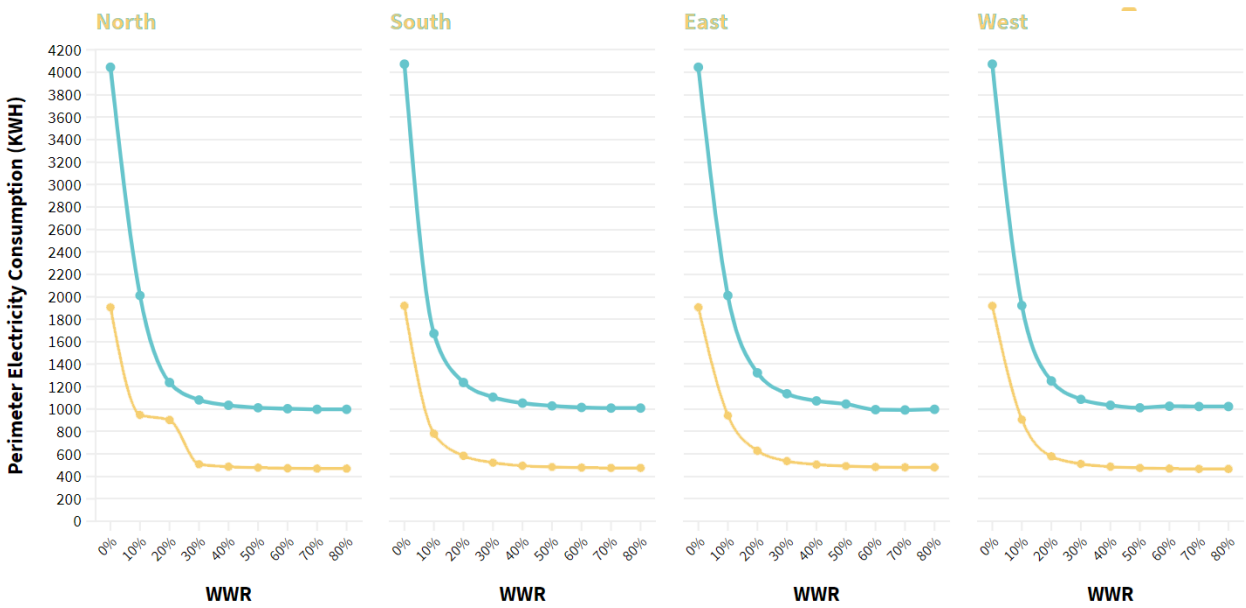


Figure 4.42 Annual Electricity Consumption in Perimeter Zone

4.3.9 Annual Lighting Energy Consumption (KBTU) in Perimeter Zone

In all the WWR plots, the LED lighting energy was about half of the fluorescent lighting energy in all directions. The sharp slope in the fluorescent cases, especially when moving from 0% to 10% and 20% WWR, demonstrated the significance of daylight illumination in reducing the lighting loads.

- North-South Axis

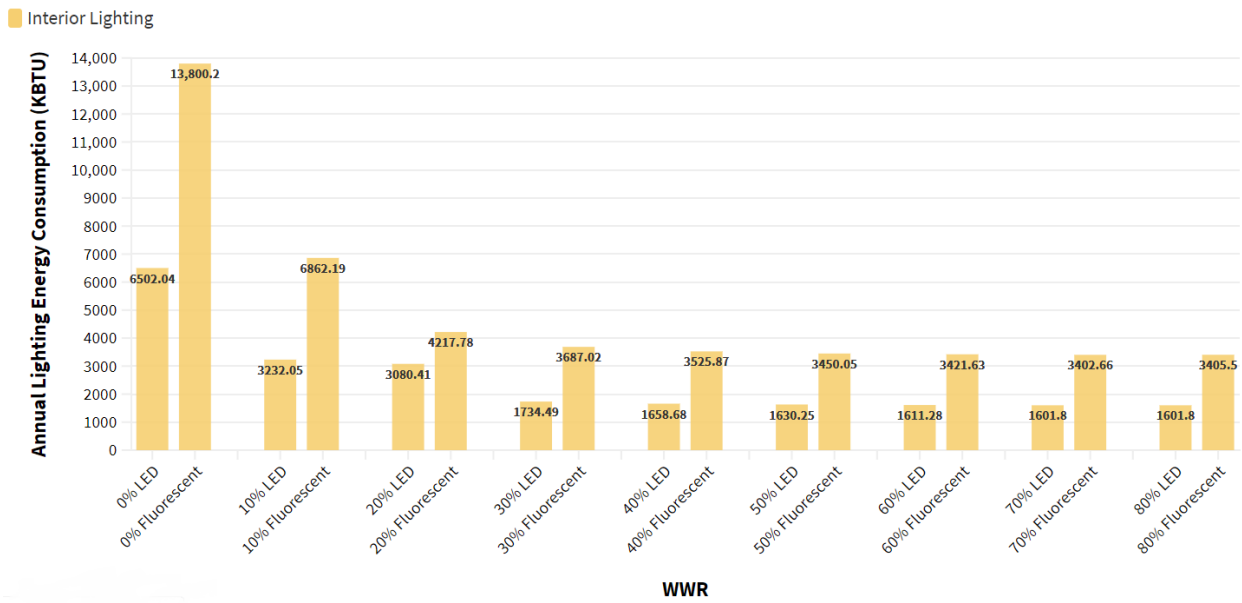


Figure 4.43 Annual Lighting Energy Consumption (NS)

- East-West Axis

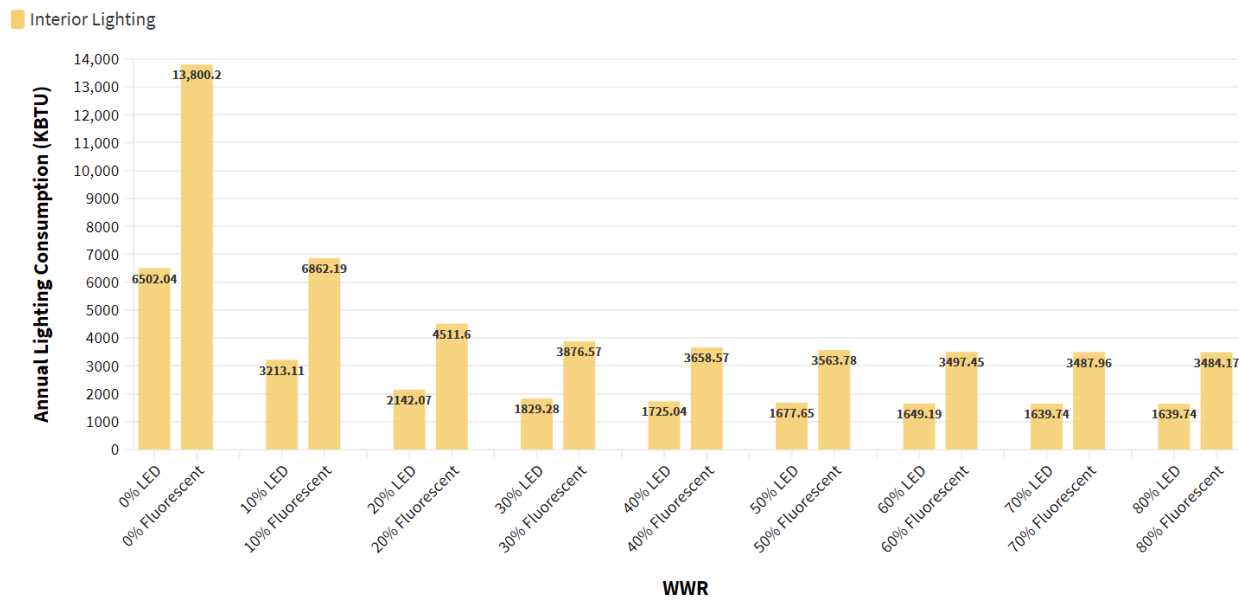


Figure 4.44 Annual Lighting Energy Consumption (EW)

4.3.10 Annual Cooling Energy Consumption (KBTU) in Perimeter Zone

In both light sources, the space cooling energy increased linearly, moving from 0% to 80% WWR. In the North-South axis, the annual cooling energy consumption for fluorescent cases was generally more than LED cases with a significant difference in 0%, 10%, and 70% WWR plots. In the East-West axis, there was a fixed 2000 KBTU difference in LED and fluorescent cases with fluorescent plots having more space cooling energy. One hypothesis for this conclusion is that fluorescent luminaires emit more heat to spaces than LED luminaires, which further increases the cooling load. Note that all the scenarios had higher space cooling energy in the East-West axis compared to the North-South axis.

- North-South Axis

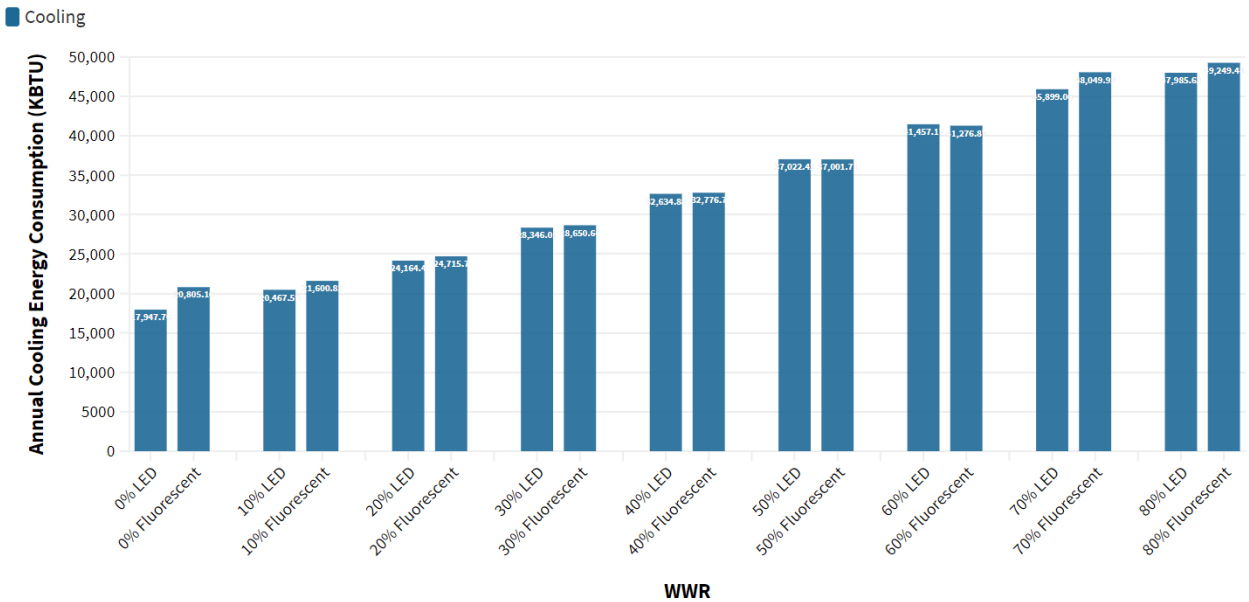


Figure 4.45 Annual Cooling Energy Consumption (NS)

- East-West Axis

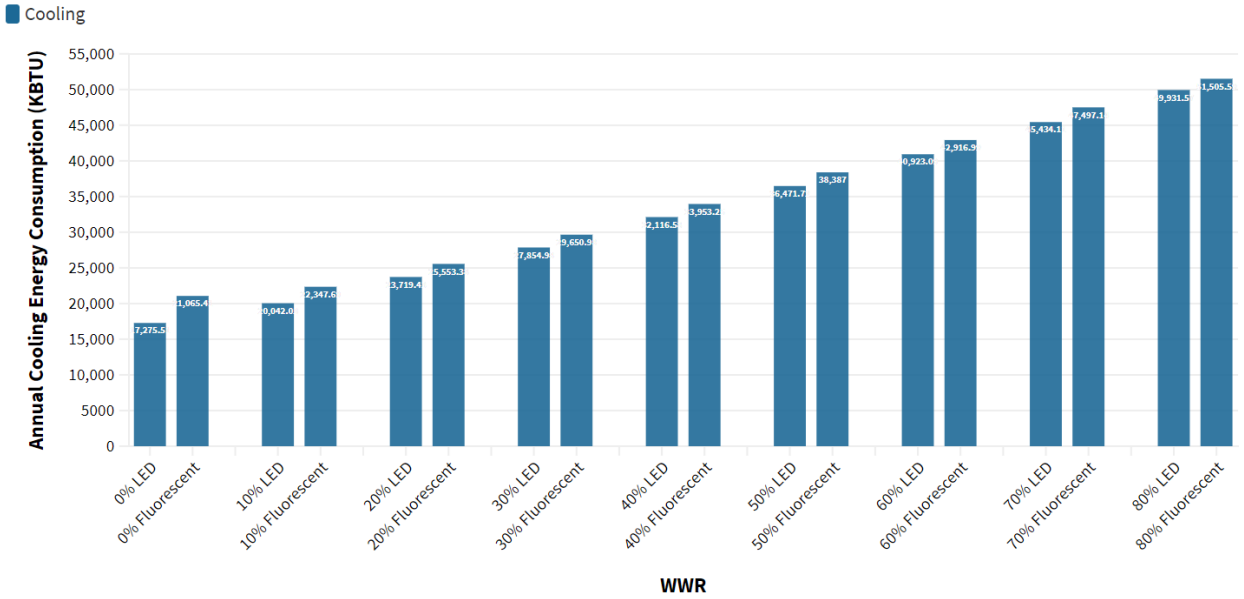


Figure 4.46 Annual Cooling Energy Consumption (EW)

4.3.11 Annual Heating Energy Consumption (KBTU) in Perimeter Zone

Unlike the space cooling energy, the space heating energy decreased by the increase in WWR. However, similar to the space cooling energy, the changes were linear starting from 0% and moving toward 80% WWR. The heating energy in LED alternatives was higher than the heating energy in fluorescent alternatives. One reason for this finding could be that less heat production by LED luminaires cannot

compensate for the heating load. Also, the space heating energy for LED and fluorescent cases in the North-South axis was more than the East-West axis because more heat was received in the East-West axis and therefore, less heating load was required.

- North-South Axis

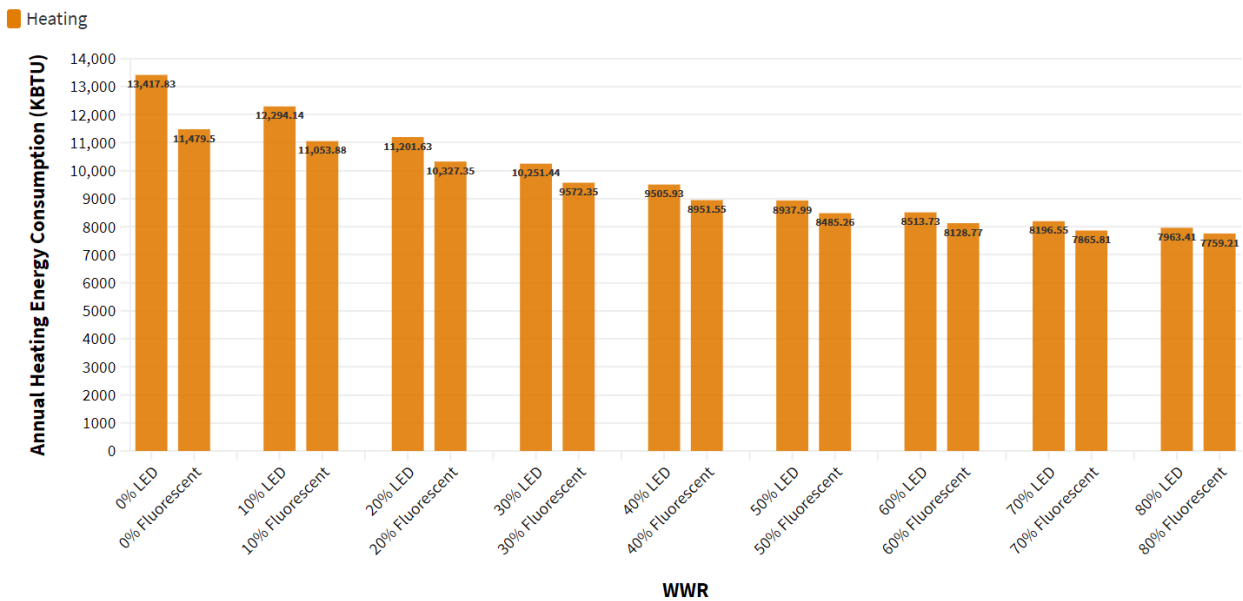


Figure 4.47 Annual Heating Energy Consumption (NS)

- East-West Axis

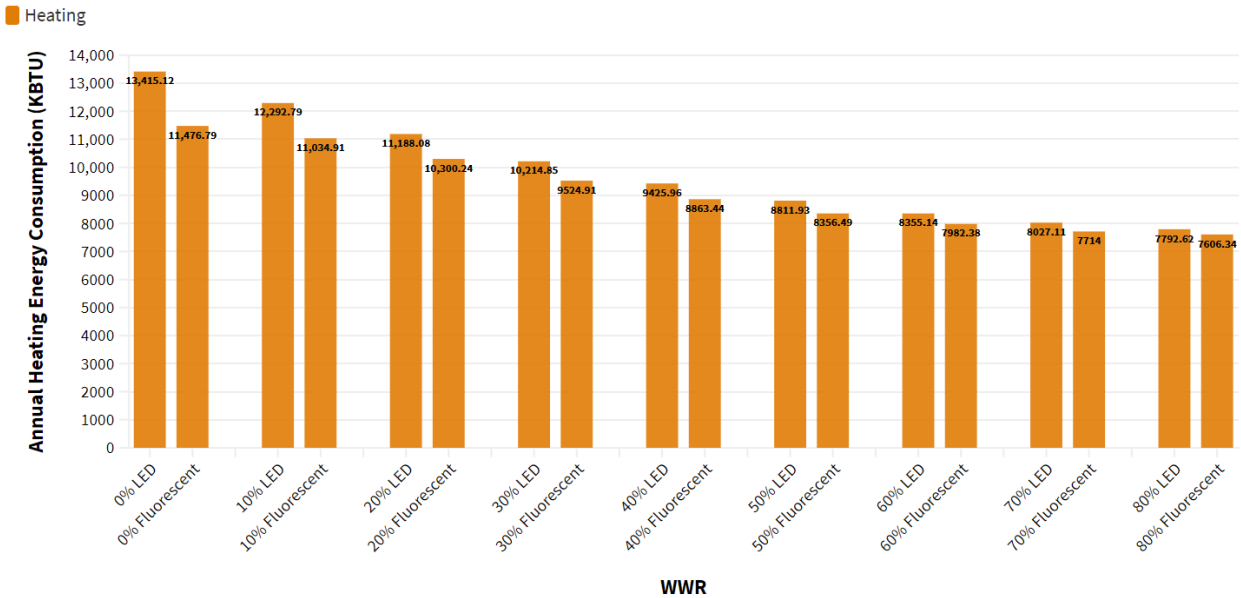


Figure 4.48 Annual Heating Energy Consumption (EW)

4.3.12 Heating Load (KBTU/hr) in Perimeter Zone

In both LED and fluorescent alternatives, the heating load in the 0% WWR plot had the highest value, because solar energy was not available and the sun could not be used as a heating source. Heating loads in the North and East were higher than heating loads in the South and West because spaces oriented toward South and West had already been preheated by solar energy during the morning and therefore, required less heating energy. In addition, except for the 0% WWR, heating loads of the LED scenarios were slightly more than the heating loads of fluorescent scenarios. This may have been due to fluorescent lamps generating more heat than LED lamps. One contradiction evident in the graph is that both light sources in the 0% WWR had a similar heating load. However, the 0% WWR LED plot should have a higher heating load than the fluorescent plot.

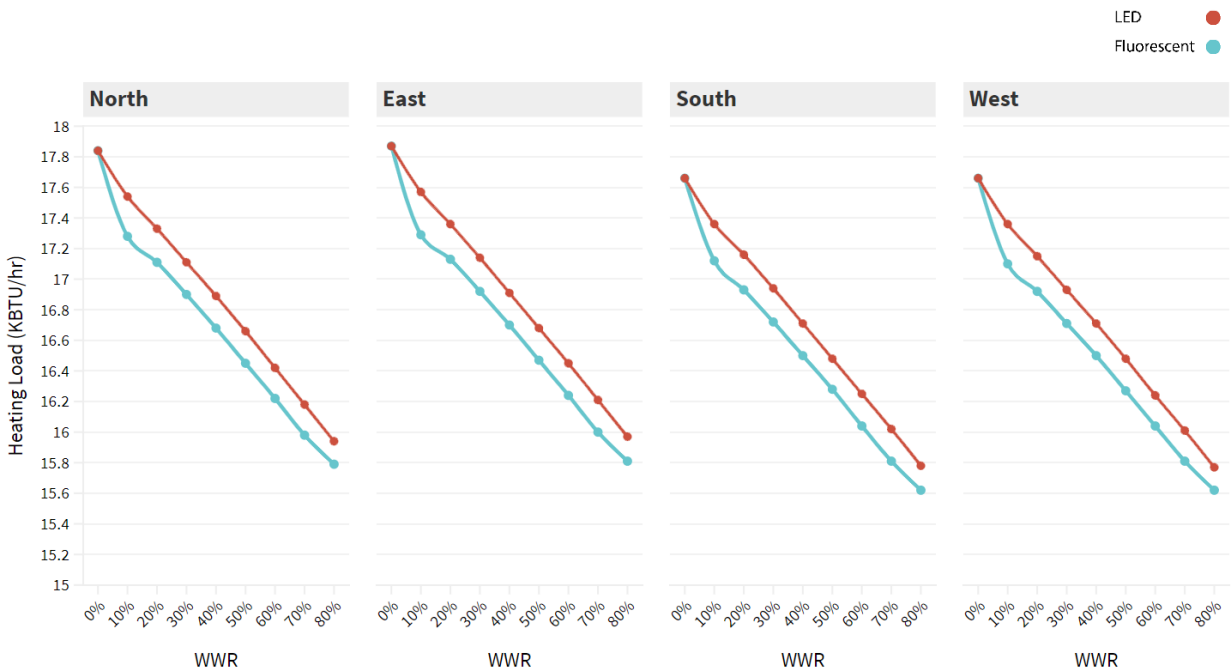


Figure 4.49 Heating Load in Perimeter Zone

4.3.13 Cooling Load (KBTU/hr) in Perimeter Zone

Although the cooling loads for both light sources were relatively similar, they were slightly higher in fluorescent scenarios, especially in 0% and 10% WWR. The small amount of difference in cooling loads was due to the increased heat generated by fluorescent lamps, which added to the space cooling load. Especially in the 0% WWR, the cooling load difference between LED and fluorescent scenarios was significant because the lamps were utilizing full power. With increasing the WWR, luminaires of both light sources were able to work with lower energy and emit less heat to space.

Also, the cooling loads in the North and South were drastically lower than cooling loads in the East and west. This could have been due to higher solar intensity in East and West directions, which resulted in heat gain and a higher temperature.

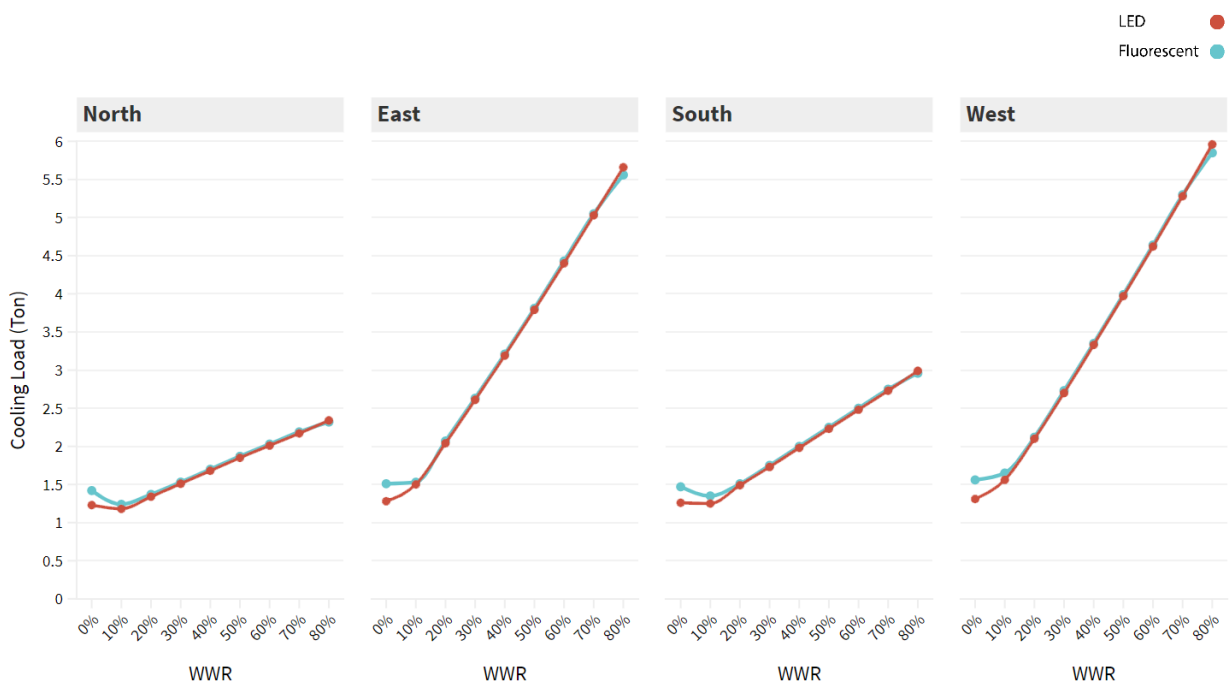


Figure 4.50 Cooling Load in Perimeter Zone

4.3.14 Light Sensible Heat Gain (KBTU) In Perimeter Zone

In all directions, the light sensible heat gain demonstrated the highest value in 0% WWR because no daylight was available to reduce the electrical light load, and therefore, electrical lamps operated under full capacity. But in 10% WWR, the light sensible heat gain dropped by half in all cardinal directions. The light sensible heat gains for LED and fluorescent scenarios were very close in all four directions except for the 10% WWR plot, in which the South direction had a lower value compared to other directions. One hypothesis might be due to the southern perimeter zone having the best opportunity for daylight harvesting, which can further reduce the artificial lighting load.

The light sensible heat gain in the fluorescent cases was two times more than the light sensible heat gain in the LED cases. Thus, LED lamps emit less heat than fluorescent lamps. In LED lamps, between 75 to 80 percent of the heat is produced in the form of convection, while in the fluorescent lamps this portion is 40%. LED lamps do not generate any radiant heat while fluorescent lamps produce about 40% radiant heat. Unlike infrared radiation, which is absorbed by the surfaces and have a time lag effect, convective heat is more manageable in terms of collection and can be used in the return air duct for preheating or disposal.

- Fluorescent

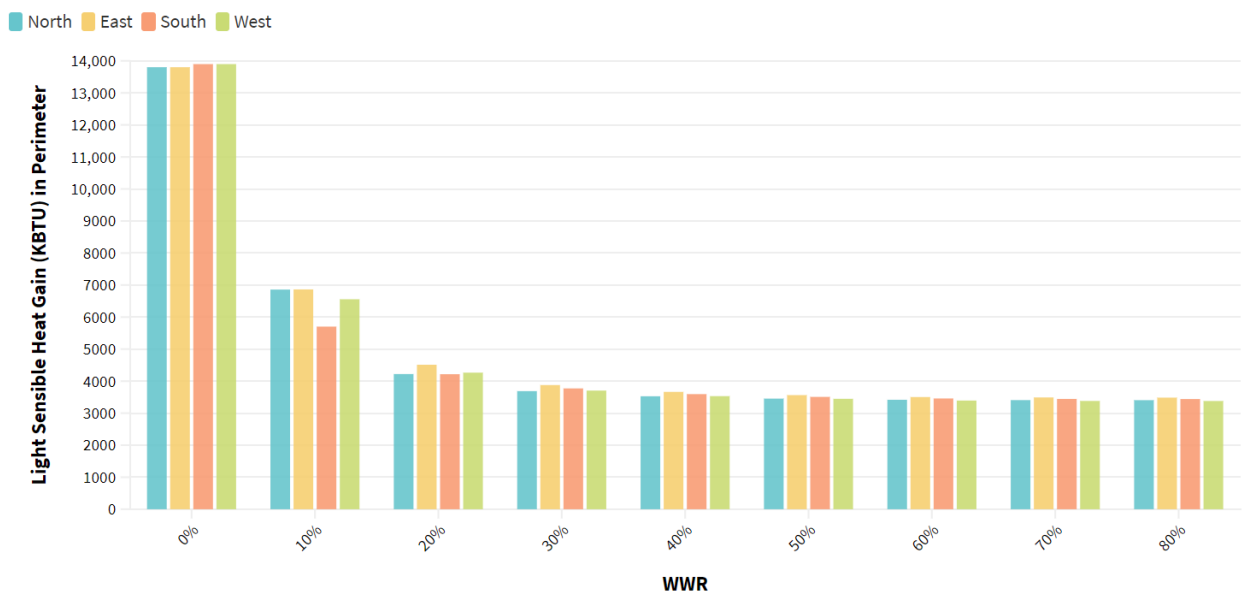


Figure 4.51 Light Sensible Heat Gain (Fluorescent)

- LED

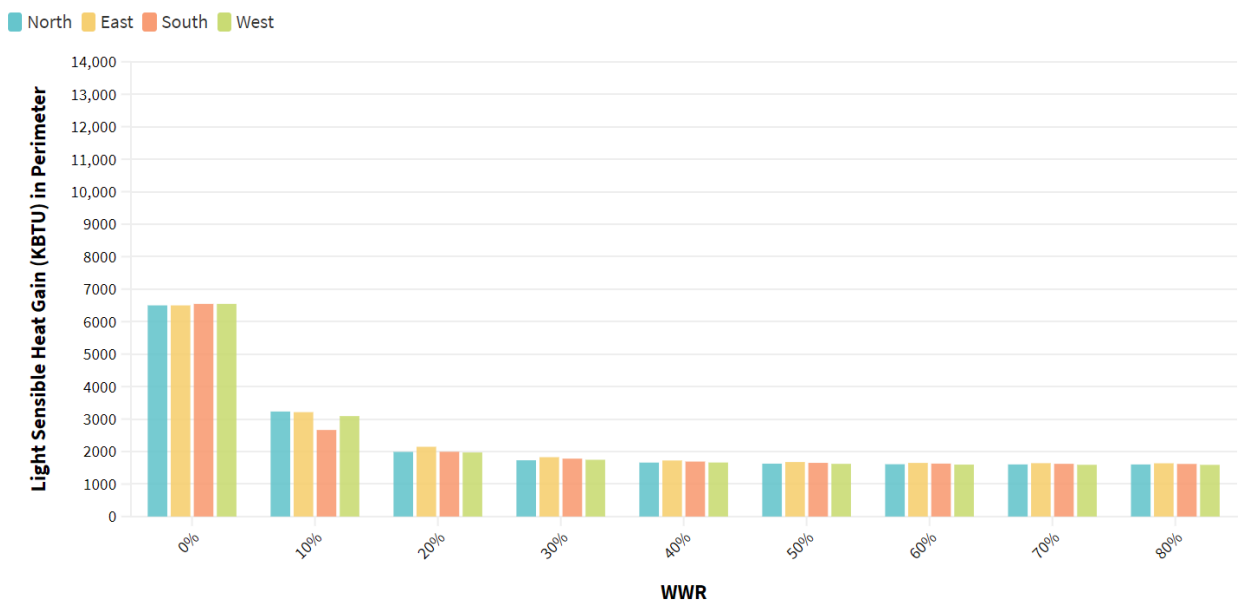


Figure 4.52 Light Sensible Heat Gain (LED)

4.3.15 Annual Sensible Heat Gain and Heat Loss Through Windows (KBTU)

The annual sensible heat gain and the annual sensible heat loss in LED cases were less than fluorescent cases. Also, the light sensible heat gain and the light sensible heat loss were greater in the East-West axis in both LED and fluorescent scenarios.

- LED North-South Axis

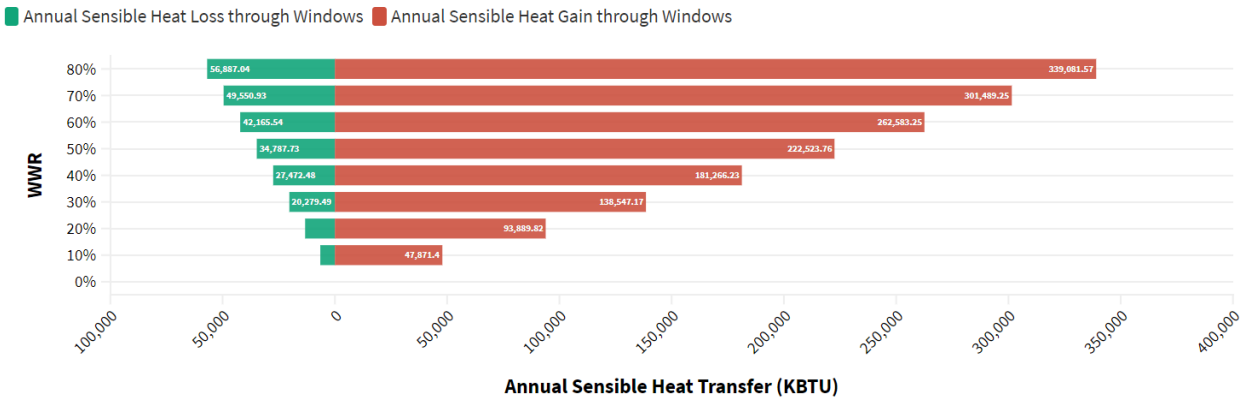


Figure 4.53 Annual Sensible Heat Transfer (LED, NS)

- Fluorescent North-South Axis

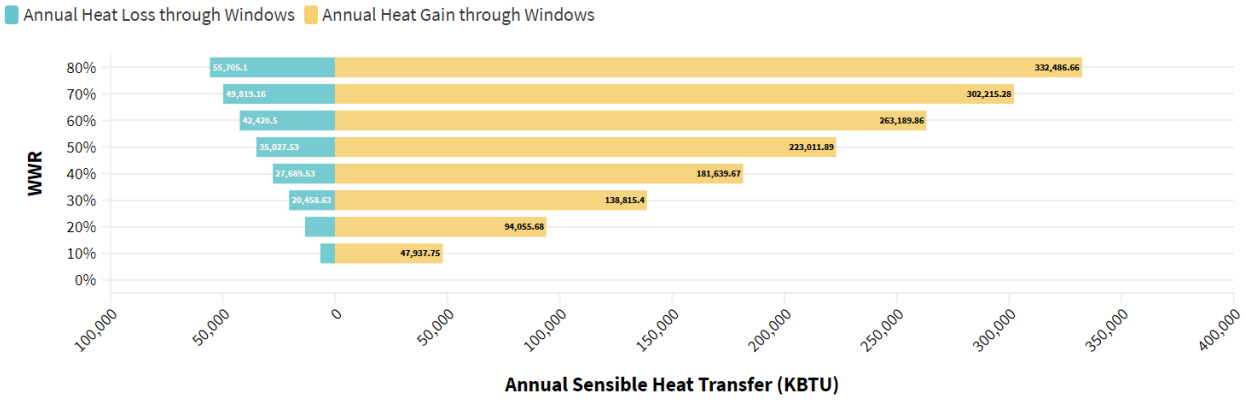


Figure 4.54 Annual Sensible Heat Transfer (Fluorescent NS)

- LED East-West Axis

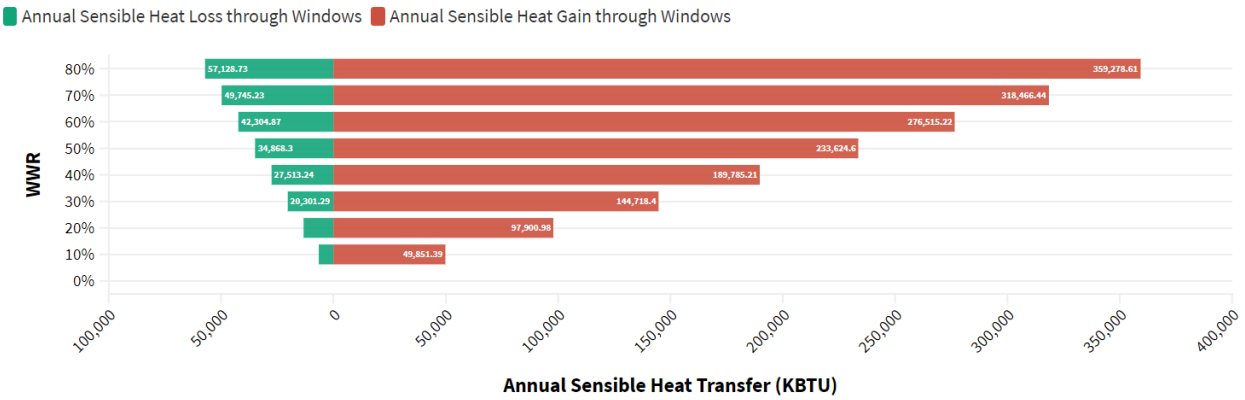


Figure 4.55 Annual Sensible Heat Transfer (LED, EW)

- Fluorescent East-West Axis

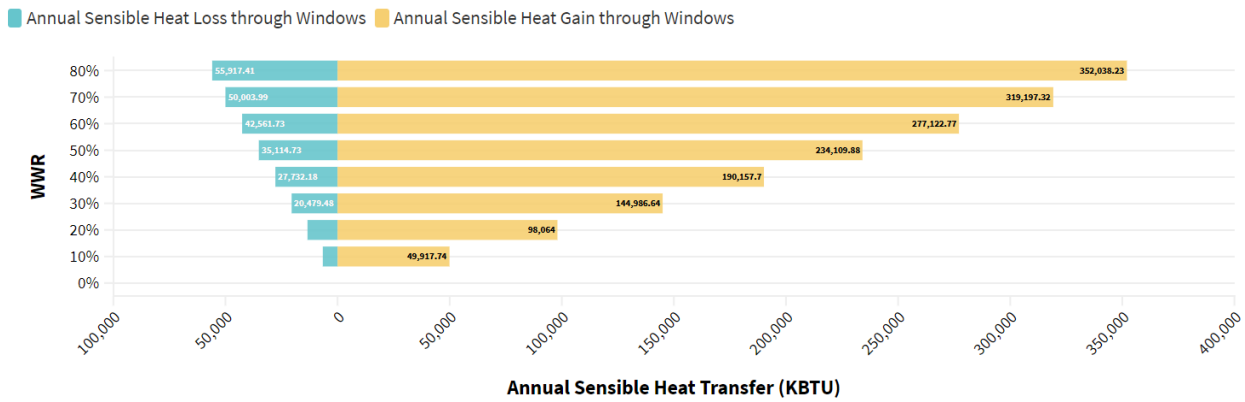


Figure 4.56 Annual Sensible Heat Transfer (Fluorescent, EW)

4.3.16 Heat Gain (KBTU): Lamps vs Windows

The red and yellow bars in the figures below represent the annual sensible heat transfer, which is the subtraction of annual sensible heat gain and annual sensible heat loss. With moving from 0% to 80% WWR, the annual sensible heat transfer linearly increased and the lamps' annual sensible heat gains decreased. While the light sensible heat gain in fluorescent cases was more than the LED cases, the annual heat transfer through windows in fluorescent cases was generally lower than LED cases.

- North-South Axis, LED

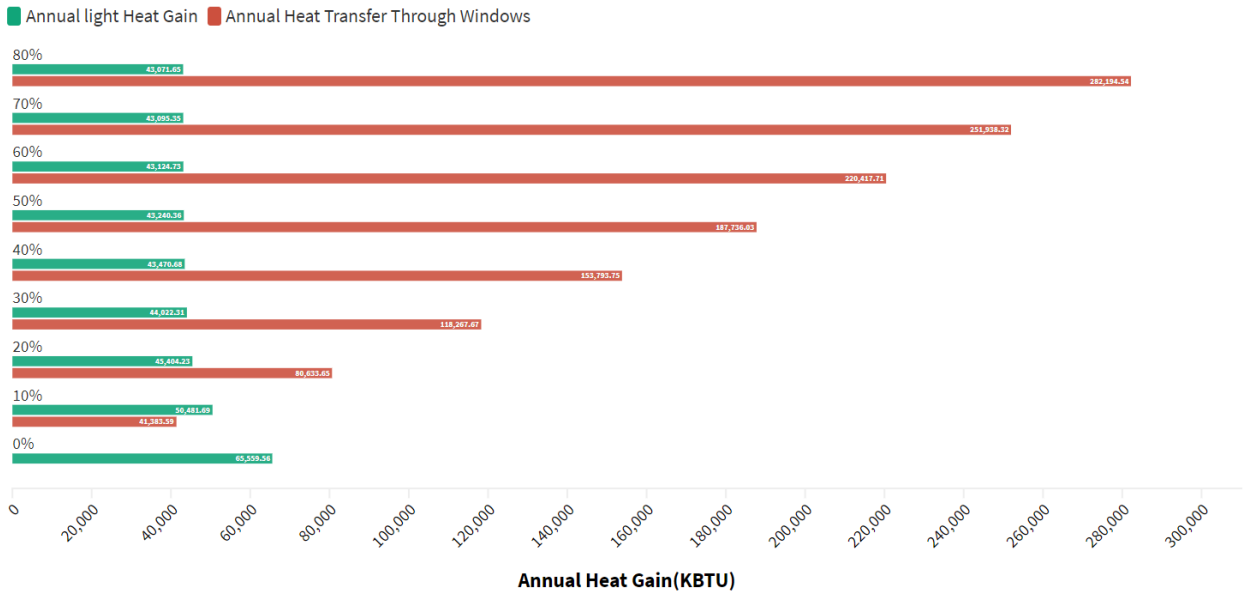


Figure 4.57 Annual Heat Transfer Vs. Annual Luminaires Heat Production (LED, NS)

- North-South Axis, Fluorescent

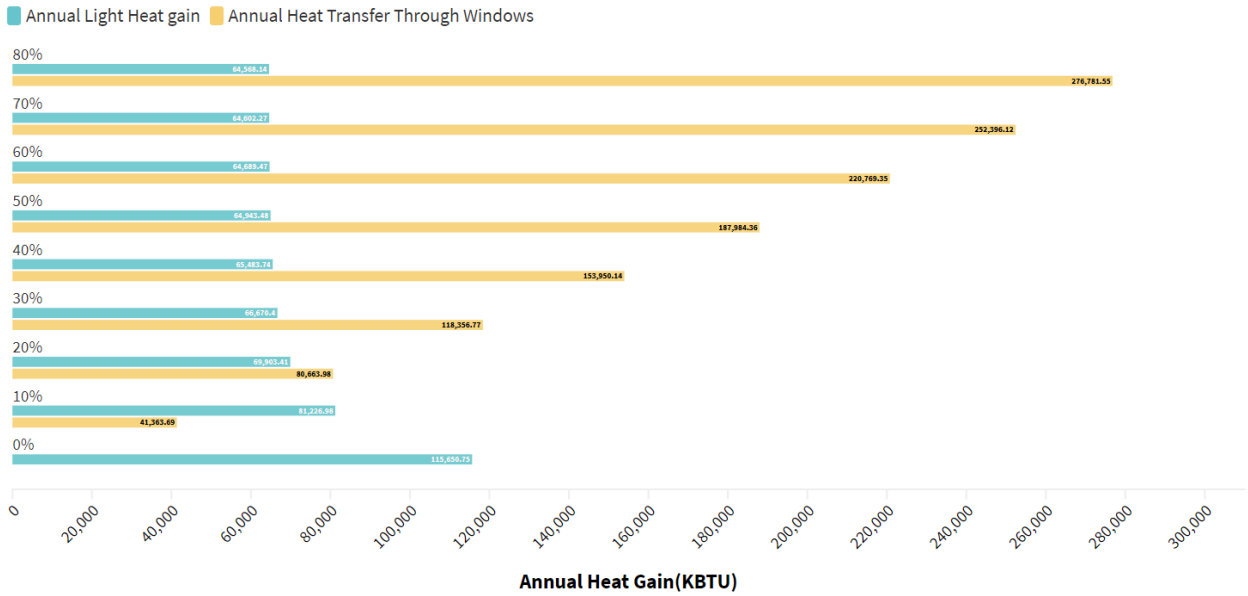


Figure 4.58 Annual Heat Transfer Vs. Annual Luminaires Heat Production (Fluorescent, NS)

- East-West Axis, LED

The annual heat transfer through window openings in the East-West axis is higher than the North-West axis.

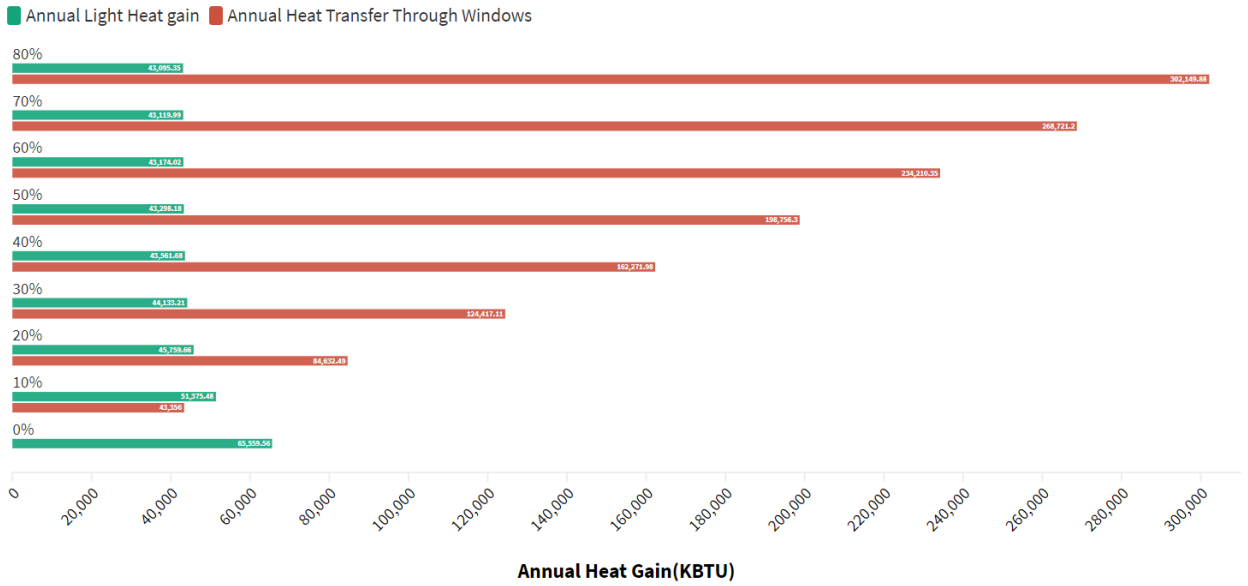


Figure 4.59 Annual Heat Transfer Vs. Annual Luminaires Heat Production (LED, EW)

- East-West Axis, Fluorescent

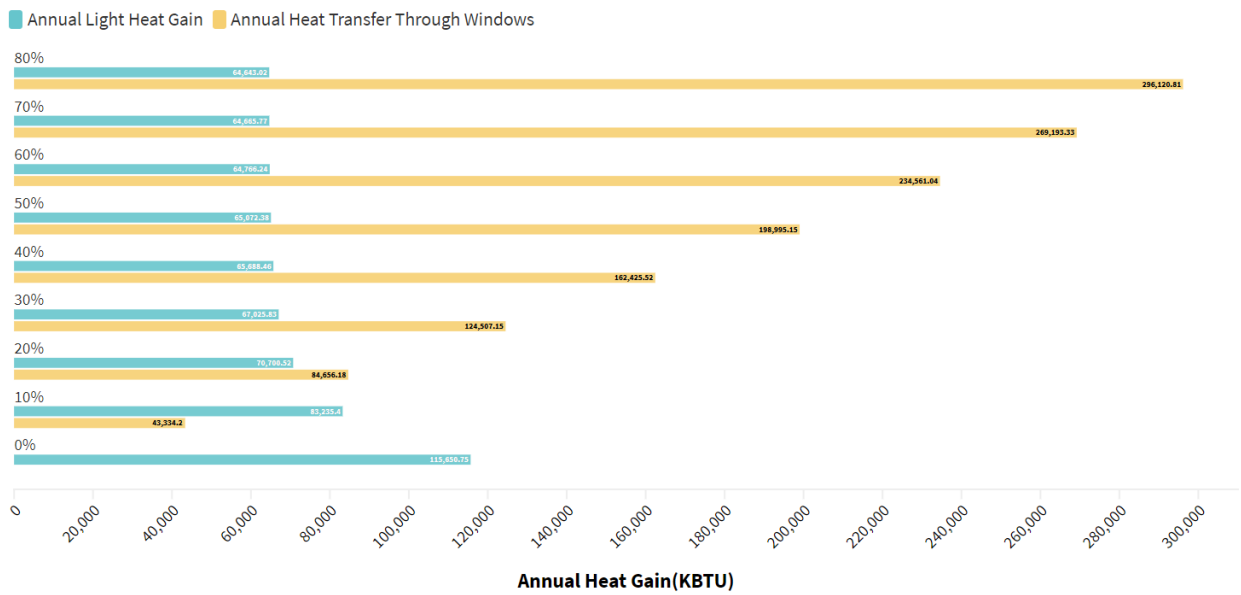


Figure 4.60 Annual Heat Transfer Vs. Annual Luminaires Heat Production (Fluorescent, EW)

4.3.17 Light Sensible Heat Gain (KBTU)

The reduction pattern for both light sources was similar, except that in the fluorescent cases, the plunge was steeper in the transition from 0% to 10% WWR. In the 0% scenario, the light sensible heat gain in the fluorescent plot was about twice the LED plot and the gap remained between 20000-30000 KBTU in rest of the scenarios. Also, light sensible heat gains in the East-West axis were slightly more than those of the North-South Axis. The reason is due to the specific angle of the sun in the East and West directions, which cause lamps to work with higher power and generate more heat.

- North-South Axis

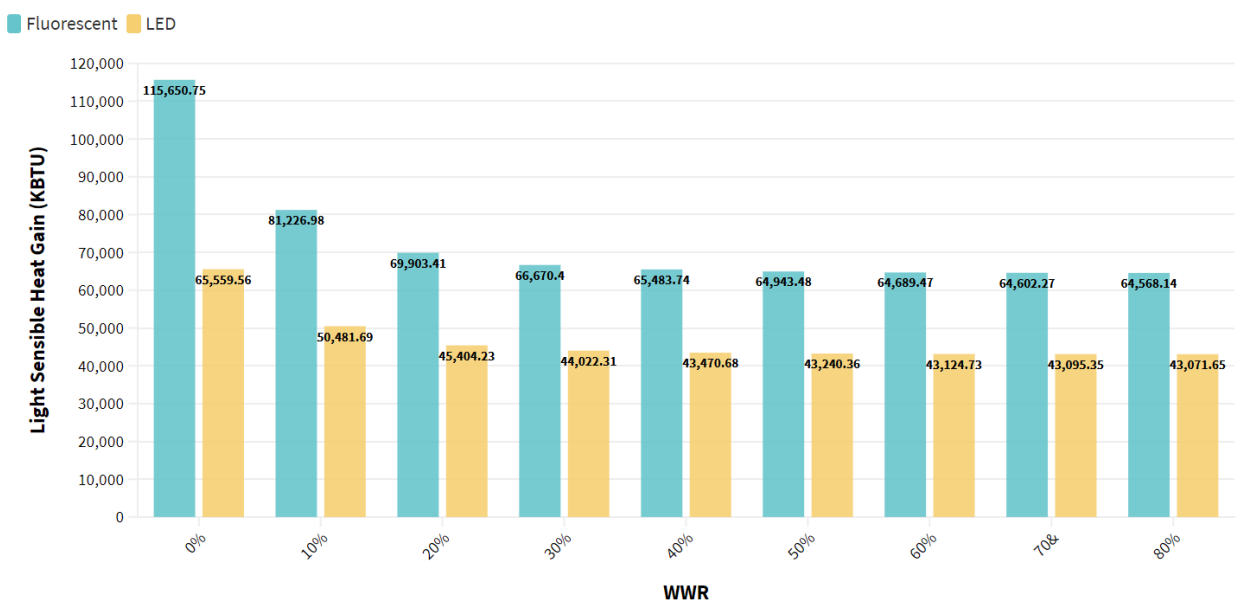


Figure 4.61 Light Sensible Heat Gain (NS)

- East-West Axis

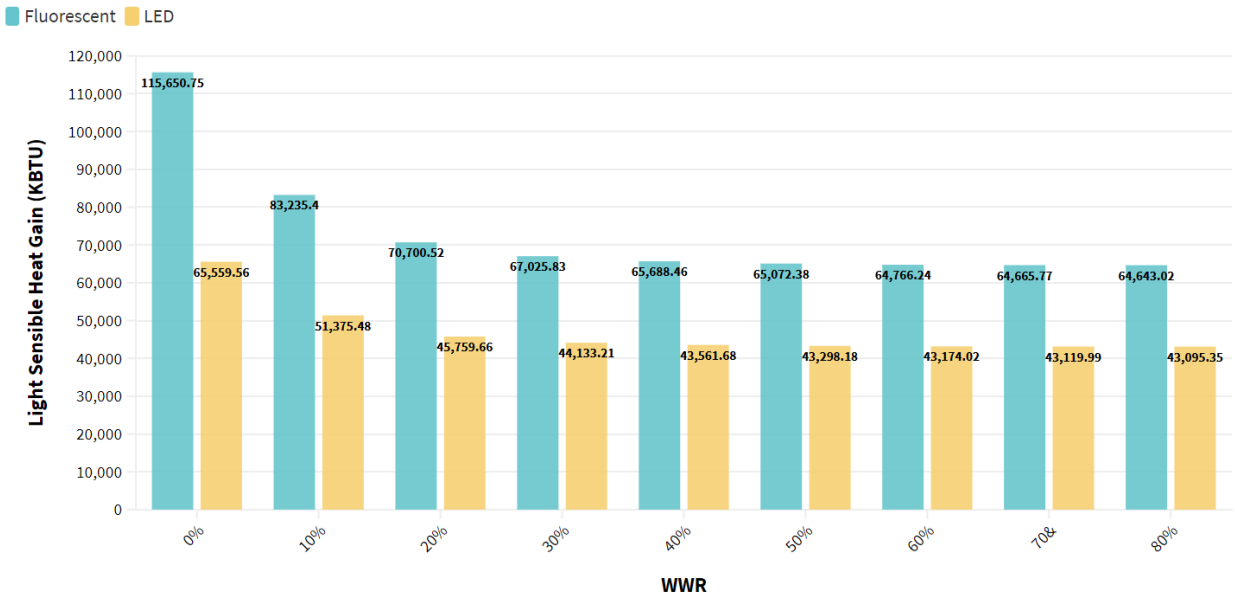


Figure 4.62 Light Sensible Heat Gain (EW)

Chapter 5 : **Conclusion and Summary**

5.1 Discussion and Conclusion

Harnessing daylight using windows helps to offset the amount of electric lighting needed to properly light a space, and decreases the total building energy consumption. This is accomplished by using glazed materials to admit daylight and lighting control systems, which can respond to the dynamic light level. However, improper implementation of a passive daylighting strategy may cause increased energy consumption. Sunlight is accompanied by infrared radiation which can increase the HVAC load of a space and compromise the energy savings achieved by daylighting. Therefore, a balance between solar heat and light gain is required to fully take advantage of solar energy without reverse impacts. Concerning the mentioned balance, recent advancements in lighting technology question the effectiveness of natural light in reducing whole-building energy consumption. Due to the high energy efficiency of LED luminaires, lighting power consumption is rather low, even when the lighting system operates at full capacity. Therefore, it is unclear whether the solar energy coming through glazed materials works to the advantage or disadvantage of total building energy consumption. This study hypothesized that the total energy consumption of an open office with LED luminaires would be less in absence of solar energy compared to a scenario which utilizes the solar energy. A simulation-based methodology, using a combination of photometric computation and building energy simulation tools, was utilized to examine the hypothesis and explore the impacts of lighting systems on the optimum window-to-wall ratio. This chapter summarizes the findings and proposes several future enhancements.

Findings indicated that bringing daylight through window openings into an open office with an LED lighting system resulted in energy savings only when 20% of the façade was covered by windows. In other words, more than 20% of window openings in a space increase total energy consumption rather than decrease it, as previously assumed. In general, increasing the WWR increased the cooling load and decreased the heating and lighting loads in the Blacksburg Climate zone. However, in excess of 20% WWR, the increase in cooling load was much higher than the decrease in heating and lighting load, in such a way that the energy savings through lighting and heating cannot offset the rise in space cooling energy consumption. Overall findings demonstrate that, in terms of energy, in open offices with an LED lighting system, the optimal WWR is about 10%. And exceeding 20% WWR will not help in reducing energy consumption.

In open offices with a fluorescent lighting system, increasing the WWR up to 40%- 45% can save energy and decrease the whole building energy consumption. By adding window openings to the spaces, daylight substitutes for a portion of the electrical light load, which results in a significant drop in energy consumption. However, by going above 50% WWR, the entire building energy consumption starts to become more than the energy consumption associated with the window-less scenario. More than 50% WWR not only does not reduce energy consumption, but also will increase it because the increase in cooling load becomes much more than the decrease in heating and lighting load. In terms of energy, findings indicate that 20% WWR is the most optimal WWR for open offices with a fluorescent lighting system.

The difference between light sources' energy performance caused one of the sources (LED) to be less affected by daylight than the other (fluorescent). LED light sources are so energy efficient that using

solar energy will adversely affect the cooling load rather than working in favor of lighting load. In contrast, lower energy efficiency in fluorescent sources causes daylight illumination to significantly reduce the lighting load and boost whole building energy consumption.

All this is not to conclude that 10% or 20% WWR is the ultimate WWR for open offices. As was previously stated, this study only considers energy performance while a high-quality design should address other criteria such as aesthetics, stability, economics, and spatial quality. Various studies have concluded that providing a visual connection to the outside can improve the occupants' health and overall experience in the spaces. Several studies have demonstrated the critical role of daylight and view on the seniors' and patients' health, and many hypotheses have been formed around the connection of humans with nature such as biophilia. In conclusion, to find the ultimate WWR for a building, window percentage should be evaluated with respect to several factors and a value should be selected which satisfies all the factors up to a reasonable level.

5.2 Comparison of results with current codes

ASHRAE standard 90.1- 2010 limits the vertical fenestration area to 40% of the gross above-grade wall area for a baseline building. In the exception of some building types, the area of west and east-oriented vertical fenestration must not exceed the area of south-oriented vertical fenestration. The maximum fenestration area stated by ASHRAE has not been categorized based on specific lighting or HVAC system and it is a general requirement for most of the building types. However, architects, even those who are green design advocates, push for about 60% window-to-wall ratio for addressing the view and appearance trends. Daylight harvesting is usually provided as a justification for this decision [40]. This is possible if the design team proves that the increase in the WWR helps the building performance through daylighting, natural ventilation, and other relevant factors.

This study suggests that the standard WWR could be specified based on building systems. According to results, up to 40% window for a building with a fluorescent lighting system can save energy. This number is very close to the maximum WWR mandated by ASHRAE Standard. However, the 20% window ratio which can save energy in a building with an LED lighting system is much less than the 40% mandated by ASHRAE Standard. Thus, considering building systems when setting the allowable WWR results in more energy savings.

5.3 Future works

This study has the potential to be expanded and strengthened by improvements in several areas explained below.

1. Modifying the exposed concrete ceiling to a dropped ceiling and using recessed luminaires

75-80 percent of LED lamps' heat is produced in the form of convection, 20-25 percent in the form of visible light, and 0 percent in the form of radiant heat. As a result, it is reasonable to collect all the convective heat directly and at once from the return air plenum. The plenum space above the drop ceiling can be considered as a return air path. The heatsink of the recessed luminaires could be placed in this space, so that heat generated by the luminaires directly collected in the return air plenum. The

advantage of this strategy is a more efficient HVAC cycle and less energy consumption. This strategy prevents the heat to be added to the space zone and increases the cooling load. The same method can be applied to the fluorescent scenario and lead to a reduction in cooling load. Given that the convective heat produced by fluorescent sources is only about 40%, the strategy is more effective with the LED luminaires. By using a drop ceiling in the design, more savings would take place in terms of the cooling and heating load, and thus, the difference in LED and fluorescent results might be even more significant.

2. Adding to or changing the stimulation parameters

This study has 17 parameters, each of which can be examined as a primary or related variable and thus, lead to a significant change in the results. For instance, the thermal properties of LED and fluorescent light sources vary in each type of luminaries and there is no absolute value for them. Changing the share of convective, radiant, and visible fraction, change the results significantly. Thus, each of the parameters introduced in the Methodology chapter can potentially become a variable and change the results.

3. Studying the impact of glazed material on the optimum WWR

High-performance glazed materials can block solar heat while admitting visible light. Advancements of glazed materials during recent years have allowed architects to increase buildings' window area without compromising the project's sustainability. As a result, features of the glazed material are key parameters that can profoundly impact the optimum WWR. In this regard, the high-performance low-E coated glazed system used in this study might have decreased the common 30%- optimum WWR suggested by existing literature. Further investigations are required to precisely determine the role of glazed materials in WWR and the energy pattern.

4. Considering the illuminance share of each luminaire type

Finding the illuminance associated with each type of luminaire help to better understand their sole effect on the overall light level and estimate their contribution to the HVAC load, based on their heat properties and operational schedules. The information can also be helpful when a separate dimming strategy is in place.

5. Running the daylight simulation through EnergyPlus

As stated previously, EnergyPlus has two lighting simulation algorithms which use two different daylight simulation methods including Radiosity and Splitflux. In this study, the Radiance engine was used for daylight calculations, which uses the backward Raytracing method. Simulating through different methods can change the accuracy of lighting results and helps to estimate the level of deviation from reality.

6. Using optimization algorithms to find the global optimal WWR

The results of this research have demonstrated the optimum local WWR. However, by using algorithmic methods such as diagonal, Morris Method, or Genetic Algorithm (GA), more precise optimization can be generated. The ultimate goal is to bring the results as close as possible to the global optimal values, which is the most optimal solution that can exist within the feasible solution domain.

7. Using Virtual and Augmented Reality technology to find the preferred WWR by the help of a survey

A survey using VR technology can be conducted to find out the WWR percentage that satisfies occupants the most. The optimum WWR delivered by this study can then be integrated with the occupants' preferred WWR, to propose the ultimate window percentage that satisfies the spatial quality in addition to energy performance.

8. Studying the office layout with respect to dimension and position of the windows

Changing the WWR has a profound impact on space and furniture layout. It would be interesting to explore the possibilities of designing high-quality spaces with a small percentage of windows. It requires discovering the critical spots and proper ratios for window openings that can affect the occupants' experience the most.

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