A SIMULATION-BASED CASE STUDY OF DECIDUOUS TREE IMPACTS ON OFFICE BUILDING DAYLIGHTING

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Abstract

The presence of full-grown trees near buildings affects daylight availability and reduces glare. This study presents dynamic simulations that assess how deciduous trees at various distances (10 m, 15 m, 20 m) from the façade of an office building impact Useful Daylight Illuminance (UDI) and Daylight Glare Probability (DGP). The results show that closer trees (10 m) reduce glare significantly but also decrease desirable daylight levels to a large extent. Careful tree placement is crucial to balance daylighting and visual comfort in buildings. By considering trees early in the design process and utilising available calculation methods, we can effectively integrate them so as to enhance both the building and its surroundings.

Keywords

Office building, daylighting, deciduous trees, useful daylight illuminance, glare

1 INTRODUCTION

The impacts of climate change are now a pressing global environmental concern. Climate change is causing long-term shifts in temperatures and weather patterns, resulting in extreme weather events such as intense droughts, water scarcity, severe fires, rising sea levels, intense rainfall causing flooding, major storm activity, melting glaciers, large temperature fluctuations, declining biodiversity, and ecosystem disruption. These changes are negatively impacting human health and posing a risk to both private and public property [1], [2], [3]. A number of factors contribute to climate change, but globally, the largest contributor to global warming is greenhouse gas emissions, primarily stemming from human activities within various economic sectors [3]. The building construction and maintenance sector alone accounts for up to 39% of such emissions. In response, the fields of architecture and building design are seeking innovative solutions, materials, and technologies to reduce the production of greenhouse gases [2], [3], [4].

One positive response within the building sector to address the negative impacts of construction on climate change is the growing body of research investigating the role of green infrastructure. These studies demonstrate that vegetation, particularly trees, has a significant impact on the surrounding environment and can contribute to the mitigation of climate change impacts by reducing the energy demands of buildings. Solutions include the design and construction of green roofs and façades, as well as the strategic planting of vegetation, such as trees and shrubs [4]. Incorporating tree planting and greenery into residential areas not only significantly improves environmental quality but also enhances the aesthetic appeal of the landscape and offers recreational benefits. Trees can reduce CO_2 emissions, capture rainwater, cool and humidify the air, provide shade, reduce wind speed, noise, and dust levels, all of which positively affect human health and psychological well-being [4], [5]. Strategically placed trees around buildings create shade, preventing direct sunlight from reaching the façade during the summer months, thus influencing the need for cooling and shading of interior spaces. The shading potential of trees depends on several factors, including tree type (deciduous or evergreen), canopy size and density, leaf shape and size, and the location and orientation of the trees relative to the building and its surroundings [6], [7], [8].

However, the impact of trees on the indoor environment of buildings is often neglected in simulations, as trees are not considered permanent shading obstacles. While numerous studies have investigated the impact of trees on building heating and cooling demands [4], [8], [9], [11], [13], their influence on the microclimate and long-

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term energy consumption of nearby buildings is undeniable. The effect of trees on the quantity and quality of daylighting in indoor spaces has received relatively little attention to date. This is partly due to the characteristic complexity of trees, which leads to diverse light transmission phenomena – reflection, diffusion, and varying degrees of light shading – that change depending on the sun's position, the time of year, and weather conditions. For example, the amount of light passing through a tree canopy depends on the angle of incidence of the sunlight, canopy dimensions, leaf density and area, and the proportion of gaps along the solar vector. When assessing light transmission through tree canopies onto building façades., it is crucial to consider seasonal variations and the spatial relationship between the trees and building façade in question. Deciduous trees present a particular challenge due to their phenological changes and leaf drop, which affect leaf density and colour throughout the year. Furthermore, the diversity of tree genera and species adds to the modelling complexity, as they exhibit a wide range of seasonal and morphological characteristics. The distance and height of a tree relative to a building are key parameters that significantly influence its shading effectiveness [15].

2 METHODOLOGY

This study aimed to evaluate, through computer simulation, how seasonal changes in deciduous tree foliage affected the daylighting availability of an office building in Bratislava (48.15°N, 17.11°E). The analysis is focused on quantifying the monthly variations in solar radiation on the building facade and assessing their subsequent impact on interior daylighting metrics.

The 3D model of the building (Fig. 1), a proposed two-storey office building with an L-shaped floor plan, was created using Rhinoceros V8 [10]. The analysis is focused on an open-plan office space located on the first floor, oriented east-west, as the most sun-exposed room, designed for 32 employees (Fig. 2), and covering a total area of 260 m^2. The office features a regular array of windows measuring 1.2 m x 3.25 m (W x H). The glazing was considered as clear insulating three-pane glass with a light transmittance value τ = 0.6. The windows are additionally equipped with dynamic shading devices - textile roller blinds (opaque).

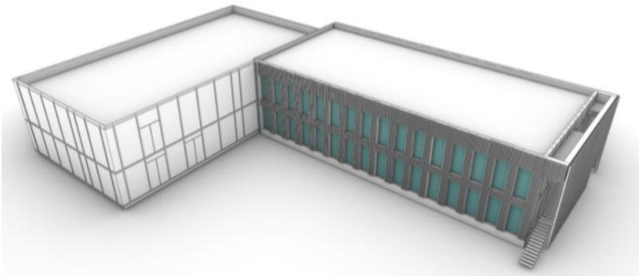

Fig. 1 3D model of the evaluated office building.

ClimateStudio V2.0 [12] was used as the simulation tool to calculate daylight availability and glare metrics. Climate data for Bratislava were incorporated using a Typical Meteorological Year (TMY) weather file (SVK_BL_Bratislava-Stefanik.AP.118160_TMYx.2004-2018) with an hourly time step, selected from the ClimateStudio software library. The control method for the fabric roller blind was set as manual, as is stated in the LM-83 methodology in the IES-NA LM-83 standard [14].

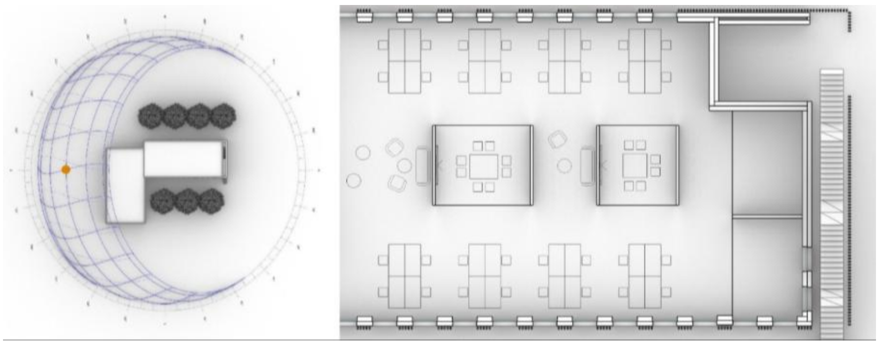

Fig. 2 Top view with cardinal directions (left) and a floor plan of the space (right).

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The roller blind was applied in the computational model during the year-round simulation under the following condition: more than 2% of the control points in the room received excessive direct sunlight (defined here as direct horizontal illuminance exceeding 1000 lux). The control points were placed on a horizontal reference plane, in a 250 mm grid, at a height of 850 mm above the floor. The shading blind was only returned to the open position in the simulation at a subsequent time step where this condition was no longer met [16].

To accurately simulate the dynamic nature of deciduous trees, they were modelled as blocks with dynamic leaf materials within ClimateStudio. This approach allowed for the representation of foliage changes throughout the year. The software automatically adjusted leaf colour and density at each time step based on the specified latitude and time of year (Fig. 3), effectively simulating the presence of full foliage in summer, colour transition and leaf fall in autumn, bare branches in winter, and gradual leaf growth in spring [17].

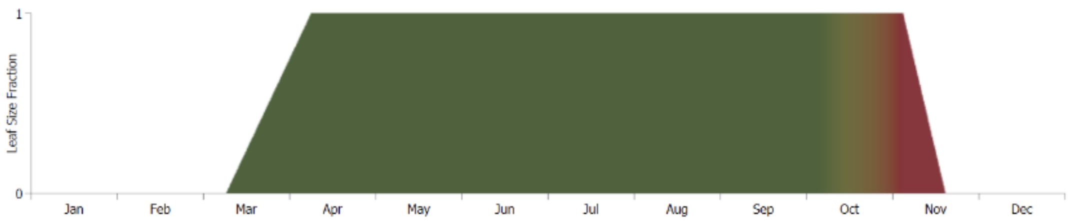

Fig. 3 Schedule: dynamic material applied to leaves.

Four scenarios were established to investigate the impact of tree proximity on daylighting (Fig. 4):

- V1 (Baseline): Building without surrounding trees,
- V2 (10 m): Trees positioned 10 metres from both the east and west façades,
- V3 (15 m): Trees positioned 15 metres from both the east and west façades,
- V4 (20 m): Trees positioned 20 metres from both the east and west façades.

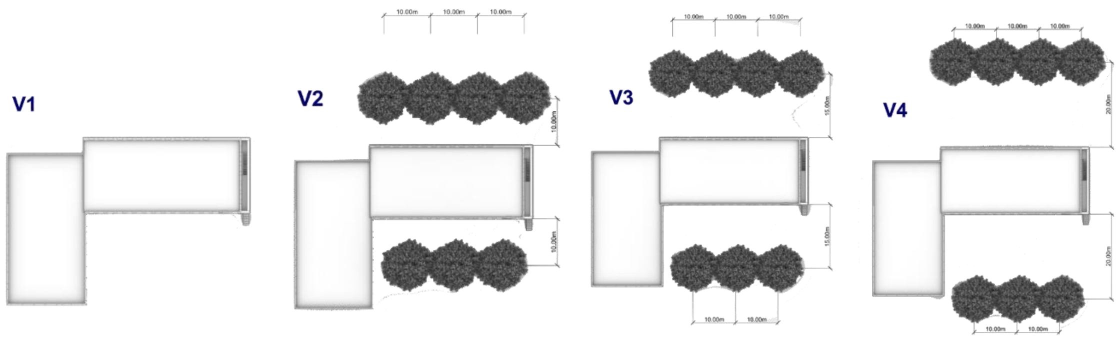

Fig. 4 Tree placement variants.

These distances were selected based on those found in the existing literature, which indicates that trees exert the most significant influence on the indoor environment when shading east or west façades at distances of 10-15 metres [8], [18]. In the model, the trees had a canopy bottom height of 3.5 metres, a canopy top height of 14 metres, and an approximate canopy radius of 5.5 metres. The building is characterised by its flat roof and a total height of 8.4 metres.

To determine the impact of shading from deciduous trees on the building's energy performance and interior daylighting conditions, an analysis of the total annual solar radiation incident on the building façade was performed for each variant (V1–V4). Additionally, the following dynamic metrics were selected to compare the quantity and quality of daylight within the selected office space: Useful Daylight Illuminance (UDI) and Daylight Glare Probability (DGP).

Introduced by Mardaljevic and Nabil in 2005 [19], UDI serves as a refinement of the traditional Daylight Autonomy metric. While only slightly more complex, UDI provides a significantly deeper insight into the spatial-temporal dynamics of daylight availability [20]. Crucially, unlike Daylight Autonomy, UDI not only identifies periods of insufficient daylight but also accounts for excessive daylight levels, which can lead to glare and visual discomfort. This makes UDI a more comprehensive metric for evaluating daylighting performance in spaces where

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both sufficient and excessive daylight are potential concerns, as is the case in this study considering the influence of dynamic shading from trees. UDI categorises illuminance levels into distinct ranges: UDI_f (failing, <100 lux) indicates areas requiring artificial lighting; UDI_s (supplemental, 100-300 lux) suggests areas potentially needing supplemental lighting; UDI_a (autonomous, 300-3.000 lux) represents the ideal range with sufficient daylight for most tasks; and UDI_e (excessive, >3.000 lux) denotes areas potentially experiencing glare [21]. This comprehensive scheme allows for a straightforward yet meaningful evaluation of both daylight availability and solar penetration, utilising realistic, climate-based conditions specific to the building's location. This approach is particularly valuable in promoting the broader adoption of climate-based modelling techniques in daylighting analysis [22].

DGP quantifies visual glare, defined as the contrast-reducing effect in the field of view caused by bright light sources. DGP is recognised as a key climate-based daylight metric for assessing daylight quality [23]. DGP values range from 0 % to 100 % and are categorised into four bands: imperceptible glare (DGP ≤ 34 %), perceptible glare (34 % < DGP ≤ 38 %), distracting glare (38 % < DGP ≤ 45 %), and intolerable glare (45 % < DGP) [24]. The European standard EN 17037 addresses glare assessment from side lighting openings and defines criteria for compliant shading. According to this standard, shading is considered satisfactory if it prevents intolerable glare (DGP > 45 %) for more than 5 % of the occupied time [25], [26].

In this study, DGP was simulated throughout the year in all variants (V1–V4) for all 32 working positions, considering their usual direction of view. For a more detailed analysis of the trees' impact on glare, the workplace exhibiting the highest percentage of distracting glare (DGP > 38 %) throughout the year in the baseline scenario (V1) was selected for further investigation.

3 RESULTS

Fig. 5 illustrates the monthly variations in total solar radiation incident on the east and west façades for each scenario (V1–V4).

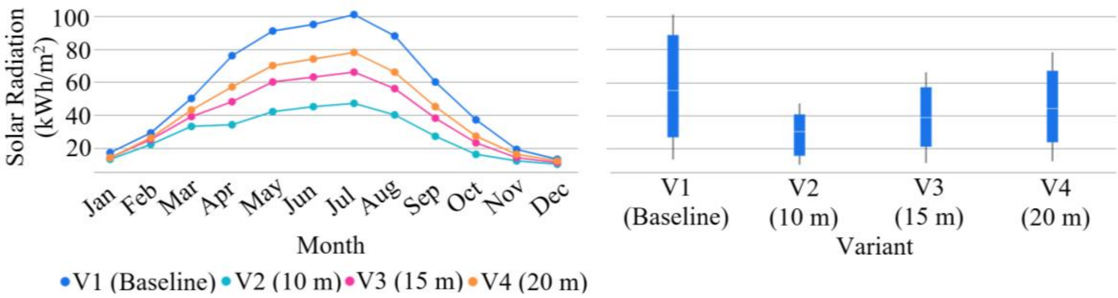

Fig. 5 Total incident solar radiation within each month on the east and west façade for each variant (left) and box plots displaying the distribution of solar radiation values for four variants (right).

Tab. 1 summarises the annual UDI results for each variant (V1–V4). The values in the table represent the percentage of occupied hours during which each UDI category was experienced within the office space. Fig. 6 to Fig. 9 depict the year-long UDI distribution within the office space for each scenario (V1–V4), respectively. These figures provide a visual representation of the temporal and spatial variations in daylight availability throughout the year as influenced by tree proximity.

Tab. 1 Summary of Annual UDI Results for Each Variant - percentage of occupied hours in each category.

Variant	UDI_f (%)	UDI_s (%)	UDI_a (%)	UDI_e (%)
1	12.52	21.34	61.31	1.83
2	18.19	35.94	45.54	0.33
3	18.00	32.35	49.03	0.62
4	17.72	28.66	52.67	0.95

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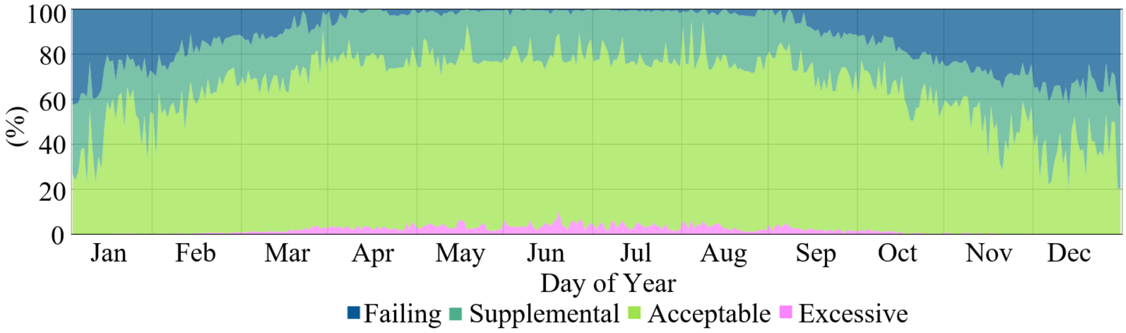

Fig. 6 Year-long UDI Pattern for V1 (Baseline).

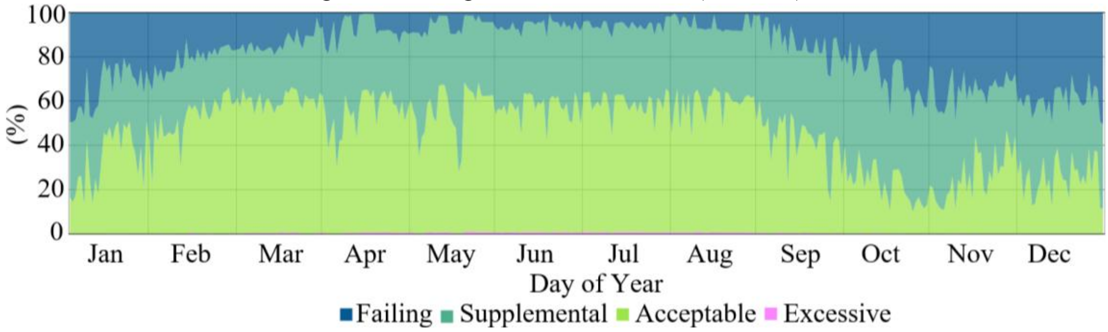

Fig. 7 Year-long UDI Pattern for V2 (10 m).

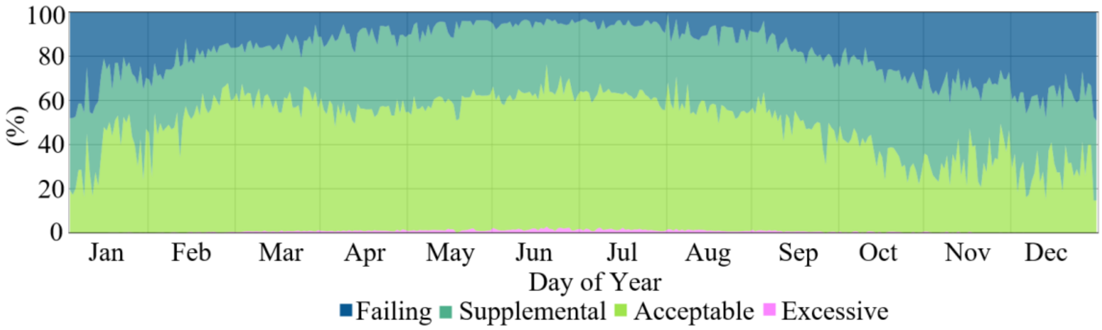

Fig. 8 Year-long UDI Pattern for V3 (15 m).

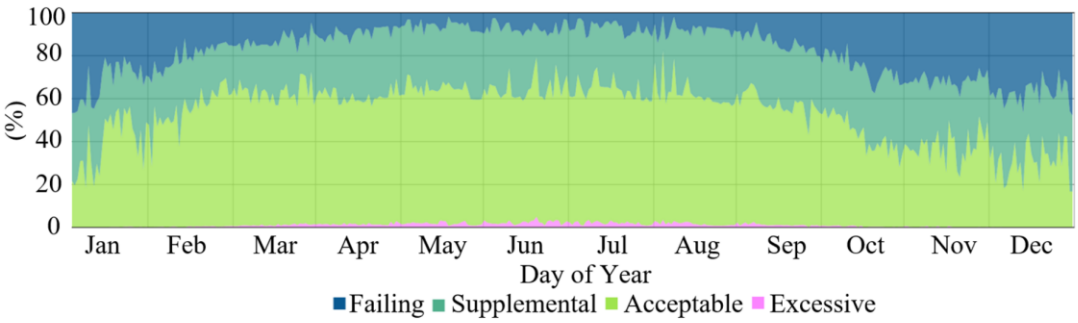

Fig. 9 Year-long UDI Pattern for V4 (20 m).

Fig. 10 to Fig. 13 illustrate the spatial distribution of disturbing glare frequencies (DGP > 38%) across the 32 working positions for each scenario: V1 (baseline), V2 (10 m), V3 (15 m), and V4 (20 m), respectively. The value associated with each position represents the percentage of occupied hours throughout the year during which disturbing glare was experienced at that location. In the baseline scenario (Fig. 10), position 32 (marked in the floor plan as P32) is identified as having the highest incidence of disturbing glare, at 6.11% of occupied hours. P32 is located next to a west-facing window. A detailed comparison of DGP values at P32 across all four variants (V1–V4) throughout the year is presented in Fig. 14. This visualisation depicts the monthly DGP variation, allowing for an evaluation of how tree proximity influences glare over the seasons. For each hour from 8:00 to 18:00 throughout the year, Fig. 15 presents the average DGP values at P32 across all four variants (V1–V4). This visualisation allows for a comparison of how tree proximity influences the average glare experienced at different times of the day.

4 DISCUSSION

The study's findings, illustrated in Fig. 5, demonstrate that deciduous trees have a significant impact on the amount of solar radiation reaching the building's east and west façades. As anticipated, the presence of trees consistently reduced solar radiation throughout the year compared to the baseline scenario (V1), which lacked any surrounding trees. The magnitude of this reduction was directly related to the proximity of the trees to the façade, with trees positioned closer to the building (V2 – 10 m) providing the most substantial shading effect. This aligns with existing literature, suggesting that trees exert the greatest influence on the indoor environment when shading east or west-facing façades at distances of 10-15 metres [8], [18]. The largest overall effect can be observed during the summer period. The overall differences between V2-V4 (trees included) were relatively small compared to the simulation with no trees.

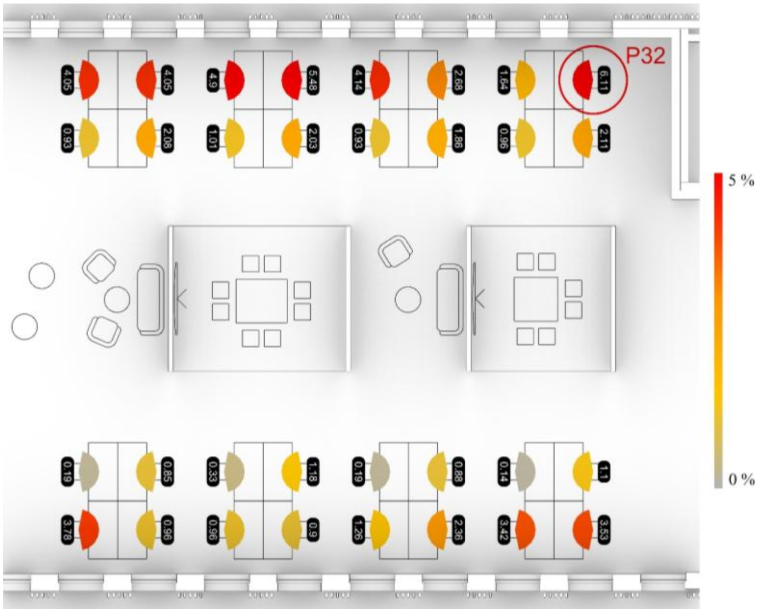

Fig. 10 Floor plan of the space with disturbing glare frequencies (DGP > 38%) for V1 - Baseline.

However, the results also underscore the dynamic nature of this shading effect. During the winter months, when deciduous trees are devoid of leaves, the difference in solar radiation between the baseline scenario and the tree scenarios was minimal. This is logical, as the bare branches allow a greater proportion of sunlight to pass through. However, as the trees began to develop foliage in the spring and reached full leaf cover in the summer, the amount of solar radiation reaching the façade decreased substantially in the tree scenarios (V2–V4). This seasonal variation in shading, driven by foliage changes, is a critical factor to consider when evaluating the overall impact of deciduous trees on building energy performance and daylighting. The most substantial reductions in solar radiation availability compared to the baseline were observed in April (55% decrease in V2), May (54% decrease in V2), and October (57% decrease in V2). These periods of reduced solar gain, coupled with potentially cloudier days and milder outdoor temperatures, could lead to increased energy consumption for heating and artificial lighting within the building due to the shading effect of the deciduous trees [25]. Therefore, careful consideration of tree placement in relation to building design is paramount for optimising both daylighting and energy performance.

The analysis of Useful Daylight Illuminance (UDI) provides further insights into the effects of deciduous trees on both daylight availability and the potential for excessive daylight levels within the office space. The results, summarised in Tab. 1, reveal a clear trend: as trees were positioned closer to the building, the percentage of occupied hours with sufficient daylight UDI_ decreased. This reduction was most significant in V2 (10 m),

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where trees were located closest to the façade. Conversely, the percentage of occupied hours with either supplemental (UDI_s) or failing (UDI_f) daylight levels increased with tree proximity. These findings support the hypothesis that closer tree proximity leads to lower overall daylight availability within the interior of the office space.

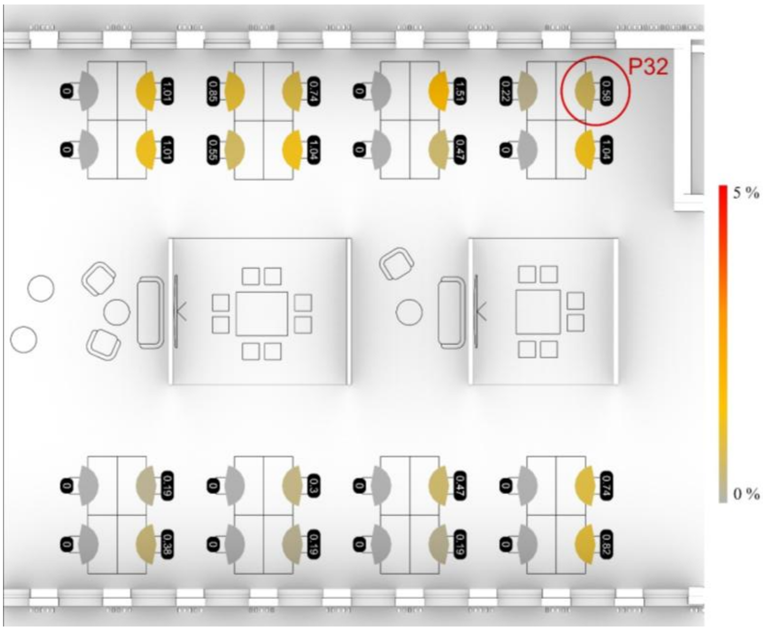

Fig. 11 Floor plan of the space with disturbing glare frequencies (DGP > 38%) for V2 (10 m).

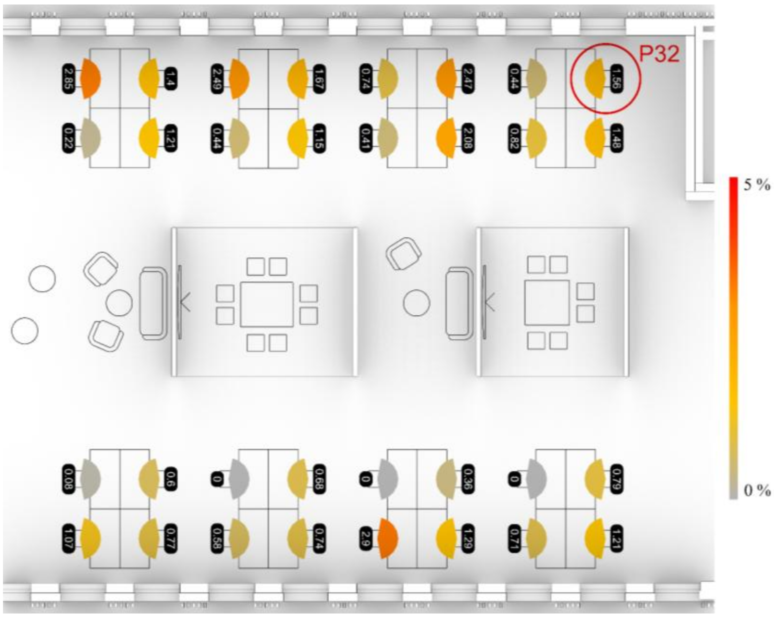

Fig. 12 Floor plan of the space with disturbing glare frequencies (DGP > 38%) for V3 (15 m).

However, it is important to recognise that the trees also mitigated excessive daylight levels (UDI_e). The percentage of occupied hours with excessive daylight was significantly lower in all three scenarios (V2–V4) compared to the baseline (V1), which had no trees. This reduction in excessive daylight is particularly relevant for visual comfort, as it can help minimise glare and associated visual discomfort.

Furthermore, the year-round UDI distributions, depicted in Fig. 6 to Fig. 9, reveal that trees had a negligible effect on indoor daylighting during the months when they were without leaves. However, during the other parts of the year, their impact was substantial.

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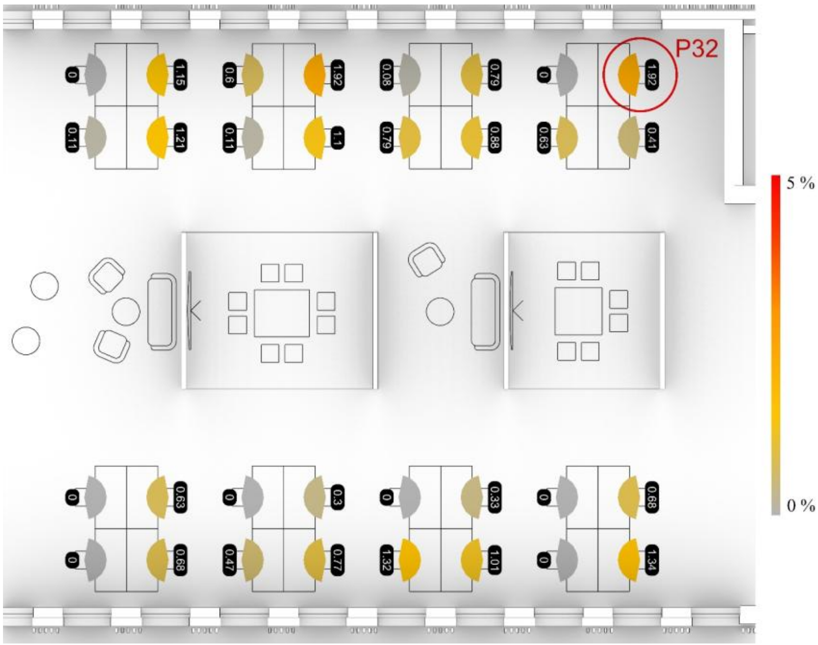

Fig. 13 Floor plan of the space with disturbing glare frequencies (DGP > 38%) for V4 (20 m).

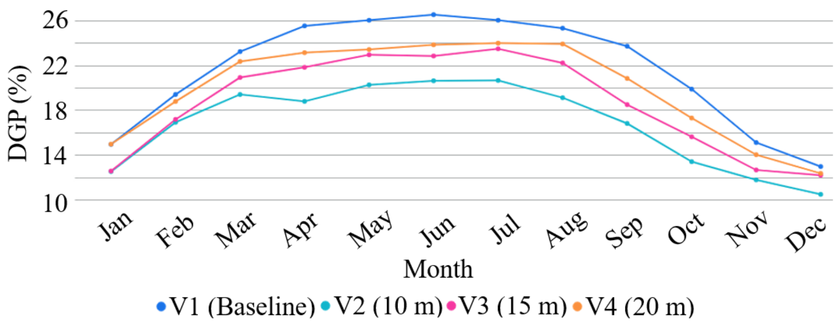

Fig. 14 Monthly DGP Values at P32 for Each Variant (V1–V4).

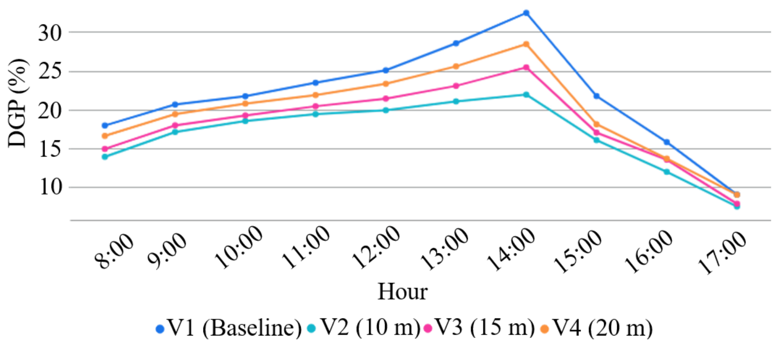

Fig. 15 Average Hourly DGP Values at P32 for Each Variant (V1–V4).

The Daylight Glare Probability (DGP) analysis provides valuable insights into the spatial and temporal distribution of glare within the office space under different tree scenarios. To assess the impact of deciduous trees on visual comfort, DGP was simulated throughout the year for all 32 working positions across the four scenarios (V1–V4). Fig. 10 to Fig. 13 illustrate the spatial distribution of disturbing glare (DGP > 38%) for each variant, revealing that the presence of trees generally reduced the incidence of disturbing glare across most workstations compared to the baseline (V1). This reduction is particularly noticeable in V2 (Fig. 11), where trees were positioned closest to the building.

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Focusing on workstation 32 (P32), identified as the location with the highest glare incidence in the baseline scenario (Fig. 10), a more detailed analysis was conducted. P32, situated adjacent to a west-facing window, experienced 6.11% of occupied hours with disturbing glare in the absence of trees.

The results, presented in Fig. 14 and Fig. 15, demonstrate that trees effectively reduced glare at P32, particularly during the summer months when the trees are in full foliage. This finding aligns with expectations, as the dense foliage can effectively block direct sunlight that would otherwise contribute to glare.

Fig 14 highlights the seasonal variations in DGP at P32. During the summer months, when the trees were in full foliage, DGP values were significantly lower in the tree scenarios (V2-V4) compared to the baseline (V1). This suggests that the trees effectively mitigated glare during the time of year when it is most likely to be problematic. The comparison of average hourly DGP values in Fig. 15 further emphasises the role of trees in glare prevention. In the baseline scenario (V1), DGP values peaked between 10:00 and 14:00, indicating that the highest risk of glare lay during these hours. However, in the tree scenarios (V2-V4), average DGP values were consistently lower during these peak hours. This observation suggests that trees can effectively mitigate glare during the most critical times of the day, contributing to a more comfortable visual environment for building occupants.

The UDI and DGP findings are interconnected and highlight the complex interplay between deciduous trees, daylight availability, and visual comfort. As observed in the UDI analysis (Tab. 1, Fig. 7 to Fig. 9), closer tree proximity (V2, V3) generally resulted in a decrease in desirable daylight levels (UDI_a) within the office space, particularly in V2 (10 m), where the reduction was most pronounced. Simultaneously, however, these scenarios also demonstrated a reduction in excessive daylight (UDI_e), which, as the DGP analysis revealed (Fig. 10 to Fig. 15), corresponded to a decrease in the incidence of disturbing glare (DGP > 38%), especially during peak hours and summer months.

This interplay underscores the need for a balanced approach to tree placement that optimises both daylight availability and visual comfort. While closer trees can effectively mitigate glare, as seen in the lower DGP values for V2, V3, and V4, particularly at the most critical times, they can also compromise daylight sufficiency, as indicated by the lower UDI_a and higher UDI_f/UDI_s values in these scenarios. Therefore, careful consideration of tree distance, building orientation, and glazing properties is essential to achieve a design that maximises the benefits of natural light while minimising the potential for glare. Further research could explore optimal tree arrangements and species selection to achieve this balance.

5 CONCLUSION

This study investigated the impact of deciduous trees on the solar energy loads and daylighting performance of an office building in Bratislava, Slovakia, with a particular focus on the interplay between daylight availability and glare. Through computer simulations, we analysed the effects of varying tree distances (10 m, 15 m, and 20 m) on solar radiation, Useful Daylight Illuminance (UDI), and Daylight Glare Probability (DGP). The findings demonstrate that deciduous trees significantly influence both the quantity and quality of daylight entering the building, with the effects varying seasonally due to foliage changes.

Closer tree proximity (particularly at 10 m) resulted in the most substantial reduction in solar radiation, especially during the spring and summer months. While this shading effect effectively mitigated glare, as evidenced by lower DGP values, it also led to a decrease in desirable daylight levels (UDI_a) and an increase in areas requiring supplemental lighting (UDI_s and UDI_f). These findings highlight the complex relationship between trees and building daylighting, underscoring the need for a balanced approach to tree placement that considers both visual comfort and daylight access. The research contributes to the growing body of knowledge on green infrastructure and its role in sustainable building design, emphasising the importance of considering the dynamic nature of trees when evaluating their impact on building performance. Future research should focus on exploring optimal tree arrangements, considering different tree species with varying canopy densities and growth patterns, and investigating the combined effects of trees with other shading devices.

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