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Effects of shading and solar reflection from surrounding built environment on building performance

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ABSTRACT

Awareness regarding the threats posed to individuals and property by uncontrolled solar reflections from the built environment has been increasing. Despite the severe adverse effects of uncontrolled solar reflections, legislation governing them is remarkably limited, and existing standards are not widely accepted. Without a proper methodology, designers cannot accurately evaluate the effect of a projected building's reflections until after construction. This study developed a methodology to investigate the effects of shading and sunlight reflections from surrounding buildings. A toolchain was developed using the parametric design platform Rhino3D and Grasshopper. An existing scenario involving spatially proximal buildings in Gurugram was identified, modelled, and simulated. Compared with a standalone building simulation, the southwest and northwest façades experienced a 12% and 28.9% increase in total solar radiation, respectively, because of reflections from surrounding buildings. These findings demonstrate that standalone building simulations are not reliable predictors of energy consumption. The novel methodology developed in this study can be used to evaluate the effects of shading and sunlight reflections from the surrounding built environment.

Keywords: built environment; façade; solar irradiance; parametric design; thermal irradiance

1. INTRODUCTION

The built environment substantially affects the rapidly increasing global energy consumption, especially in urban areas where close spatial relationships between buildings can intensify this effect (Han et al., 2017). To understand the complex interactions between closely situated buildings, the inter-building effect concept was developed. Urban residents often experience reflected sunlight from buildings. Although this phenomenon is sometimes inconvenient, it is generally accepted as a characteristic of city life. However, buildings with extensive glass façades and curved shapes can have more severe effects due to the type and amount of glass used. Given the increasing frequency of problems related to reflected daylight from building surfaces, it is crucial to evaluate the impact of building envelope design on reflected daylight at an early stage. This evaluation can help mitigate potential environmental problems and reduce the cost-related effects of construction. The reflection of sunlight from a building's exterior can brighten the field of vision, causing discomfort or impairing vision. With the advancement of new glazing technologies, the use of glass in building envelopes is becoming more prevalent.

Façade designers often favor windows with high reflectivity to reduce cooling loads and achieve energy-saving goals. However, this practice contributes to problems with reflected light from building envelopes.

Moreover, the construction of free-formed or curved façades presents another challenge (Figure 1). Without careful planning, the reflective surfaces of these curved structures can concentrate sunlight similar to solar concentrators, causing substantial discomfort for nearby residents.

The convergence of sunlight from a building's reflective surfaces in a specific direction is known as the 'death ray' phenomenon. This phenomenon can lead to environmental problems, such as glare or unexpected thermal loads on the surrounding area (Shih & Huang, 2001; Zhu et al., 2019). This study investigated the combined effects of shadow casting and reflected radiation on adjacent buildings.

Buildings' exterior designs may have an impact on the local microclimate. An important area of research for lowering energy usage and carbon footprint in urban areas is the optimization of optical characteristics of building envelopes and urban paving. Many methods to assess and mitigate the risk posed by reflected daylight can be discovered in the literature. Planning authorities have adopted legislation in many countries to address the reflected sunlight from building façades, primarily by restricting building materials based purely on their reflectivity.

The urban thermal environment is highly sensitive to building geometry resolution, building height, and building gap width. Reflective elements on building envelopes may reflect daylight into the neighborhood, resulting in glare and heat issues. A building with a curved reflective façade may sometimes concentrate light and heat in a particular area, potentially causing damage to nearby structures and vehicles or posing a fire hazard. This phenomenon was notably observed in the "Walkie Talkie" building in London, where the intense reflections melted car parts and caused pedestrian discomfort. As a result, there were heat gain problems on the walkways and within the nearby buildings. The vivid reflections caused drivers to become visually distracted. Finally, to assist in diffusing the reflections and lessen their intensity, some of the façade was roughened. While there are few studies on the impact of vegetation on pedestrian comfort, it has become necessary to reduce reflections in hardscaped areas to achieve comfort (Kaushik S et al., 2023; Patel & Kaushik S, 2023).

Researchers have developed several techniques to evaluate the effect of reflected solar radiation from building envelopes. Ronoh (2021) conducted a computer-aided analysis of the effects of reflected solar radiation from glass curtain wall structures (Figure 2). They proposed using the impact of reflected daylight projected onto the horizontal plane by building envelopes as a performance indicator termed the 'boundary of reflection area'.

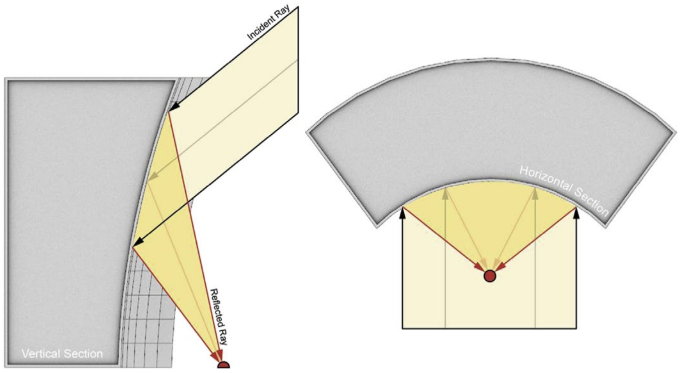


Figure 1. Convergence and deflection of sunlight from curved façade buildings (Danks et al., 2016)

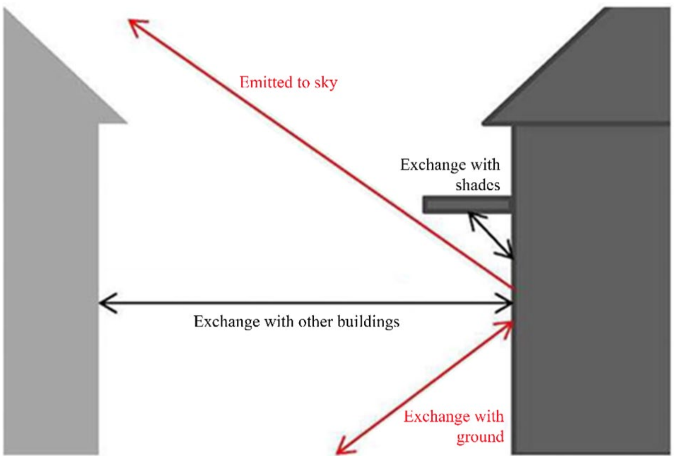


Figure 2. Exchange of reflected radiation between building façades (Ronoh, 2021)

1.1 Need for study

Although uncontrolled solar reflections pose severe threats to building performance and the surrounding environment (Yang et al., 2013), regulations addressing these reflections have not yet been established. This regulatory gap arises from the lack of widely accepted scientific standards that specify acceptable limits for reflected light and thermal irradiance in metropolitan areas. As urban environments evolve with buildings positioned closer together, there is a potential increase in urban energy consumption and negative impacts on the local microclimate. Current assessments of building energy performance often consider structures in isolation, neglecting the effect of surrounding buildings on thermal dynamics. This oversight can result in inaccurate predictions of energy consumption and building performance.

Moreover, dense urban surroundings offer a complicated setting where sunlight availability and urban daylight can become rare resources, particularly as buildings become taller. The intricate and dynamic overshadowing effects on building envelopes are mostly to blame. Therefore, a comprehensive methodology to evaluate the impact of shading and solar reflection from surrounding buildings is essential for accurate and effective building design and urban planning.

2. MATERIALS AND METHODS

2.1 Solar reflection from diffused surfaces

The effect of diffuse solar radiation reflections from building façades on pedestrians varies based on their distance from the building. In computational models, pedestrians are represented as points. The amount of diffusely reflected solar energy a pedestrian receives from a specific level of a building is determined by the angle of the reflecting arc reaching them from that floor in relation to the angle of the reflecting arc from the entire building (Takebayashi, 2016).

Previous studies have used a Monte Carlo computing technique to track a sufficient number of particles between the small separated components of the façade, road, and other surfaces (Vickers, 2017; Yuan et al., 2015; Yuan et al., 2016; Nishioka et al., 2008). The angle of solar radiation between a building façade and a pedestrian is determined using Equations 1–2.

$$\alpha_1 = \tan^{-1}\frac{H-B}{A} + \tan^{-1}\frac{B}{A} \quad (1)$$

$$\alpha_i = \tan^{-1}\frac{iH-B}{A} + \tan^{-1}\frac{(i-1)H-B}{A} \ (i = 2,3,\dots) \quad (2)$$

where A is the distance between the pedestrian and the building façade (m), H is the height of each floor (m), B is the height of the pedestrian, i is the floor number, and α_i is the angle from the building façade on each floor (rad).

The relationship between the angles from each floor of the building façade to the pedestrian is illustrated in Figure 3, with each floor assumed to be 3.5 m high. By dividing the solar reflectance value of the building façade at level i by the angle α_i, the effect of diffuse solar radiation reflections on pedestrians can be calculated.

2.2 Solar reflection from the specular or polished surfaces

The effect of specular reflections of solar radiation directed at pedestrians from a building façade depends on the incident angle of the sunlight and the distance between the pedestrian and the building façade. The height at which pedestrians remain unaffected by specular radiation from a building façade is illustrated in Figure 3 and determined using Equation 3 (Yuan et al., 2015).

$$h = A\tan\theta + B \quad (3)$$

where A is the distance between the pedestrian and the building façade (m), θ is the solar angle (°), B is the height of a pedestrian (m), and h is the height at which specular reflection of solar radiation from the building façade does not affect pedestrians (m).

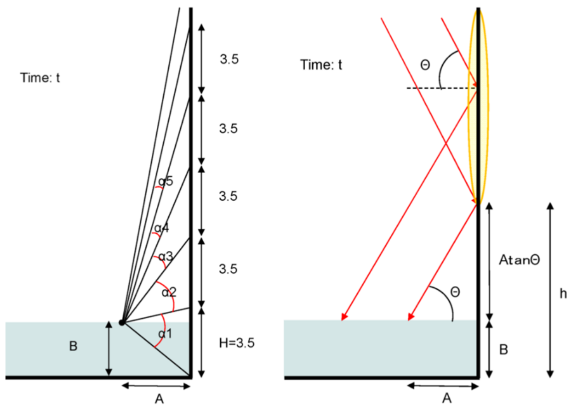


Figure 3. Angle from building façade to a pedestrian (left); height at which specular reflection does not affect pedestrians (right) (Yuan et al., 2015)

2.3 Methodology

This study was conducted in two consecutive phases (Figure 4). In Phase I, a pilot study was conducted to simulate and analyze the effects of diffuse and specular reflections. This study focused on a hypothetical scenario where two buildings are modelled in close proximity, considering ground coverage and the maximum permissible height for residential and IT industry buildings in a 3D model. The simulation was performed both with and without the surrounding building environment to assess differences in the effects of reflection. Moving further, the inquiry delves into comprehending the influence of the window-wall ratio (WWR) and the reflection of facade materials. A sequence of iterations and simulations is undertaken to scrutinize their effects. In Phase II, the research focused on the existing building scenario of the DLF Cyber Hub in Gurugram. The building was meticulously modelled using Rhino3D with plugins Grasshopper, Honeybee, and Ladybug. Factors such as geometrical form, building height, distance between structures, and façade materials were replicated based on observations from the site. This methodology was employed to gain insights into the real-life impact within an existing setting. The ensuing results have been carefully analyzed and interpreted.

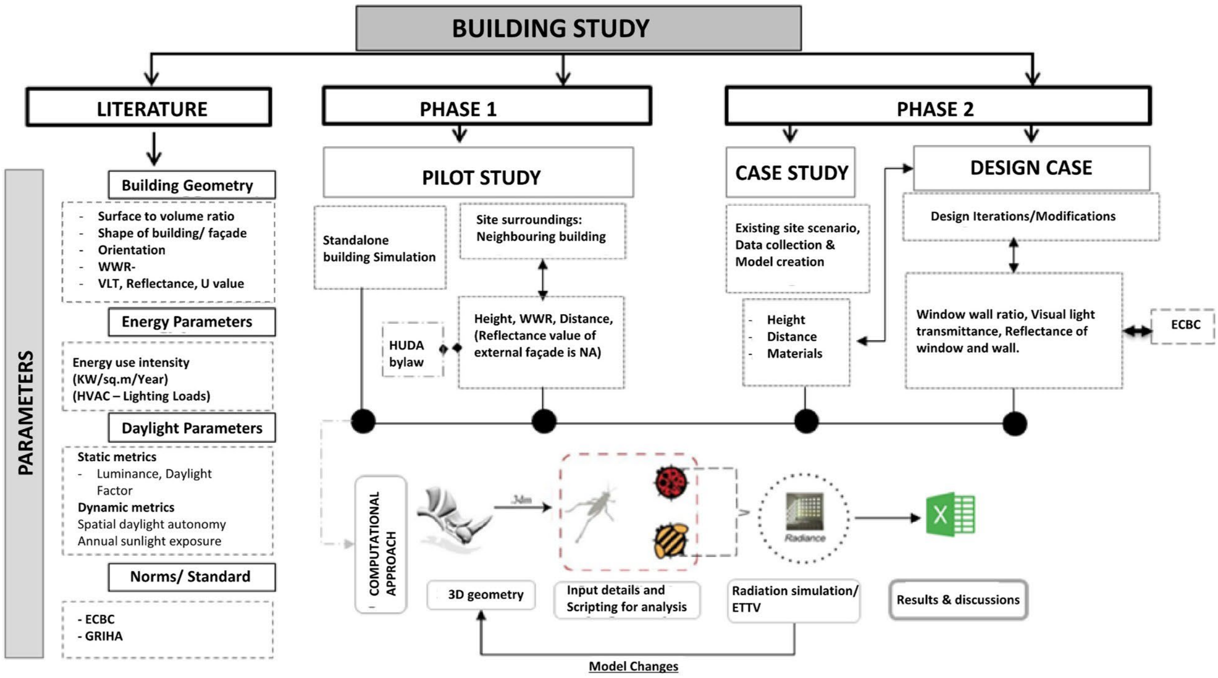


Figure 4. Study methodology, including phase I and phase II

2.4 Building model and simulation approach

Two predominant lighting modelling techniques, forward and backward ray tracing, were used to assess reflected light from building envelopes. These simulation methods, widely used in various software tools, ensure accurate reflection predictions (Curcija et al., 2015). Various factors affect the distribution of daylight reflected from building envelopes, such as incidence angle, weather conditions, and seasonal variations. Therefore, instead of focusing on specific scenarios, it is crucial to analyze the distribution using annual climate conditions. RADIANCE, along with its backward ray tracer, provides an efficient approach for employing the daylight coefficient method in time-series simulations (Curcija et al., 2015). This approach reduces the need for repetitive calculations and substantially enhances the speed of annual simulations (Figure 5).

2.5 Building model data–phase I

In Phase I, the study began by modelling a standalone residential building to simulate the solar radiation impacting its north façade. Next, an additional IT industry building was modelled in close proximity, considering ground coverage, floor area ratio (FAR = total built-up area/total site area, in percentage), and the maximum permissible height according to HUDA local bye-laws (Town and Country Planning Department, Haryana, 2023), as detailed in Table 1. This setup helped understand the interplay of shadows and reflections between the buildings (Figures 6 and 7).

The IT building category was selected because Phase II focused on DLF Cyber Hub, Gurugram, which predominantly contains mid-rise and high-rise IT buildings. Thus, the heights were set at 15 m for the residential building and 28 m for the IT building, with a 28-m distance between them. Common façade materials from DLF Cyber Hub, such as aluminium finishes and red brick, were chosen, and their properties, including reflection factors, were considered for Phase I simulations (Table 2).

The results from these simulations were used to compare the effects of solar radiation between a ‘standalone building’ and ‘two spatially proximal buildings’, providing insights into their mutual shading and reflective interactions.

3. RESULTS AND DISCUSSION

3.1 Phase I analysis

In phase I, the simulation focusing on the north façade of the standalone residential building revealed that it received approximately 180 kW/m^2 of annual solar radiation (Figure 6). This initial analysis served as a baseline for further investigations.

To investigate the effect of façade material reflectance properties (glass and brick wall) and the WWR on the surrounding environment, a series of 12 iterations were performed while keeping the height and distance between the buildings constant. These simulations (Table 3) were conducted to evaluate the impact of varying reflectance values and the WWR on a nearby building.

The permutations of WWR and reflectance values (0.1 and 0.8) for glass and brick walls were systematically arranged and assigned specific codes. Iterations with a 10% WWR were labelled A0, A1, A2, and A3, reflecting different reflectance values for glass and brick walls. Similarly, iterations with a 40% WWR were assigned codes B0, B1, B2, and B3, while those with a 60% WWR were designated C0, C1, C2, and C3.

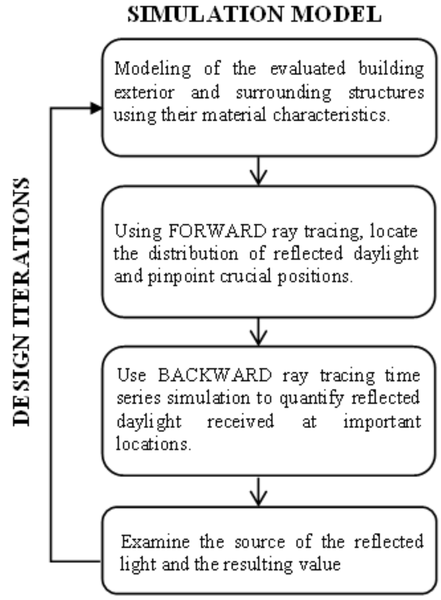


Figure 5. Flowchart of the simulation approach

Table 1. Excerpts from Haryana urban development authority: Bye-laws

Building categories	Ground coverage	Max. FAR (%)	Max. height (m)
Residential (above 3,750 sqm.)	40%	120	15
IT industries (general)	60%	150	30
IT park (technology/ cyber park)	40%	250	Unrestricted

Note: FAR = total built-up area/total site area

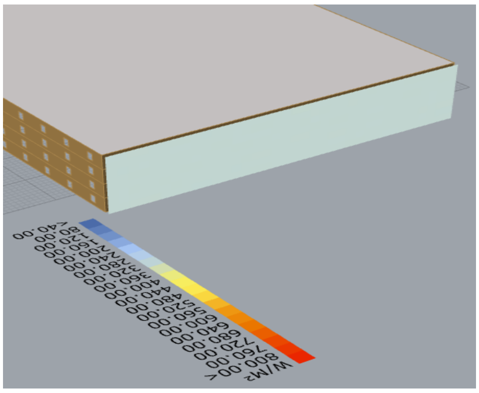


Figure 6. Radiation analysis of the north façade of the standalone buildin*g* (Town and Country Planning Department, Haryana, 2023)

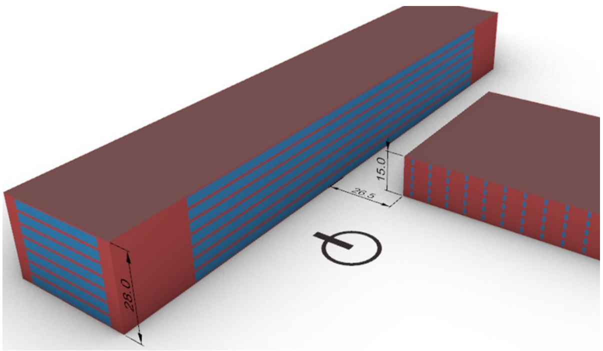


Figure 7. The target façade (Building A) faces north (Towards B)

Table 2. Reflection factor of different materials

Material	Reflection factor (%)
Aluminium, pure, highly polished	80–87
Aluminum, anodised, matt	80–85
Aluminum, polished	65–75
Aluminum, matt	55–75
Aluminum coatings, matt	55–56
Brick, red	10–15
Paint, medium grey	25–35
Paint, dark blue	15–20

The radiation analysis for these 12 iterations was conducted meticulously to discern the effects of these parameters on solar radiation distribution and reflection. This structured approach allows for a nuanced understanding of how variations in WWR and façade reflectance can influence the impact of solar radiation on adjacent structures, providing critical insights into the interplay of building design elements and their environmental consequences.

Upon completing the simulations, an elaborate graphic was prepared (Figure 8), integrating the resultant imagery and the respective radiation values impacting the building façade. These results highlight several pivotal points, substantiating the research and elucidating the intricate effects of reflected solar radiation and the shadows cast by proximate structures. Figure 9 graphically represents the annual hourly radiation per square meter incident on the façade across the various iterations, offering a detailed visualization of the data.

Table 3. Permutation chart of reflectance with WWR

Cases	A0	A1	A2	A3	B0	B1	B2	B3	C0	C1	C2	C3
WWR	10%				40%				60%			
Reflectance of glass	0.1	0.8	0.1	0.8	0.1	0.8	0.1	0.8	0.1	0.8	0.1	0.8
Reflectance of wall	0.1	0.1	0.8	0.8	0.1	0.1	0.8	0.8	0.1	0.1	0.8	0.8

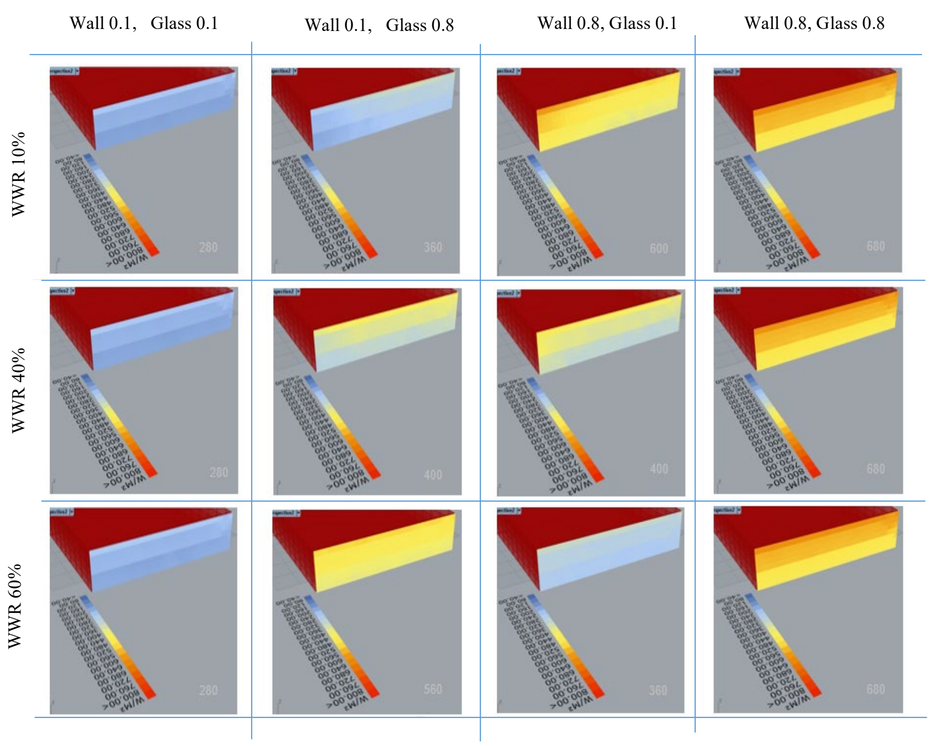


Figure 8. Results of simulations showing radiation falling on façades

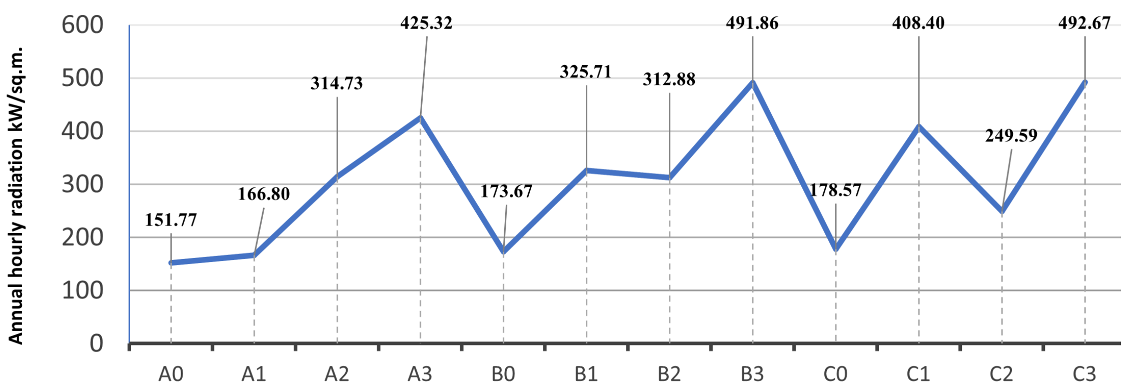


Figure 9. Average annual hourly radiation across 12 cases

The preliminary simulation of the standalone residential building revealed an annual solar radiation of approximately 180 kW/m^2 on its north façade, serving as a foundational benchmark for subsequent simulations involving an adjacent building positioned 28 m away. This proximity introduced significant variations in solar radiation values depending on the WWR and the reflectance properties of the materials used.

The standalone building simulation did not accurately predict the radiation on the façade because of the exclusion of reflected radiation from nearby structures. This discrepancy highlights the substantial effect of surrounding buildings on solar radiation analysis.

Upon comparing the standalone scenario with the presence of the adjacent IT building, significant deviations in solar radiation values were noted. Case A0 had a radiation value of 151.77 kW/m^2, a 15.6% decrease from the baseline, whereas case A1 had a radiation value of 166.80 kW/m^2, reflecting a 7.3% decrease. By contrast, cases A2 and A3 demonstrated substantial increases of 74.9% and 136.3%, respectively, in radiation values because of the high reflectance properties of glass and brick walls. In the 40% WWR scenarios, case B0 displayed a marginal 3.1% decrease to 173.67 kW/m^2, whereas cases B1 and B3 surged by 80.9% and 173.3%, respectively. The 60% WWR cases showed similar trends, with case C0 closely approximating the baseline with a 1.4% reduction, whereas case C3 peaked at a 173.7% increase.

The results revealed that façade material reflectance and WWR substantially affected solar radiation. For 10% WWR cases (A0 to A3), the incremental impact of reflectance was evident: Case A1 (high reflectance glass) exhibited a 9.9% increase over A0, whereas case A3 (high reflectance for both glass and brick) displayed a marked 180.2% increase. In the 40% WWR category, the progression was even more pronounced: Case B1 (high reflectance glass) increased by 87.5% from B0, whereas case B3 (high reflectance for both) increased by a marked 183.2%. The 60% WWR cases further accentuated this trend, with case C1 and C3 increasing by 128.7% and 175.9% from C0, respectively. These findings indicated that even if a façade does not receive direct solar radiation due to the sun–earth relationship, it might still be subject to reflected radiation from surrounding buildings.

The comparison between the standalone building and cases A0, B0, and C0 reveals a compelling observation regarding the distribution of solar radiation. This discrepancy prompts an exploration into the intricate dynamics of solar irradiance influenced by the spatial arrangement of nearby structures. In cases A0, B0, and C0, where buildings are in close proximity, the presence of neighboring structures obstructs the diffusion of reflected radiation from the sky onto the north-facing façade. This obstruction arises from the physical barrier of adjacent buildings in front of the north façade. In contrast, the standalone building enjoys an unobstructed radiation diffusion due to the absence of neighboring structures.

Consequently, it receives a more significant influx of diffused radiation, surpassing the radiation levels observed in the spatially proximal configurations. This underscores the significant role of shadows cast by neighboring buildings in shaping solar irradiance dynamics. The discernible reduction in radiation levels in cases A0, B0, and C0 compared to the standalone scenario vividly illustrates the impact of these shadows, which obstruct direct radiation and lead to diminished radiation levels. Moreover, this reduction is further influenced by factors such as WWR and material reflectance properties, highlighting the intricate interplay between architectural design elements and solar radiation dynamics. Thus, it becomes evident that the interplay of shadows cast by neighboring structures constitutes a critical determinant in understanding solar irradiance modulation.

These results underscore the critical role of WWR in modulating solar radiation; higher WWR invariably amplifies radiation due to the increased glass surface area, which inherently possesses a higher reflective capacity. The reflectance properties of the materials magnify this effect. High reflectance glass (0.8) consistently resulted in substantial increases in solar radiation, a trend further amplified with higher WWR. Similarly, high-reflectance brick walls contributed to increased radiation, though to a lesser extent than glass. Nevertheless, the combination of high-reflectance glass and brick walls resulted in the highest radiation levels observed, as evidenced in cases A3, B3, and C3.

The simulations revealed that integrating a proximate building with reflective materials significantly alters the solar radiation dynamics on the north façade of the residential building. The results demonstrate the importance of material selection and façade design in urban architectural planning. The findings indicate that reflective properties and WWR are crucial factors modulating the effect of solar radiation on adjacent structures. Key inferences include the substantial increase in solar radiation with high reflectance materials and higher WWR, indicating the need for meticulous consideration in design to optimize energy efficiency and mitigate adverse solar exposure.

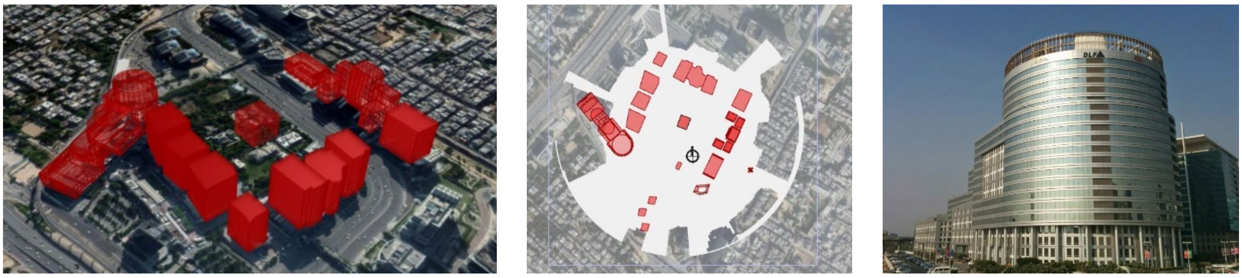
3.2 Phase II analysis: DLF cyber hub (Gurugram)

The present study examined the intricacies of solar irradiance within the densely built environment of DLF cyber hub in Gurugram (Figure 10). To achieve this, a detailed 3D model, including all material specifications, was created to simulate the current scenario and analyze solar radiation dynamics accurately. The study focused on a target building at the center of the cluster, with its four façades—southwest (SW), southeast (SE), northwest (NW), and northeast (NE)—to understand the complex impacts of surrounding structures. Phase II of the study further explored this by delineating three cases to investigate the effects of shadows and reflections from the neighboring buildings.

In case 1, the effects of direct and diffuse solar radiation on the central building were evaluated, with surrounding structures considered only as shadow-casting obstructions. The reflective properties of these surrounding buildings were excluded to isolate the impact of shadows alone on solar irradiance (Figure 11). By contrast, in case 2, the effects of direct and diffuse radiation on the central building were examined in the absence of any surrounding structures (Figure 12). This scenario serves as a comparative benchmark, providing valuable insights into baseline radiation levels without the influence of nearby buildings.

The core of the investigation is presented in case 3, wherein the interplay of direct, diffuse, and reflected radiation from the surrounding buildings was examined (Figure 13). By including the reflective properties of the surrounding structures, this case provides a comprehensive understanding of the combined impact of shadow and reflection on solar irradiance dynamics. These carefully designed cases can unravel the multifaceted nuances of solar radiation within the intricate urban fabric of DLF cyber hub.

Analyzing the annual hourly radiation falling on all four façades for each case reveals notable variations (Figure 14). In case 1, where only shadows from surrounding buildings are considered, the radiation levels on all four façades of the target building are significantly lower compared to other scenarios. This reduction ranges from approximately 28% on the SW façade to about 33% on the NW façade. Specifically, the SW façade receives 1,171 kWh/m^2 of radiation, showing a decrease of around 28% compared to case 2, where no surrounding buildings obstruct sunlight. Similar reductions in radiation levels are observed on the SE, NE, and NW façades. This decrease highlights how shadows cast by neighboring structures obstruct direct sunlight from reaching the target building's façades, affecting the overall solar irradiance. The variation in radiation levels across different orientations emphasizes the nuanced impact of surrounding buildings on solar irradiance, with some façades experiencing more pronounced reductions than others.

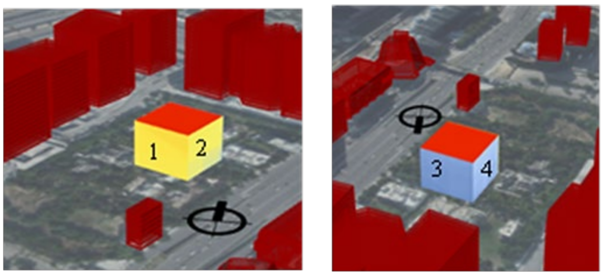


Aerial View of Buildings modelled in Rhino with Grasshopper

Shadow mask of the DLF Cyber Hub

Outer façade - DLF Cyber Hub

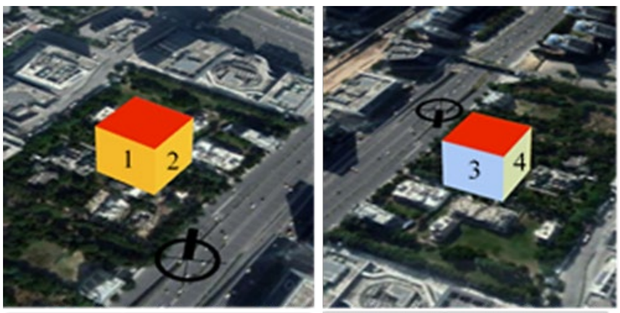
Figure 10. Identified building cluster in DLF cyber hub in Gurugram with its aerial view, shadow mask and outer façade



1-SW	1171
2-SE	916

3-NE	508
4-NW	628

Figure 11. Radiation on All four Façades in case 1—Direct and diffused radiation with surrounding (with shadow but no reflection)



1-SW	1633
2-SE	1595

3-NE	605
4-NW	701

Figure 12. Radiation on all four façades in case 2—Direct and diffused without surrounding

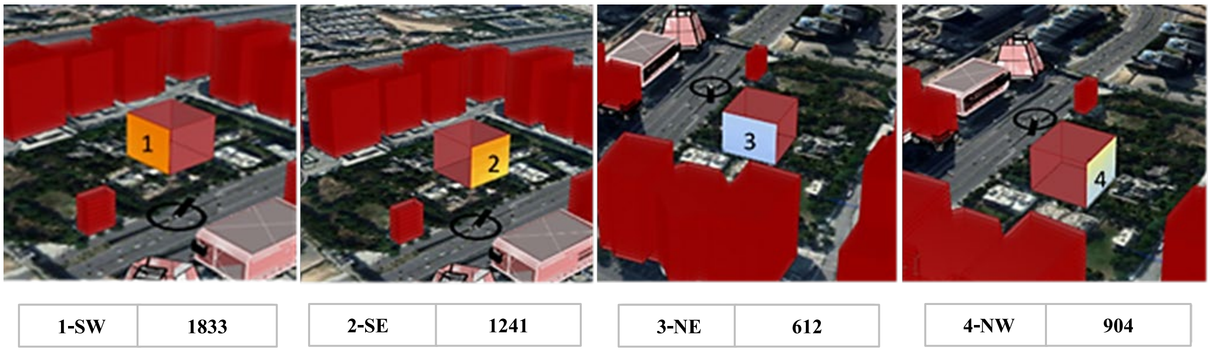


Figure 13. Annual hourly radiation falling on all four of the façades for case 3—Direct, diffused and reflected radiation from the surrounding buildings

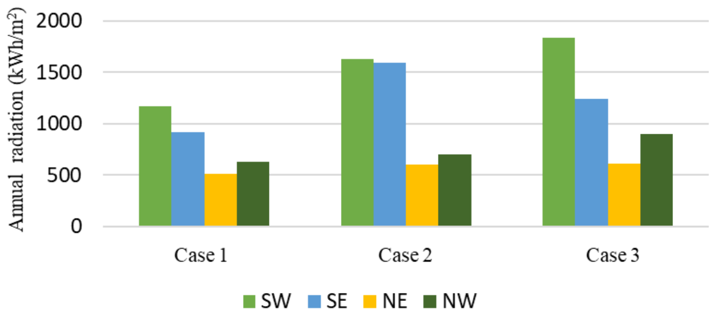


Figure 14. Radiation across cases in kWh/m²

Case 2 serves as a baseline, examining the influence of direct and diffuse radiation without surrounding structures. Here, radiation levels on all façades are higher compared to case 1, reflecting unobstructed access to sunlight. The SW façade, for instance, receives 1,633 kWh/m^2 of radiation, a substantial increase from case 1. Insights into the spatial distribution of solar irradiance in the absence of neighboring structures are gained from the variability in radiation levels across different orientations within this case.

In case 3, which accounted for both shadow and reflection from surrounding buildings, higher radiation levels were observed across all façades compared with case 2. The SW façade received the highest radiation level at 1,833 kWh/m^2, representing an approximately 12% increase over case 2. Similarly, the NW façade experienced a significant increase, highlighting the amplifying effect of reflections from surrounding buildings. This increase indicates the combined impact of shadow and reflection on solar irradiance, emphasizing the need to consider both factors in urban planning and building design.

Cross-comparing each orientation within the same case provides further insights into the spatial variability of solar irradiance. For instance, in case 1, the SE façade experiences a more substantial decrease in radiation levels than the SW façade, indicating varying degrees of shadow obstruction across different orientations. Similarly, in case 3, the NW façade receives the highest radiation level, suggesting spatial asymmetry in the distribution of reflected radiation from surrounding buildings.

These findings underscore the significant impact of surrounding buildings on solar irradiance dynamics. The decrease in radiation levels in case 1 highlights the obstructive effect of shadows cast by neighboring structures, corroborating existing studies on the shading effect in urban environments. Conversely, the increase in radiation levels in case 3 emphasizes the role of reflection from surrounding buildings in augmenting solar irradiance, aligning with research on the reflective properties of building materials and their impact on nearby surfaces.

These trends highlight the complex interplay of factors affecting solar irradiance, including building orientation, surrounding structures, and the reflective properties of materials. The analysis elucidated the delicate balance between shadow and reflection in shaping solar radiation patterns in densely built urban environments. The detailed analysis highlights the multifaceted nature of solar irradiance dynamics in urban environments, suggesting opportunities for optimizing building design to maximize solar energy utilization while minimizing adverse impacts on surrounding structures.

4. CONCLUSION

The detailed examination of solar radiation impacting building façades offers a critical framework for developing zoning policies, architectural layouts, and energy consumption strategies, especially in rapidly growing nations. The authors conducted an in-depth inquiry to understand spatial interactions among closely situated buildings and to investigate the effects of mutual shading and reflected solar radiation within the built environment. Using the computational capabilities of Rhino and Grasshopper, the study performed detailed numerical simulations to analyze the effects of shading and reflection by adjacent buildings on the target building's façade.

Through the deployment of multifarious case scenarios, the investigation unearthed that the solitary consideration of a standalone building is insufficient to forecast the annual solar radiation it encounters, given the omission of reflective and shadowing influences from neighboring structures. The empirical findings accentuate the pivotal role of reflective properties and WWR in modulating solar radiation's impact on contiguous constructions. Noteworthy deductions include the pronounced escalation in solar radiation attributable to materials with high reflectance and elevated WWR, thereby highlighting the exigency for scrupulous design considerations to optimize energy efficiency and mitigate detrimental solar exposure.

The findings emphasize the importance of balancing shadow and reflection in urban planning. The use of materials with low absorptivity and reflectivity can improve the urban thermal environment. Future simulations should employ high-resolution 3D city models for greater accuracy. In addition, a design-simulation loop tool should be developed to evaluate various solutions for enhancing the urban thermal landscape. The research highlights the need for regulatory measures in urban policies to cap external reflectance thresholds, which is crucial for managing urban thermal loads.

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