Identifying Height-Based Parameters of Roof Shading as a Passive Cooling Strategy in Buildings

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Abstract
Roof shading is an effective passive strategy in tropical climates for reducing building cooling loads. This study examines the impact of height of roof shading and height-to-depth ratio (HDR) on the thermal performance of large office buildings in warm and humid climates. Using parametric simulation and statistical analysis, the study finds that the absolute height of roof shading is critical in determining impact of roof shading on cooling loads of top floor. Whereas, the HDR in the East-West direction highly impacts the cooling loads of north and south perimeter zones of top floor, while the HDR in the North-South direction impacts the east and west perimeter zones. The results offer valuable insights for architects and designers towards enhancing energy performance of the building.

Highlights
- The study highlights the effectiveness of roof shading in reducing cooling loads in tropical climates.
- The research highlights that the impact of roof shading is significantly less over the insulated roofs compared to the uninsulated roofs.
- For large Buildings, it is observed that the height of roof shading can be the critical parameter for the roofs thermal performance.
- The study reveals that the height-to-depth ratio of roof shading can be considered by designers to take localised decisions for top floor perimeter zones.

Introduction
Passive design features play a vital role in improving the thermal performance and reducing energy consumption of buildings. Among these features, roof shading is a popular choice for its effectiveness in blocking solar radiation and reducing heat gain. In tropical climates, the roof receives the highest incident irradiation compared to all other opaque envelope components. In a survey-based study (Sadevi & Agrawal, 2019) on different envelope design features for energy efficiency in India, roof shading emerged as the most considered design feature in early design stages. Previous research has examined the effects of roof shading in various climate zones, including hot arid, warm humid, Mediterranean, and cold climates. Besides obstructing the solar irradiation received during the day, the roof shading plays a critical role in controlling the night sky radiation emitted from the structural roof. Previous researches on roof shading have focused on different roof shading typologies such as the double skin roofs, elevated mesh shading, roof shading through a solar photovoltaic array, parasol roofs, shaded roofs etc. Of all these, Double-skin roof (DSR) with a ventilated air gap between the primary (Structural roof) and secondary roof (the shading layer) layers has been gaining popularity as a passive cooling method (Sadevi & Agrawal, 2019). DSR has been found to reduce heat gain by 28-34% in different climatic zones during daytime and allow for 3-5 times more heat loss from the building compared to insulated roofs during night-time (Zingre et al., 2017). The performance of the double-skin roof varies with external environmental conditions, such as wind speed and temperature of the surrounding atmosphere, for ventilated DSR (Miller et al., 2007; Susanti et al., 2011).

Combining shading devices with other strategies, such as water ponds and ventilated tunnels, can further enhance the cooling impact in hot-arid climates, reducing internal air temperatures by more than 10°C and cooling loads by up to 88% (Kharrufa & Adil, 2012). In hot arid climates, elevated mesh shading systems have been found to reduce daytime temperatures by up to 5°C (Pearlmutter & Rosenfeld, 2008). Shaded roofs have also been shown to reduce rooftop temperatures by up to 50% and peak air conditioning loads by up to 50% in warm-humid climates (Halwatura & Jayasinghe, 2009). In addition, studies have highlighted the potential of rooftop solar photovoltaic modules in reducing cooling loads in tropical climates and heating and cooling loads in semi-arid climates. In addition to reducing heat gain, roof shading can also provide aesthetic value to a building. Parasol roofs and pergolas can add to the architectural appeal of a structure while providing shade and reducing heat gain (Sadevi & Agrawal, 2019).

The accelerated use of rooftop solar PV in buildings provides a practical case for the integration of solar PV with the secondary roofs, offering the benefits of shading and effective utilization of terrace space besides the PV generation. Such integration highlights the installation of rooftop solar PV as a driving force for the adoption of parasol roofs in future designs. Previous research has indicated that when roof shading and insulation are both provided together, the roof's performance is poor compared to roof with only shading or insulation (Sadevi & Agrawal, 2020). The effectiveness of roof shading and other envelope design features in reducing heat gain depends on the sol-air temperature, which in turn is

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affected by weather conditions such as temperature and solar radiation. The ASHRAE Handbook of Fundamentals (ASHRAE, 2021) provides envelope heat gain calculations that consider the sol-air temperature and properties of the roof. Therefore, it is important to modulate the diurnal sol-air temperatures by shading elements to improve the thermal performance of buildings.

Previous studies have mainly focused on double skin roofs with small, ventilated air gaps between the structural roof and the shading layer to examine the effect of roof shading. Majority of the studies have verified the impact through testing cells, with very small roof areas and the shading layer provided over the testing cells. The height of the shading across such studies have been limited to 200mm and in one case up to 400mm (Garcia-Solorzano et al., 2020; Lai et al., 2008; Villi et al., 2009). However, the roof’s thermal performance under the roof shade depends upon the height of the roof shading due to the variation in the direct/indirect solar radiation received on the primary roof. Also, architects are exploring the parasol roofs with considerable gap between the primary and secondary roof. Couple of such examples are shown in Figure 1.

![Figure 1](image1.png)

*Figure 1: a. Dutch Embassy Building in Ghana by AtelierZ (Zavrel) Architects; b. The Mwabwindo School in Zambia by Selldorf Architects.*

In previous studies, due to small gap between the primary and secondary roof, no consideration for HDR of ventilated DSR has been considered. As a result, the impact of primary roof's exposure to the direct and diffused radiation has also been ignored. In the case of higher gaps, it is evident that amount of roof shaded and exposed to direct light is dependent upon the HDR as shown in the Figure 2.

As shown in the Figure 2, the top two cases and bottom two cases have same height of roof shading over the primary roof of the building. However the percentage of the shaded portion of roof varies significantly. This variation is proportionate but different at different times of the day owing to the continuous variation of the solar azimuth and altitude.

![Figure 2](image2.png)

*Figure 2: Primary roof's exposure to direct solar radiation in different roof shading configurations*

Apart from the direct solar radiation, the roof’s thermal performance is also dependent upon the diffused solar irradiation received on the primary roof and also the night sky emission from the primary roof, both of which are dependent upon the sky-view factor. The sky-view factor of the primary roof is a defining parameter for the roofs thermal performance under shade, which is in turn dependent upon the HDR.

\[
\text{Sky view factor} = 1 - V F_{P R-SR} \quad \text{Equation 1}
\]

Where \( V F_{P R-SR} = \text{View factor from primary roof to secondary roof, and } V F_{P R-SR} \) is a function of HDR (Narayana, 1998) as shown in Equation 2 and Figure 3.

\[
V F_{P R-SR} = f(x,y) \text{ where } x = \frac{l}{h} \text{ and } y = \frac{w}{h} \quad \text{Equation 2}
\]

Hence, the HDR of the roof shading above the structural roof is a significant factor for ascertaining thermal performance of the roof. Rather than considering absolute height as a critical parameter, it is vital to account for the influence of the HDR. Therefore, this study aims to investigate the impact of the HDR in both East-West (E-W HDR) and North-South (N-S HDR) directions, as defined in Figure 3, along with absolute height.
Hypothesis and Objectives

The study is based on the hypothesis that HDR would be the most significant parameter for roof shading, in addition to the absolute height of the roof shading for the thermal performance of the primary roof. This study proposes to investigate the correlation between the energy performance of the top floors and three height-based parameters: height, HDR on the North-South direction, and HDR on the East-West direction. The HDR in the two directions might play significant roles due to the dynamic sun path and the varying directions of radiation received at different times of the day. This study aims to establish the relationship between these parameters and the energy performance of the top floors in large office buildings in warm and humid climates. The study further investigates the impact of roof shading over the roofs with different U-values.

Methodology

Approach and Methods

Parametric simulation approach has been undertaken for this study to verify the impact of the height of shading on roofs thermal performance. Multiple iterations of base case are formulated with variation of parameters such as building aspect ratio, height of the roof shading over the roof, and the roof U-Value. While the building aspect ratio and the roof shading height define the variation in the HDR of the roof shading, the roof U-value has been considered to verify the impact of the roof shading height for different U-Values of the primary roof.

Base-case definition

A base case has been established for a warm-humid climate zone in Kolkata, India, using the reference building proposed by Bhatnagar et al. (Bhatnagar et al., 2019). The base model is an 8-hour operated, 9-floor office building with an aspect ratio of 2:3, covering a total floor area of 31,381 sq.m as shown in Figure 4 (Building aspect ratio of 2:3). The performance of the base model has been validated against the EPI criteria of the reference building as per the ECBC case. For this study, the building aspect ratio has been modified to include five ratios: 1:1, 3:4, 2:3, 1:2, and 1:3, with two orientations tested for each ratio, one with the north direction as shown in Figure 4 and other rotated 90 deg clockwise. All other parameters were kept consistent with the ECBC case.

The areas of different zones were maintained the same as the base case scenario, while the proportions of the spaces have been adjusted according to the building aspect ratio as shown in Figure 4.

The building parameters considered for the ECBC-compliant base case include a maximum allowed WWR of 40%, equal window sizing on all four directions, an exterior wall construction with a U-Value of 0.4 W/m²K, and a roof assembly consisting of roof tile, extruded polystyrene, concrete, and cement plaster. Glazing is provided with a maximum prescribed U-Value of 3 W/m²K, a maximum SHGC of 0.27, and a minimum VLT of 0.27. Lighting power density is set at 9.5 W/m² and occupancy and daylight controls are as per ECBC specifications.

Figure 5: Base case model indicating the roof shade over the building.

The base case scenario for a warm and humid climate considers an air-cooled VAV HVAC system with a COP of 5.6, an occupancy of 14 m²/person, ventilation of 2.5 L/s/person + 0.3 L/s/m², thermostat set points of 25°C cooling and 20°C heating, a set back of 30°C cooling and 15°C heating, and a plug load of 16.4 W/m². The roof shade covers the exact extent of the building in this study, while the height is varied from 1m to 10m in the parametric study. Alongside the height of the roof shading, the roof U value has been varied from the stringent specification of super ECBC compliance of 0.2 W/m²K to a typical roof construction case of 150mm reinforced cement concrete roof of 4 W/m²K. As listed in Table 1, the combination of all variations led to a total of 900 cases that were simulated.

Table 1 Different parameters considered for simulations

<table>
<thead>
<tr>
<th>Base-case Building - Aspect Ratio and Orientation</th>
<th>Roof Shading Height (m)</th>
<th>Primary Roof U-Value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>3:4 - 0 deg orientation</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>3:4 - 90 deg orientation</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>2:3 - 0 deg orientation</td>
<td>4</td>
<td>1.0</td>
</tr>
<tr>
<td>2:3 - 90 deg orientation</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>1:2 - 0 deg orientation</td>
<td>6</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Results

The reference building with an aspect ratio of 2:3 results in an Energy Performance Index (EPI) of 123.5 kWh/m²/year which lies within 10% variation compared to the reference building's EPI of 133 kWh/m²/year; hence the base case stands validated against the reference building. The simulation results of the all the base models simulated indicate the range of EPIs from 122.4 kWh/m²/Year to 125.6 kWh/m²/Year, a variation of 2.57% in the overall building EPI owing to the change in aspect ratio, despite having the same floor areas. Additionally, the simulation results indicate that heating energy consumption is almost negligible (less than 0.5%) compared to the cooling energy consumption which can be attributed to the prevailing weather conditions of warm humid climates that require minimal heating throughout the year. The energy consumption of the top floor zones of each simulated case is considered as the base to calculate the respective energy consumption reduction percentage (ECRP) of all the top floor zones.

<table>
<thead>
<tr>
<th>1:2 - 90 deg orientation</th>
<th>7</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:3 - 0 deg orientation</td>
<td>8</td>
<td>3.0</td>
</tr>
<tr>
<td>1:3 - 90 deg orientation</td>
<td>9</td>
<td>3.5</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----</td>
<td>-----</td>
</tr>
<tr>
<td>10</td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

Data collection methods and tools

EnergyPlus IDF (Input Data File) files were created for the nine base models that cover each building aspect ratio and orientation to conduct this study. These IDF files were then simulated for all identified cases using JEPlus, a Java-based tool for parametric EnergyPlus simulations. The simulations were performed using Kolkata ISHRAE weather data from the EnergyPlus website. The primary objective variables analyzed in this study are the total energy consumption of the building and the cooling and heating energy consumption of the top floor, which is extracted from all simulation results.

Data analysis techniques

Energy consumption data for all zones on the top floor and total building energy consumption were collected from the simulation results. Cooling and heating loads were separately extracted for the top floor zones. Energy consumption reduction percentage (ECRP) is preferred to absolute energy consumption as the objective variable since the base case energy consumption differs for each building model. The cooling/ heating ECRP of the total top floor is verified against the height-based parameters and for different U-Values using the Pearson correlation coefficient. The same has been verified for the perimeter zones and central zones separately for the impact of the height and HDRs on the zones.

Limitations and assumptions

For the purposes of this study, the shading layer over the roof was modeled as a component block that was assumed to be thermally neutral in accordance with EnergyPlus simulation procedures. However, since the aim of the study was to verify the impact of shading geometry, simulations based on both DesignBuilder and EnergyPlus were considered acceptable. The study assumes that shading material has no impact on heat transfer between shading and primary roof layers, and the roof shading extent is limited to the roof area. However, the projection of the roof beyond the building line may shade walls and windows, reducing heat ingress. It is important to note that this study focused solely on the city of Kolkata and that the impact of shading geometry may vary in different locations due to differences in the sun path and the solar irradiation caused by variations in topographical characteristics and latitude. For this study, the reference building is a large office or business building as stated in the study referred. It should be noted that the impact of roof shading height may have varying effects on smaller buildings, as their smaller dimensions can result in much higher Height-to-Width Ratios (HDRs).
The Pearson correlation among the different zones and the three height parameters are listed in Table 2 and Table 3. The Person correlation values highlight that ECRP values of all the zones have a negligible correlation to all three height parameters. The negative correlation across the zones indicates that the increase in height results in reduced energy savings due to increased energy consumption, which is certainly due to increased exposure to solar radiation and increased sky-view factor.

**Table 2. Correlation Matrix of ECRP of different zones and height parameters for Roof U-Value 3.93 W/m²K**

<table>
<thead>
<tr>
<th>Shading Height (m)</th>
<th>E-W_HDR</th>
<th>N-S_HDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Perimeter Zone ECRP (%)</td>
<td>-0.79</td>
<td>-0.97</td>
</tr>
<tr>
<td>East Perimeter Zone ECRP (%)</td>
<td>-0.93</td>
<td>-0.65</td>
</tr>
<tr>
<td>South Perimeter Zone ECRP (%)</td>
<td>-0.92</td>
<td>-0.88</td>
</tr>
<tr>
<td>West Perimeter Zone ECRP (%)</td>
<td>-0.94</td>
<td>-0.63</td>
</tr>
<tr>
<td>Central Zones ECRP (%)</td>
<td>-0.91</td>
<td>-0.90</td>
</tr>
<tr>
<td>Top Floor (All Zones) ECRP (%)</td>
<td>-0.96</td>
<td>-0.90</td>
</tr>
</tbody>
</table>

**Table 3. Correlation Matrix of ECRP of different zones and height parameters for Roof U-Value 0.2 W/m²K**

<table>
<thead>
<tr>
<th>Shading Height (m)</th>
<th>E-W_HDR</th>
<th>N-S_HDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Perimeter Zone ECRP (%)</td>
<td>-0.40</td>
<td>-0.78</td>
</tr>
<tr>
<td>East Perimeter Zone ECRP (%)</td>
<td>-0.78</td>
<td>-0.40</td>
</tr>
<tr>
<td>South Perimeter Zone ECRP (%)</td>
<td>-0.76</td>
<td>-0.88</td>
</tr>
<tr>
<td>West Perimeter Zone ECRP (%)</td>
<td>-0.73</td>
<td>-0.32</td>
</tr>
<tr>
<td>Central Zones ECRP (%)</td>
<td>-0.82</td>
<td>-0.90</td>
</tr>
<tr>
<td>Top Floor (All Zones) ECRP (%)</td>
<td>-0.89</td>
<td>-0.92</td>
</tr>
</tbody>
</table>

For all the zones, the ECRP is negatively correlated to all the three height-based parameters studied indicating that the ECRP decreases with the increase in height and HDR in both directions. In the case of roof with U Value 3.93 W/m²K, the correlation of the height of the roof shade to the ECRP is observed to be above 0.9 for all the zones except the north perimeter zone (0.79) implying that the increase in height of the roof shading results in significantly decreased ECRP. For the roof with U-Value 0.2 W/m²K, the correlation ranges between 0.4 and 0.89, with 0.4 for the north perimeter zone, implying that the change in height of roof shading has less impact on the ECRP of the insulated roofs.

The north perimeter zone in the case of un-insulated roof shows highest correlation of 0.97 with the HDR in East-West direction. It is observed that the ECRP of North and south perimeter zones are hugely impacted by HDR.
in East-West direction compared to the HDR in North-South direction. A similar trend is observed for East and West perimeter zones that are hugely impacted by the HDR in North-South direction compared to that of East-West direction. The core zones’ performance and the overall top floor performance are also significantly correlated to the height of roof shade and the HDR in the East-West direction compared to the North-South direction.

Discussion

The findings of this study highlight the varying energy saving potential of roof shading at different heights over the roofs with different U-Values. The correlation values between the ECRP and the height of roof shade among all the cases studied indicate that the increase in height leads to a decrease in ECRP for any given Roof U-Value. However, the impact is found to be more significant in the uninsulated roofs compared to the insulated roofs. The study hypothesized that HDR would be the most significant parameter for roof shading, in addition to the absolute height of the building. However, the findings indicate that absolute height may be used as a primary parameter for determining performance of roof for large buildings in warm-humid climatic conditions. The maximum HDR of all the cases simulated in this study is 0.295 (or 1:3.8). Therefore, for large buildings with roof shading HDR within the above limit, the absolute height can be used as a primary parameter instead of the HDR. The performance of the perimeter zones in different directions was found to vary significantly, which is closely related to the HDRs in the East-West and North-South directions. This information can be helpful for designers in making informed decisions about the treatment of perimeter zones to achieve better thermal comfort and energy efficiency. The present study found that the effect of changing height of shading on insulated and uninsulated roofs exhibits a similar trend but with varying degrees of significance. In particular, the impact of shading on insulated roofs was observed to be much lesser. This implies that provision of roof shading over an insulated roof in a warm humid climate might not result in financial viability.

This study identifies several areas for further research on the thermal performance of roofs. The location and latitude of the building have a significant impact on the roof's energy efficiency due to the variation in sun path and climatic conditions. Future research should include more diverse locations and climatic zones to confirm the impact of these factors on the roof's thermal behaviour. Finally, the limitations of the simulation software used in this study, which does not account for the thermal behaviour of the roof shade material, highlight the need for further investigation into the impact of shading material's thermo-physical parameters on the primary roof's thermal performance. Addressing these areas of inquiry will advance our understanding of the thermal behaviour of shaded roofs and inform strategies for enhancing building energy efficiency.

Conclusion

In conclusion, this study investigates the impact of the height and height-to-depth ratio (HDR) of the roof shading on the roof's thermal performance of large office buildings in warm and humid climates. The study uses parametric simulation to validate the relationship between the energy performance of the top floors and the roof shading height, HDR in the North-South direction, and HDR in the East-West direction of the roof shading. The study also examines the impact of shading on the roof's thermal performance for different U-Values of the roof. The results of the study indicate that the ECRP is higher in the case of uninsulated roofs (U value of 3.93 W/m²K) with ECRP ranging from 37% to 45%, whereas the same is within the range of 10% for uninsulated roofs (U value of 0.2 W/m²K). The findings suggest that the impact of shading is not that significant over insulated roofs, and the optimal balance between insulation and roof shading must be identified to achieve optimal performance. The results indicate that the absolute height can be a crucial parameter addressing the shading impact of the roof shading; the height-to-depth ratio can be used to define the localized decision for the thermal performance of the perimeter zones in different directions. The HDR in the East-West direction highly impacts the north and south perimeter zones, while the east and west perimeter zones are impacted by the HDR in the North-South direction. The study provides valuable insights for architects and designers on optimizing shading elements in office buildings for enhanced energy performance.

Nomenclature

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers
ECBC Energy Conservation Building Code
ECRP Energy Consumption Reduction Percentage
EPI Energy Performance Index
HDR Height-to-Depth Ratio
IDF Input Data File
ISHRAE Indian Society of Heating, Refrigerating and Air Conditioning Engineers
PV Photovoltaic
SVF Sky View Factor
U-Value Thermal Transmittance (W/m²K)
VF View Factor
WWR Window to Wall Ratio

References


Sadevi, K. K., & Agrawal, A. (2019). Energy-efficient building envelope design features in India. *Conference on Advanced Building Skins, C1 Architectural Membranes for High-performance En*


