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Impact of Window-to-Wall Ratio on Lighting Load in Municipality Building-A Case Study of Bharatpur Metropolitan Administration Block

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ABSTRACT–Visual comfort is a critical aspect of indoor environments, contributing to occupant satisfaction, well-being, and overall productivity. In the face of rapid urbanization, particularly in regions like the Chitwan District, understanding and enhancing visual comfort in built environments take on heightened significance. The primary focus of this study is to explore how varying Window-Wall Ratios (WWR) affect the energy performance of buildings. The research begins with an in-depth review of existing literature on building energy efficiency, focusing on the significance of WWR in determining natural lighting penetration. Field measurements are collected to establish a baseline understanding of the building's lighting performance. Utilizing advanced simulation tools, the study explores various WWR scenarios to simulate the potential impact on lighting load. The analysis considers both energy efficiency and occupant comfort, aiming to identify an optimal WWR that balances natural lighting benefits with energy conservation goals. The study finds that a 30% WWR represents the ideal balance for effective electricity consumption for lighting. Monthly analysis underscores its significance by revealing diminishing returns beyond this point. Consequently, recommended optimal WWR values stand at 25% for the ground floor and 30% for both the first and top floors. The findings hold significant importance for designers and policymakers in making informed design and policy decisions.

KEYWORDS – ***Lighting Consumption, Metropolitan building, WWR, Daylight***

1. Introduction

Maximizing the benefits of natural daylighting can drastically cut down on the amount of energy and artificial lighting required (Yassin et al., 2017). To add natural light to a space during the day, daylighting involves exposing vertical windows and wall openings to solar radiation (Muneer & Kambezidis, 1997). Daylighting is the use of natural light to complement or replace artificial light. If windows are sized, shaped, and have the proper glazing options, daylight can significantly reduce the need for artificial lighting. When daylighting strategies are incorporated into electrical lighting controls, they can automatically adjust to provide the least amount of light while consuming the least amount of electricity (Muneer & Kambezidis, 1997). In office buildings, windows should be considered as a component of the fenestration system style in order to balance the need for daylighting against the need to minimize solar gains.

The use of daylight in buildings can result in a decrease in the need for electricity for lighting, but it may also contribute to increased cooling demands if there is an allowance for excessive solar gains in the occupied space (Tzempelikos & Athienitis, 2005). In order to satisfy the occupants' needs for both quantity and quality of lighting, appropriate fenestration and lighting controls are also utilized to modulate daylight admittance and minimize electric lighting. For a number of reasons, daylighting is a wise design choice, particularly in office buildings: Delightful, cozy areas with natural light have the potential to boost owner and tenant contentment and lower absenteeism. Employee productivity is a crucial business asset. Daylighting buildings that use less energy have a positive impact on the environment because they use fewer power plants and produce fewer pollutants as byproducts, which also saves money (Orlando & Berkeley, 1997).

To assess the influence of Window-Wall Ratio (hereafter, WWR) on lighting energy consumption in structures within the Chitwan district, a case study was undertaken at the Bharatpur Metropolitan Administration building. The research aims to investigate the impact of different WWR on building energy performance. To achieve this overarching goal, specific objectives have been outlined. Firstly, the study involves assessing the current WWR in a chosen public building, evaluating its energy performance, and establishing a benchmark for the case study structure. Additionally, the research aims to determine the optimal WWR range that effectively balances energy efficiency in municipal buildings located in Chitwan. These objectives collectively contribute to a comprehensive understanding of the relationship between WWR and building energy performance, with a focus on informing practices for improved energy efficiency in the specified context. The findings from the study is important in informing practices for improved energy efficiency within specific context, offering practical implications for sustainable building designs and policy decisions.

1.1 Window-Wall Ratio, Daylighting, and Building Performance

Daylighting, as a deliberate design approach, strategically incorporates elements like windows, skylights, reflective surfaces, and various openings in building structures to capitalize on natural sunlight for effective internal illumination. Numerous studies attest to the transformative impact of quality light on worker performance and productivity across diverse environments such as offices, industrial spaces, and retail establishments. Research findings indicate a substantial 15% increase in employee productivity when exposed to enhanced daylight conditions, translating into significant financial gains for businesses. Beyond the workplace, studies underscore the positive correlation between daylighting and educational outcomes, revealing that classrooms with high WWR or ample daylight contribute to students scoring 7% to 18% higher on standardized tests compared to environments with limited natural light (Heschong, 2002). By optimizing the utilization of natural light, daylighting not only fosters energy efficiency but also plays a pivotal role in creating well-lit and comfortable indoor spaces that positively impact human performance and well-being.

1.2 Window-to-Wall Ratio (WWR)

One measure that can impact the energy consumption of the entire building and establish the equilibrium between solar heat gain and visible light is the WWR. According to ASHRAE-IESNA (2007), it is the percentage of the above-grade wall area that is covered by windows. The following equation shows how to calculate WWR:

$$\mathrm{WWR}\ (\%) = \frac{\sum \text{Glazing Area}(\mathrm{m}^2)}{\sum \text{Gross Exterior Wall Area}(\mathrm{m}^2)} \quad \text{(Eq. 1)}$$

Windows give buildings design, let light in, provide views, and act as a thermal barrier. Consequently, windows are thought to be among the most crucial parts of a commercial building envelope system. The amount of exterior wall surface area that is glazed (made up of windows) is known as the WWR, and it has an impact on a variety of building characteristics. The size of the window defines the visual and physical connection to the outside and the environmental effects of the material used (Islam et al., 2014). Through heat transfer (conduction), solar heat gain (radiation), air leakage or ventilation (infiltration), and daylighting (lighting demand offset), WWR influences building energy use and occupant comfort (Ashrae, 2013).

A model energy code known as ASHRAE Standard 90.1 establishes a maximum WWR of 40% for commercial buildings that follow the prescriptive path to compliance and serves as the starting point for the performance path. It also defines the characteristics of buildings to ensure least energy savings for each US climate zone (ASHRAE, 2013). Several simulation-based studies have been conducted in an effort to identify the ideal WWR (Alibaba, 2016; Ascione Nicola; De Masi Rosa Francesca; Mauro Gerardo Maria; Vanoli Giuseppe Peter, 2015; Didwania Srijan et al., 2014; Ghisi John A., 2005; Goia, 2016a; Mangkuto Mardliyahtur; Asri Anindya Dian, 2016; Su Xu, 2010) under various circumstances, and some suggest WWRs less than 40% minimize energy use (Goia Matthias; Perino Marco, 2013; Gratia André, 2003; Ma Lin-Shu; Guo Nianhua, 2015; Yang Meng; Shu Chang; Mmereki Daniel; Hossain Uzzal; Zhan Xiang, 2015). Proposals to reduce the maximum WWR to 30% during the 2013 revision of ASHRAE 90.1 met some controversy and were ultimately rejected (Athalye et al., 2013; Sanders & Podbelski, 2015), but WWR remains an important topic in building design and operation.

2. Research Methodology

2.1 Research Design

The research methodology employed in this study involves a multifaceted approach, primarily consisting of an extensive literature review, on-site surveys, and energy modeling. To determine the optimal window-to-wall ratio for public buildings, a comprehensive analysis of relevant literature and past research conducted in climates akin to that of Chitwan is undertaken. The insights gleaned from this literature review form the basis for identifying an appropriate ratio. Subsequently, the validity and applicability of this ratio are further confirmed through energy modeling specifically conducted on the Bharatpur metropolitan administration building. This methodological framework ensures a comprehensive exploration of factors influencing the window-to-wall ratio, integrating theoretical insights with practical application in the specific context of Chitwan's climatic conditions and the architectural dynamics of the Bharatpur metropolitan administration building.

2.2 Bharatpur Metropolitan

The Bharatpur metropolitan city is situated in Nepal's Province No. 3's Chitwan district. There are 29 wards in all in Bharatpur, and they are dispersed over an area of 433 square kilometers. It serves as both the district's headquarters and its commercial hub.

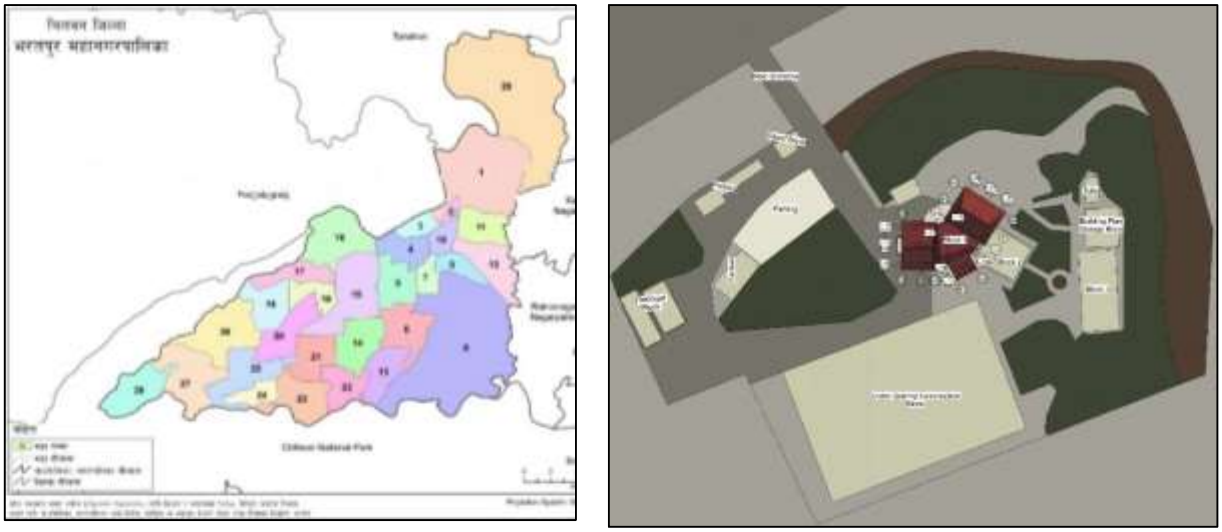

Figure 1. Site Location and Plan of Bharatpur Metropolitan City office

As the headquarters and commercial hub of Chitwan district, it plays a pivotal role in the regional landscape. The city's establishment dates back to 2035 B.S. (1979 A.D.) when it was declared a municipality in 2048 B.S. (1991 A.D.). Notably, on March 10, 2017, Bharatpur earned the distinction of being upgraded to the status of a Metropolitan City, reflecting its evolving significance and role in the administrative and economic spheres of the region.

2.3 Climate Study

The meteorological data for Chitwan spanning the years 2010 to 2020 A.D. was gathered from the Department of Hydrology and Meteorology located in Babarmahal, Kathmandu. This comprehensive dataset formed the basis of our analysis, allowing us to delve into various climatic factors affecting the region. By scrutinizing this collective data, we gained insights into temperature patterns, precipitation levels, and other meteorological parameters that characterize Chitwan's climate over the specified timeframe.

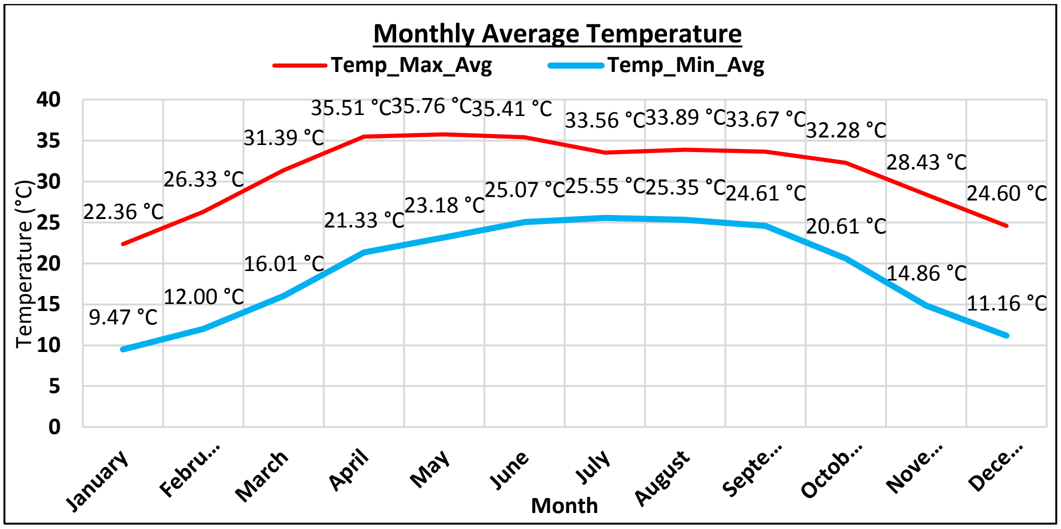

Figure 2. Average monthly maximum and minimum temperature data of Chitwan from 2009-2020

The climate in this region exhibits notable variations throughout the year. May experiences the highest average temperature, reaching 35.76°C, providing a warm ambiance. In stark contrast, January witnesses the lowest average temperature, dipping to 9.47°C, signaling cooler conditions. The precipitation patterns also peak significantly, with July receiving the maximum rainfall at 589.83 mm, contributing to a potentially wet monsoon season. Conversely, December sees the minimum precipitation, with only 3.13 mm of rainfall, indicative of drier winter months. Additionally, the solar radiation levels demonstrate seasonal changes. March and April emerge as the peak months, boasting maximum solar radiation at 385 w/sq. m., while January experiences the lowest solar radiation levels, measuring at 217 w/sq. m., suggesting reduced sunlight during the winter period.

2.4 Case Study

The Bharatpur metropolitan administration building (Block 1) was taken under study for case study. There are 3 major blocks in Bharatpur Metropolitan City: Block 1, Block 2, and Block 3. Among all these blocks, block 1 is the oldest block which is load load-bearing structure whereas block 3 is the recently built prefab steel structure. The Block 1 faces a huge problem with the lighting in the office area.

Block 1 **Block 2** **Block 3**

Figure 3. Block in Bharatpur Metropolitan City

Almost all of the rooms in the building have artificial light for doing the office job which has huge energy-saving potential. The building is made up of a minimum size of window. Block 1 consists of 4194 sq. ft. Ground coverage with 3 floors. The floor Height of the building is 11' 10". It consists of 10 nos of room in Ground Floor, 7 nos of room with meeting hall in second floor and 8 no's of room in top floor. The main administration work and store are allocated in this building along with the room for the City Mayor and Deputy Mayor. As per the room size and the size of the window, there is high potential for optimization of the building and finding the optimum WWR that can help to achieve optimum lighting consumption.

Figure 4. Ground Floor Plan

Figure 5. First Floor Plan

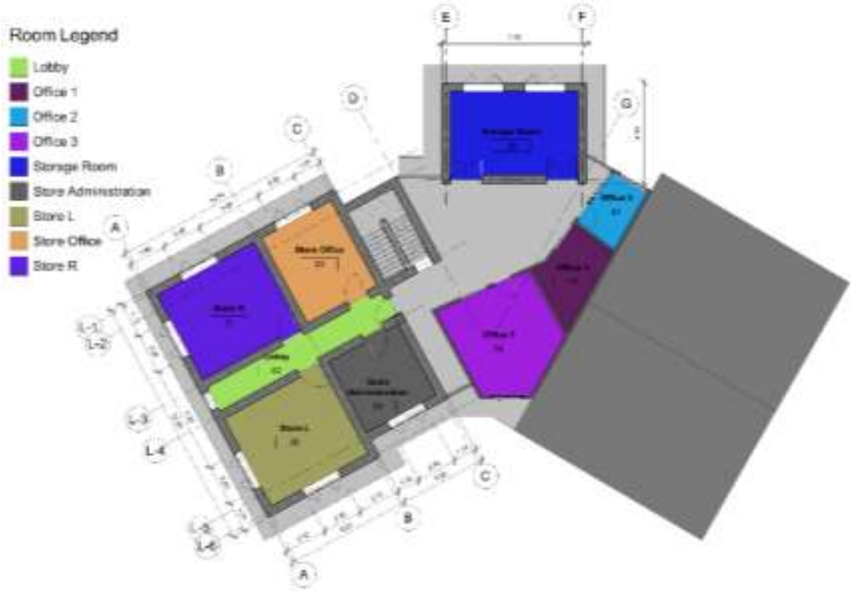

Figure 6. Roof Plan

2.5 Building Modeling

The initial phase of this study involved modeling the existing building as a base case scenario, meticulously incorporating all specifications based on actual site measurements and conditions, as well as insights gathered from comprehensive interviews with local authorities. This model was built to closely mirror the real-world features of the building, ensuring an accurate representation of on-site findings. Subsequently, the energy optimization process was performed through the exploration of various scenarios, ranging from Scenario 1 to 7.

Scenario 1:
All the window are changed to 10 % WWR keeping all material same as base case Scenario

Scenario 2:
All the window are changed to 15 % WWR keeping all material same as base case Scenario

Scenario 3:
All the window are changed to 20% WWR keeping all material same as base case Scenario

Scenario 4:
All the window are changed to 25 % WWR keeping all material same as base case Scenario

Scenario 5:
All the window are changed to 30% WWR keeping all material same as base case Scenario

Scenario 6:
All the window are changed to 35 % WWR keeping all material same as base case Scenario

Scenario 7:
All the window are changed to 40 % WWR keeping all material same as base case Scenario

Figure 7. Various Design Builder Scenario

Each scenario involved adjustments to the WWR to gauge the optimal planning for the given building. The WWR modifications started from an initial 10%, incrementally increasing by 5% up to a maximum of 40%. This systematic approach aimed to assess the impact of different WWRs on energy consumption, contributing valuable insights into the most efficient and sustainable planning for the building under consideration.

3. RESULTS AND DISCUSSIONS

In Figure **1**8, we can see that the increment in WWR from 10% to 30% is shown to result in a significant reduction in lighting load, amounting to 4206.2 kWh. This corresponds to 54% saving in lighting energy consumption. This outcome suggests that the modification in WWR, which likely involves optimizing natural light penetration and distribution within the building, has a profound effect on the need for artificial lighting. This emphasizes the importance of thoughtful design in harnessing natural light to reduce reliance on electrical lighting, contributing significantly to energy savings.

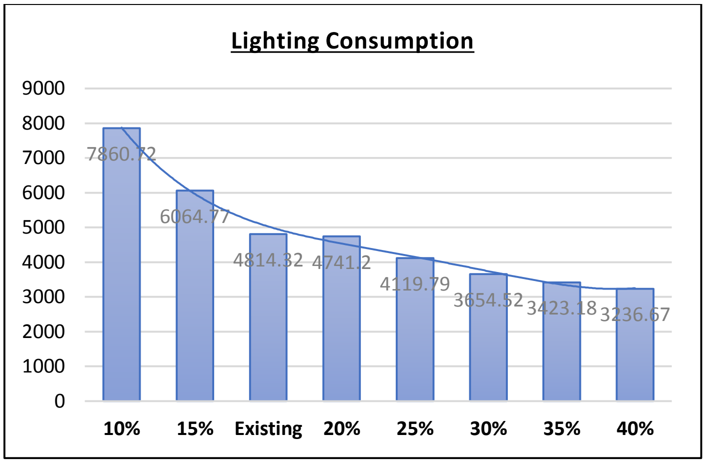

Figure 8. Electricity Consumption for lighting of Various WWR

Continuing the discussion, the subsequent reduction in WWR from 30% to 40% leads to an additional lighting load reduction of 417.85 kWh, representing an 11% further saving. While the absolute reduction is smaller compared to the first stage, it underscores the incremental benefits of increasing the WWR even within a narrower range. Moreover, the overall reduction in lighting consumption from transitioning an existing building to the optimum WWR is quantified at 1160 kWh, equating to a 24% saving. The data highlights that the optimization of WWR up to a point, when considered comprehensively, not only reduces the need for artificial lighting but does so in a manner that contributes significantly to the overall energy efficiency of the building.

3.1 Monthly Analysis

The chart visually depicts a significant reduction in electricity consumption for lighting, reaching a noticeable decrease up to a 30% WWR. Beyond this point, the chart indicates a diminishing difference in the area of chart, suggesting that further increases in

WWR do not result in a meaningful decrease in consumption. This observation leads to the conclusion that a 30% WWR represents the optimum balance, offering the most efficient electricity consumption for lighting purposes. The chart's clear representation of diminishing returns in terms of energy efficiency emphasizes the importance of thoughtful and strategic decisions in establishing the optimal WWR to achieve maximum lighting benefits while minimizing energy consumption.

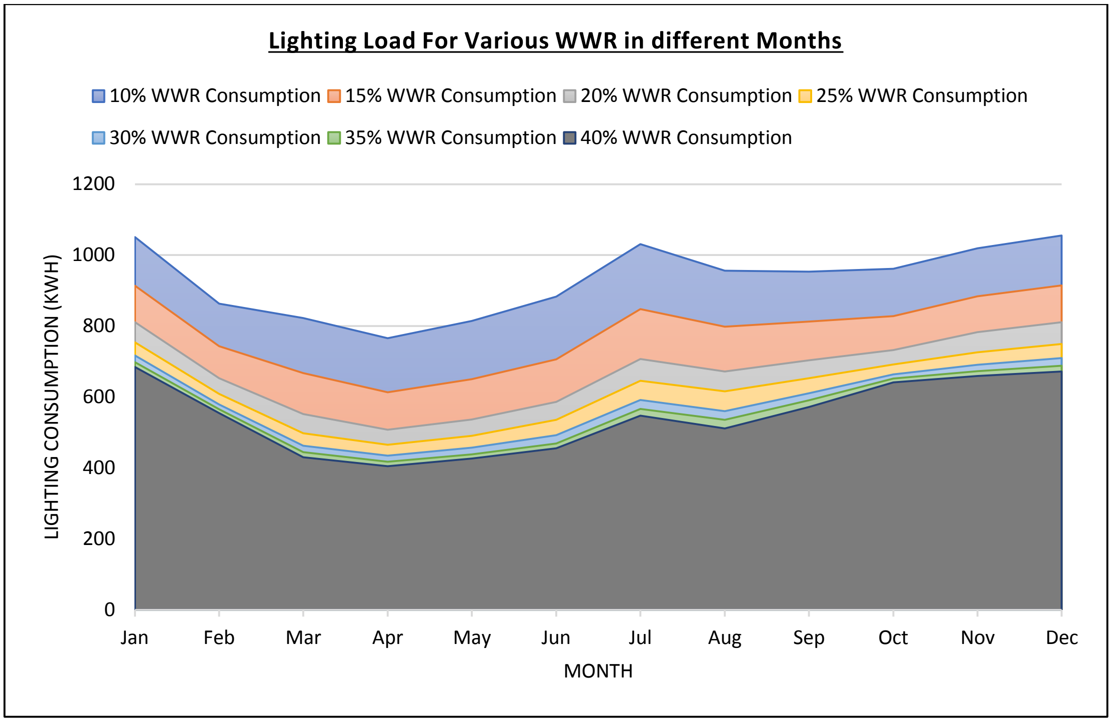

Figure 9. Electricity Consumption for lighting of various WWR for Different Months

The data highlights distinct peaks in lighting load during January and December, indicating a potential correlation with the winter season's characteristics, marked by reduced solar incident and shorter daylight hours. The need for heightened artificial lighting during these months becomes apparent as a response to the diminished natural illumination. Furthermore, an additional peak in lighting load is observed in July, which could be attributed to the rainy season. During this period, increased cloud cover or heavy rainfall may contribute to darker and gloomier conditions, necessitating higher artificial lighting usage. These fluctuations underscore the seasonal influence on lighting demands, emphasizing the importance of adaptive energy strategies to address varying environmental conditions throughout the year.

3.2 WWR as per Floor

The analysis provides detailed insights into the relationship between Window-Wall Ratio (WWR) and lighting consumption for different floors of the building. In the analysis of the ground floor, a discernible pattern emerges, revealing a significant decrease in lighting consumption savings once the WWR exceeds 25%. This is clearly depicted by the graph's shift from a gradual slope to almost a flat line, indicating a constant consumption level of 999.07 kWh. Consequently, the optimal WWR for the ground floor is determined to be 25%. The reductions in lighting load on the ground floor are quantified as substantial, amounting to 1411.91 kWh (59% saving) during the transition from a 10% to a 25% WWR. Furthermore, from a 25% to a 40% WWR, an additional 298.53 kWh is saved, contributing to a 30% further reduction. The cumulative effect of optimizing the ground floor's WWR, from the existing building to the identified optimum, results in a calculated overall reduction of 112.41 kWh, representing a significant 10% decrease in lighting consumption. This detailed examination underscores the critical role of selecting an appropriate WWR to achieve substantial energy efficiency gains, particularly for the ground floor of the building.

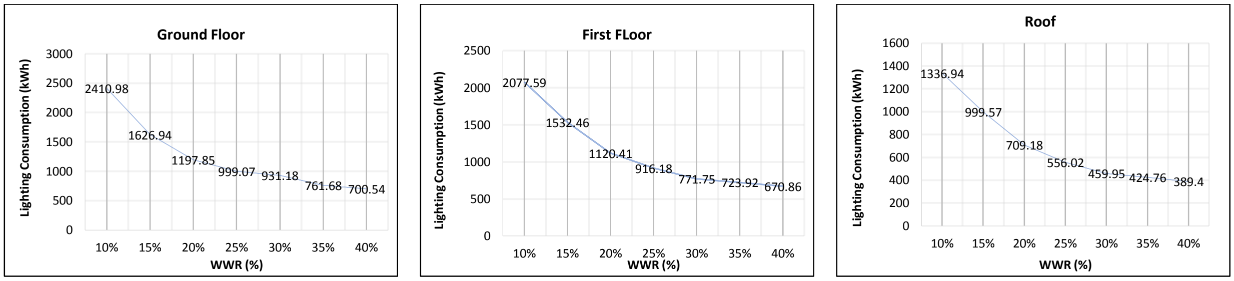

Figure 10. Electricity Consumption for lighting For Various Floor

Upon examining the first floor, a parallel trend emerges, showcasing a substantial decrease in lighting consumption savings as the WWR surpasses 30%. The graph depicts a flattening pattern, indicating a consistent consumption level of 771.75 kWh and pointing to the optimal WWR for the first floor being 30%. The reductions in lighting load on the first floor exhibit a remarkable decline in savings, amounting to 1305.84 kWh (62%) when transitioning from a 10% to a 30% WWR. Subsequently, from a 30% to a 40% WWR, an additional 100.89 kWh is saved, contributing a 13% further reduction. The holistic impact of optimizing the first floor's WWR, from the existing building to the identified optimum, is calculated at a noteworthy 920 kWh, reflecting an impressive 54% overall reduction in lighting consumption. This analysis underscores the importance of fine-tuning the WWR to achieve significant energy efficiency gains, particularly on the first floor of the building.

Similarly, for the top floor, there is a substantial decrease in lighting consumption savings beyond a WWR of 30%, signified by a transition from a sloped line to a flat line with a constant consumption of 459.95 kWh. Consequently, the optimal WWR for the top floor is identified as 30%. The reduction in lighting load for the roof floor is quantified as 876.99 kWh (66% saving) when transitioning from 10% to 30% WWR and 70.55 kWh (15% further saving) from 30% to 40% WWR. The overall reduction in lighting consumption from the existing building to the optimum WWR is calculated as 701.46 kWh, representing a substantial 60% saving. These findings emphasize the critical role of optimizing WWR in achieving significant energy efficiency gains, particularly for the lighting requirements on the top floor of the building.

3.3 Discussions

The primary factor influencing interior air quality, thermal comfort, and visual comfort is the WWR. The ideal WWR should provide excellent thermal, visual, and air quality for the occupants while consuming relatively little energy. The ideal value of WWR varies depending on the climate, zone, or area, as well as the occupants' needs and the intended use of the space. Thermally stable indoor environments with little heat loss to the environment are produced by minimum WWR values (Ghosh & Neogi, 2018; Uprety et al., 2021). The ideal WWR should be in the lower range if the thermal aspect is the only factor considered. This is because building windows have a higher thermal conductivity, which increases the possibility of required and superfluous energy gains or losses from the structure. As a result, the range is closer to 10% at lower values (Alibaba, 2016; Özer Yaman, 2022).

WWR has a particularly noticeable impact on cooling load (Troup et al. 2019). Energy consumption can be decreased in warmer climates where high WWR causes an increase in cooling load by installing fixed or dynamic shading devices with optimal angle and geometry (Golzan, Pouyanmehr, and Naeini 2021; Zayed et al. 2018). While fulfilling the visual requirements of office buildings is crucial, a higher WWR, which necessitates increased cooling load, may lead to decrease the reliance on artificial lighting. However, the use of low WWR, which in turn increases the dependence on artificial light, is associated with negative impacts on occupant health. Recognizing the importance of visual comfort in optimizing WWR, optimum WWR range between 25% and 30%. The similar data can be found in various research. Ayoosu et al., (2021) utilized IES-VE software for simulations, finding that in a typical lecture theatre with a 12×20 m floor plan, 6 m ceiling height, and 13% window WWR, daylighting performance improved with increasing WWR up to 30%, beyond which a decline was observed, establishing 30% as the optimal window-wall ratio for effective daylighting in tropical climate lecture theatre retrofitting. Goia, (2016) integrated thermal and lighting simulations identified optimal WWR for diverse climates (35° to 60° N), testing the results' robustness through sensitivity analyses; the findings revealed a relatively narrow range ($0.30 < WWR < 0.45$) for most ideal values, with exceptions for south-oriented facades in extreme climates. Wen, Hiyama and Koganei, (2017) identified an optimal WWR range of 30% to 50% for various locations in Japan, having minimum CO2 emissions. Shaeri et al., (2019) identified the optimal window area for the northern building facade as 20–30% across all climates, and for the southern facade in Bushehr, Shiraz, and Tabriz, the recommended ranges are 20–30%, 10–30%, and 20–50%, respectively.

4. CONCLUSIONS

The study utilizing DesignBuilder simulations to investigate the influence of Window-to-Wall Ratio (WWR) on lighting energy load in Chitwan's Metropolitan administrative buildings has revealed important insights into energy performance and potential efficiency enhancements. The research emphasizes the substantial impact of glazing proportions on lighting energy consumption, revealing a clear correlation between increased WWR and decreased reliance on artificial lighting due to enhanced natural daylight penetration. This underscores the pivotal role of thoughtful architectural design in optimizing energy use. The transition from 10% to 30% WWR demonstrates a significant 54% reduction in lighting load, showcasing the substantial benefits of enhancing natural light penetration. While the subsequent reduction from 30% to 40% yields a smaller but still notable 11% saving, the overall reduction in lighting consumption by optimizing WWR is a significant 24%. The monthly analysis reinforces the importance of a 30% WWR, indicating diminishing returns beyond this point and establishing it as the optimum balance for efficient electricity consumption for lighting purposes. Peaks in lighting load during certain months, particularly in winter and during the rainy season, underscore the need for adaptive energy strategies to address seasonal variations in environmental conditions. The floor-specific analysis further highlights the nuanced relationship between WWR and lighting consumption. Optimal WWR values of 25%, 30%, and 30% are identified for the ground floor, first floor, and top floor, respectively. The substantial percentage reductions in lighting consumption for each floor, ranging from 59% to 66%, underscore the critical role of fine-tuning WWR for achieving significant energy efficiency gains. The research concludes the criticality of strategic decisions in setting WWR to maximize lighting benefits and minimize energy consumption, significantly enhancing overall building energy efficiency. These findings inform improved energy efficiency practices in specific contexts, guiding sustainable building designs and policy decisions.

5. ACKNOWLEDGEMENT

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