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Evaluation of the Natural Lighting Performance of Skylights in the Circulation Areas of Building V at Istanbul Aydın University: A Digital Twin-Based Study

* [1] **Ezgi Yılmaz** , [2] **Ayberk Paşaoğlu**
[1 & 2] Department of Architecture, Faculty of Architecture, Istanbul Aydın University, Istanbul, Türkiye
[1] E-mail: ezgiyilmaz@aydin.edu.tr , [2] E-mail: ayberkpasaoglu@stu.aydin.edu.tr

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Abstract

Natural lighting plays a fundamental role in enhancing visual comfort, reducing energy consumption, and supporting user well-being in sustainable architectural design. This study aims to evaluate the daylight performance of circulation areas beneath skylights in Building V at Istanbul Aydın University through a digital twin-based approach. A parametric digital twin model of the building was developed, and climate-based daylight simulations were conducted using Ladybug and Honeybee tools. Within the scope of the study, both the existing skylight configuration and a newly proposed alternative geometry were analyzed with two different glazing materials. A reference illuminance level of 100 lx, in accordance with TS EN 12464-1:2011 and EN 17037:2018 standards, was adopted as the baseline criterion. The simulation results indicate that both glazing properties and skylight geometry have a significant impact on daylight distribution, illuminance levels, and spatial uniformity. The study provides a quantitative framework for optimizing skylight design in educational buildings and contributes to reducing dependence on artificial lighting systems. The findings highlight the importance of integrating digital twin methodologies with daylight performance metrics in sustainable building design processes.
Keywords: Daylight performance; Skylight design; Digital twin; Climate-based simulation; Educational buildings.

1. Introduction

Natural lighting plays a fundamental role in architectural design, extending beyond visual comfort to influence energy efficiency, user health, and spatial quality. The effects of daylight on human physiology, particularly in relation to circadian rhythm, cognitive performance, and psychological well-being, have been comprehensively established in the literature (Boyce, 2014; Edwards & Torcellini, 2002). Consequently, the effective integration of natural lighting is recognized as a core component of sustainable architectural approaches.

A significant portion of energy consumption in the building sector originates from lighting systems. In this context, optimizing natural lighting strategies directly contributes to reducing energy consumption (Reinhart & Wienold, 2011). However, poorly designed opening systems may cause problems such as insufficient lighting levels and excessive solar radiation exposure in interior spaces (Tregenza & Wilson, 2011). This situation necessitates evaluating daylight performance not only in terms of quantity but also in terms of distribution, uniformity, and glare risk.

In deep-plan buildings and spaces with limited direct facade access, such as circulation areas, skylights play a critical role in providing natural lighting. The literature emphasizes that when properly designed, skylights provide more balanced and deep daylight to interior spaces; however, geometric form, aperture ratio, and glass properties are determined to be decisive for performance (Heschong, 2002; Li & Tsang, 2008; Shirzadnia, Goharian, & Mahdavinejad, 2023). Furthermore, in skylight design, not only the illuminance level but also the distribution of light within the space and user comfort must be considered.

Recent multi-objective optimization studies have approached skylight design from a quantitative perspective, treating opening area, shape, and orientation as decision variables that can be systematically tuned against competing performance criteria such as spatial daylight autonomy, annual sunlight exposure, and energy use intensity (Fang, Cho, Wang, & He, 2024; Mangkuto, Wijaya, & Utami, 2024). These studies consistently report that skylight geometry exerts a stronger influence on daylight distribution than any single material parameter considered in isolation, which suggests that geometric optimization should precede, rather than follow, material selection in the early design process. At the same time, several authors caution that climatic context plays a decisive role in determining the optimal skylight configuration, since strategies that perform well in temperate or overcast climates may produce excessive solar gain and glare risk in regions with high direct-beam radiation (Vojdani Fakhr, Mahdavinejad, Rahbar, & Dabaj, 2023). This climate dependency underlines the need for locally calibrated simulation studies rather than the uncritical transfer of design guidelines between different geographic and climatic contexts.

In the evaluation of daylight performance, traditional static methods are increasingly being replaced by more advanced simulation techniques. Climate-Based Daylight Modelling (CBDM) allows for more realistic analyses by considering sky conditions varying throughout the year (Reinhart, Mardaljevic, & Rogers, 2006). Metrics such as Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), used within this method, are accepted as fundamental performance indicators that evaluate daylight sufficiency and the risk of excessive solar exposure together (IES, 2012). Multi-objective optimization studies have shown that skylight geometry and skylight-to-floor ratio strongly affect such metrics in the early design stage (Fang, Cho, Wang, & He, 2024).

The European standard EN 17037 provides a comprehensive framework for evaluating daylight performance, addressing criteria such as daylight access, external view, solar radiation exposure, and glare control through an integrated approach (European Committee for Standardization [CEN], 2018). This standard encourages the integration of not only quantitative but also qualitative dimensions of daylight into the design process. However, the evaluation of daylight performance in spaces with complex geometries remains an important research area (Mardaljevic et al., 2011).

In recent years, with the development of parametric modeling and performance-oriented design approaches, rapid testing of numerous alternative scenarios has become possible during the architectural design process. In particular, tools such as Ladybug and Honeybee enable the integration of climate data-based daylight analyses into architectural design processes (Roudsari & Pak, 2013). These tools allow early-stage evaluation of the impact of design decisions on performance.

Parallel to these developments, the concept of digital twin has emerged as a new approach in building performance analyses. Digital twins support data-driven decision-making in design, analysis, and optimization processes by creating a high-accuracy digital representation of a physical structure (Boje et al., 2020). The integration of Building Information Modeling (BIM) with sensor-based data streams further enables real-time and offline performance analysis of indoor environments (Boje, Guerriero, Kubicki, Rezgui, & Hadjidemetriou, 2023; Eneyew, Capretz, & Bitsuamlak, 2022). This approach strengthens performance-oriented decision mechanisms, particularly in sustainable design processes.

While digital twin applications have historically concentrated on structural health monitoring, energy management, and HVAC fault detection, their extension into daylight and lighting performance evaluation remains comparatively underexplored (Hauer et al., 2024; Kor, Yitmen, & Alizadehsalehi, 2023). This gap is notable given that lighting-related decisions are typically finalized early in the design process and are costly to reverse once construction is complete. A digital twin framework that incorporates daylight simulation alongside conventional energy and comfort metrics can therefore provide architects with a more complete performance picture before physical commitments are made. Moreover, because digital twins are continuously updatable with new geometric, material, or climatic data, they offer a flexible platform for testing design alternatives iteratively, which is particularly valuable in renovation or retrofit scenarios where existing buildings must be evaluated against multiple candidate interventions (Hosamo, Nielsen, Kraniotis, Svennevig, & Svidt, 2023).

The literature shows that most studies on daylight performance focus on facade openings and office spaces, with limited studies on secondary but heavily used spaces such as circulation areas. The lack of detailed analyses regarding the daylight performance of circulation areas with large interior volumes in educational buildings is particularly notable.

This study aims to evaluate the natural lighting performance of circulation areas beneath skylights in Building V at Istanbul Aydın University. Within the scope of the study, the existing skylight system and an alternative design proposal are comparatively analyzed, and the effect of different glazing materials on performance is examined. In this direction, daylight distribution, illuminance levels, and spatial uniformity performance criteria were evaluated using digital twin-based modeling and climate-based simulation methods together.

In this respect, the study focuses on skylight performance in circulation areas, which are limitedly addressed in the literature, and aims to contribute to the existing body of knowledge by presenting a quantitative analysis framework supported by a digital twin approach.

2. Materials and Methods

This study adopts a quantitative, simulation-based research approach to evaluate the natural lighting performance of skylights. The research is structured around the digital twin method, which enables high-accuracy representation of the spatial and physical characteristics of a real building. The digital twin approach is a method that allows physical structures to be modeled in a digital environment and their performance to be analyzed, and has been widely used in building performance evaluations in recent years (Boje et al., 2020; Hosamo, Nielsen, Kraniotis, Svennevig, & Svidt, 2023; Kor, Yitmen, & Alizadehsalehi, 2023).

Within the scope of the study, the performance of the existing skylight system and a proposed alternative design were comparatively examined. In this direction, the effects of geometry and material parameters on natural lighting were analyzed.

2.1 Study Area and Spatial Characteristics

The circulation areas in Building V at Istanbul Aydın University, illuminated by skylights, were selected as the research area. These areas are characterized as spaces with limited direct facade access, a deep plan, and heavy user movement throughout the day. In such spaces, where natural lighting is largely provided through overhead apertures, the performance of skylights becomes critical (Heschong, 2002). In the analyses, the work plane height was taken as 0.80 m, as commonly accepted in the literature (Reinhart & Wienold, 2011).

2.2 Development of the Digital Twin Model

In the study, the three-dimensional model of the building was created parametrically in Rhinoceros 3D and Grasshopper environment. During the modeling process, the skylight geometry, space depth and volume relationships, and interior surface properties were defined in detail. Reflectance values of interior surfaces were assigned in accordance with the ranges recommended in the literature: ceiling approximately 0.80, walls approximately 0.50, and floor approximately 0.80. These values are fundamental parameters that affect the distribution of daylight within the space, and are widely used in simulation studies (Tregenza & Wilson, 2011; Baydoğan & Özkantar, 2023).

The geometric accuracy of the digital twin was verified by cross-checking key dimensions, including circulation corridor width, ceiling height, and skylight aperture coordinates, against architectural drawings and on-site measurements. This verification step is essential because even minor discrepancies between the physical building and its digital representation can propagate into the simulation results, particularly for metrics that are sensitive to surface area and volume ratios, such as spatial daylight autonomy. Once geometric fidelity was confirmed, the model was segmented into discrete analysis zones corresponding to the areas directly beneath the skylights and the adjacent transitional zones, allowing illuminance values to be reported both for the most favorably lit areas and for the more challenging peripheral regions of the circulation space.

2.3 Simulation Tools and Climate Data

Natural lighting analyses were conducted using Ladybug and Honeybee plugins. These tools are based on validated Radiance and Daysim calculation engines and provide reliable results in architectural daylight analyses (Roudsari & Pak, 2013; Reinhart et al., 2006). Typical Meteorological Year (TMY) data for Istanbul was used in the simulations, ensuring that the analyses were conducted considering the real climate conditions varying throughout the year. The study was conducted using the Climate-Based Daylight Modelling (CBDM) approach, which allows the temporal and spatial variation of daylight to be dynamically evaluated (Reinhart et al., 2006).

2.4 Simulation Scenarios

In the study, analysis was performed on three main variables: (1) Skylight Geometry - existing system and proposed alternative form (geometric improvement); (2) Glazing Material - two different glass types were evaluated: Glass A (Sisecam Neutral 50/33) with visible light transmittance (VT) of 0.50, and Glass B (Guardian SN 70/35) with VT of 0.70. The visible light transmittance of the glazing material is a critical parameter that directly affects the amount of daylight entering the interior space (Li & Tsang, 2008; Li & Wu, 2025; Wienold, Jain, & Andersen, 2022); (3) Combined Scenarios - both geometries were evaluated with two different glasses, and a total of four scenarios were created: Scenario 1 (existing geometry + Glass A), Scenario 2 (existing geometry + Glass B), Scenario 3 (proposed geometry + Glass A), and Scenario 4 (proposed geometry + Glass B).

2.5 Performance Evaluation Criteria

In the study, natural lighting performance was evaluated with both standard-based and performance-based metrics. For circulation areas, a reference value of 100 lx was adopted as the illuminance level. This value is based on TS EN 12464-1:2011 and EN 17037:2018 standards (CEN, 2018; Hraška & Čurpek, 2024). Spatial lighting uniformity was calculated with the formula $U0 = Emin/Eavg$, and the simulation process consisted of the following steps: development of the digital twin model, definition of material and geometry parameters, integration of climate data, creation of scenarios, execution of daylight simulations, and obtaining and comparing result data.

In addition to the average and minimum illuminance values, the spatial daylight autonomy (sDA) metric was calculated for each scenario to express the percentage of the analyzed floor area that achieved the 100 lx threshold for at least 50% of the annual occupied hours. This metric was complemented by an average daylight autonomy (DA) calculation, which captures the percentage of the year during which the threshold illuminance is met across the entire circulation area rather than at a single point, thereby providing a more representative picture of temporal performance continuity. All simulations were run for the full calendar year using hourly climate data, and results were post-processed in a spreadsheet environment to generate comparative tables and distribution maps for each of the four scenarios. This combination of spatial and temporal metrics allowed the study to distinguish between improvements in peak illuminance and improvements in the consistency of daylight provision over time, which is a distinction that is often overlooked when only single-point or single-day measurements are reported.

3. Results

3.1 General Illuminance Levels

As a result of the daylight simulations performed, illuminance levels in the circulation areas were quantitatively determined for all scenarios examined. The obtained results show that the existing skylight system cannot provide sufficient illuminance in some areas. For the existing geometry and standard glass (Scenario 1), the average illuminance level was calculated to be approximately 98 lx, and minimum illuminance values were found to drop to 96.52 lx in the deep areas of the space. This situation shows that the 100 lx reference value cannot be achieved in certain parts of the analysis area.

In scenarios where the alternative skylight geometry was used (Scenarios 3 and 4), an increase in average illuminance levels was observed. This increase was calculated to be approximately 0.51-0.67% compared to the existing situation. In particular, it was determined that illuminance levels increased in the central and deep areas of the space.

3.2 Comparison of Scenarios

When the average illuminance values obtained within the scope of the four different scenarios were compared, the highest values were determined to be obtained in the combination of the proposed geometry and high-transmittance glass (Scenario 3). In contrast, in scenarios where low-transmittance glass was used (Scenarios 2 and 4), average illuminance levels were found to be relatively lower. A decrease of approximately 0.58% in illuminance values was determined in these scenarios. When all scenarios are evaluated together, it was observed that the change in skylight geometry had a more pronounced effect on illuminance levels compared to the glazing material.

3.3 Spatial Illuminance Distribution

When illuminance distribution maps were examined, it was determined that light was not distributed homogeneously within the space in the existing skylight system. High illuminance values were obtained in areas under the skylight apertures, while significant decreases were observed in areas far from the apertures. In scenarios created with the proposed skylight geometry, it was found that illuminance distribution became more balanced and areas with low illuminance decreased. This situation indicates that a more widespread illumination was achieved throughout the space.

3.4 Uniformity Values

Uniformity ratios (U0) were calculated for each scenario based on minimum and average illuminance values. For the existing system, the uniformity value was determined to be approximately U0 = 0.98. This value indicates an irregular illuminance distribution within the space. In scenarios where the alternative skylight geometry was used, an increase in uniformity values was observed, and this increase was calculated to be approximately 0.51-0.67%. It was determined that uniformity performance reached the highest level particularly in Scenario 4.

3.5 Reference Value Compliance Analysis

In the evaluation based on the 100 lx reference illuminance level determined according to TS EN 12464-1:2011 and EN 17037:2018 standards, the sDA value was found to be 100% in all scenarios. This finding proves that the targeted 100 lx threshold value was fully achieved in the entire circulation area for at least 50% of the year, and that the existing structure fully complies with standards. Furthermore, when spatial illuminance continuity (average DA) was taken as the basis, it was observed that the existing system (Scenario 1) met this threshold in 98.00% of the year, while in optimized Scenario 4, this ratio increased to 98.51%. Therefore, it was observed that design interventions improved the existing performance continuity and homogeneity by approximately 0.51-0.67%, rather than creating a field-based increase.

3.6 Quantitative Summary of Findings

When all findings obtained are evaluated together: the alternative skylight geometry, although it did not create a field-based increase since maximum saturation was reached in sDA values, increased the uniformity value by providing a balancing of illuminance distribution (0.51-0.67%). The use of high-transmittance glass (Guardian SN 70/35) increased average illuminance levels (Average DA) by approximately 0.58-0.65% compared to the existing glass configuration. As a result of optimization studies, an improvement of up to 0.67% in spatial uniformity values was obtained as observed in Scenario 4. The area ratio (sDA) meeting the 100 lx threshold occurred at 100% in all scenarios, complying with TS EN 12464-1:2011 and EN 17037:2018 standards.

4. Discussion

4.1 Effect of Skylight Geometry on Performance

The findings clearly demonstrate that skylight geometry plays a decisive role in natural lighting performance. Particularly in scenarios where the alternative geometry was used, it was observed that daylight penetrated more deeply and evenly into the space. This situation not only stabilized average illuminance levels in the 97-98% band but also contributed to the improvement of spatial distribution.

This finding is consistent with studies emphasizing that the distribution of daylight within a space depends not only on the aperture area but also on the geometric form of the aperture (Tregenza & Wilson, 2011; Mangkuto, Wijaya, & Utami, 2024; Vojdani Fakhr, Mahdavinejad, Rahbar, & Dabaj, 2023). Physical effects such as light direction and refraction can be controlled through geometric arrangements, and thus more homogeneous illumination can be achieved. Therefore, in skylight design, not only increasing the aperture ratio is sufficient, but geometric optimization must also be addressed as an integral part of the design process.

4.2 Role of Glazing Material on Illuminance and Comfort

Results regarding glazing material show that glasses with high visible light transmittance provide higher illuminance levels, but this does not always mean optimal performance. It was determined that the increase in glass transmittance further improved the already high illuminance continuity by 0.58%, and the spatial distribution became more balanced. This situation reveals that instead of a "maximum illuminance" approach in daylight design, an "optimum and balanced illuminance" approach should be adopted. The literature also emphasizes that glass properties should be evaluated not only in terms of light transmittance but also together with glare control and thermal comfort (Li & Tsang, 2008; Ko et al., 2024).

4.3 Uniformity and Visual Comfort Relationship

The improvement in uniformity values stands out as one of the important findings of the study. The high uniformity values provided by the existing system have been transformed into a more balanced structure where spatial comfort is perfected by raising to the U0 = 0.99 level with alternative designs. This situation is particularly critical in terms of user experience. Visual comfort is directly related not only to providing sufficient illuminance but also to the balanced distribution of light within the space. Sudden illuminance changes and high contrast differences can cause visual discomfort in users (Boyce, 2014; Ko, Kent, Schiavon, Levitt, & Betti, 2021). Therefore, the increase in uniformity values can be evaluated as an important design output in terms of improving spatial comfort.

4.4 Importance of Daylight Performance in Circulation Areas

In the literature, it is observed that most studies on daylight performance focus largely on the main usage areas of offices, residences, and educational spaces. In contrast, it is noteworthy that transition spaces such as circulation areas are generally of secondary importance and detailed analyses are limited. This study reveals that circulation areas are often neglected despite their heavy usage throughout the day, and emphasizes the need to optimize these spaces in terms of visual comfort as well, a gap also noted in daylight assessments of Turkish educational buildings (Erdemir & Köknel Yener, 2022). In particular, considering that users frequently pass through these areas throughout the day in educational buildings, the quality of natural lighting is considered to be effective on the overall user experience. In this respect, the study presents an original contribution by focusing on a type of space limitedly addressed in the literature.

Beyond their functional role as connective infrastructure, circulation areas in educational buildings frequently serve as informal gathering points where students socialize, study, or wait between classes, which extends their effective occupancy duration well beyond simple transit time. This expanded pattern of use strengthens the argument that such spaces warrant the same level of daylighting attention typically reserved for classrooms and offices. The comparatively limited body of research on circulation-area daylighting may partly reflect the assumption that these spaces are transient by nature and therefore of secondary importance; the findings of the present study suggest that this assumption should be revisited, particularly in large educational campuses where corridors and atria constitute a substantial proportion of total floor area.

4.5 Contribution of Digital Twin Approach to Design Process

The digital twin-based modeling approach used in the study allowed different design scenarios to be evaluated comparatively. Thanks to this approach, the performance of design alternatives could be quantitatively analyzed before physical implementation. This advantage offered by digital twins contributes to the strengthening of data-driven decision mechanisms in the design process. In the literature, it is also emphasized that digital twin technologies are an important tool for sustainable design and performance optimization (Boje et al., 2020; Hauer et al., 2024). In this context, another important contribution of the study is to demonstrate the integration of the digital twin approach with daylight performance analyses.

4.6 Contribution and Limitations of the Study

This study demonstrates that skylight design should be evaluated not only from an illuminance perspective but also from the perspective of spatial distribution and homogeneity. It also presents a quantitative analysis of daylight performance in generally neglected space types such as circulation areas. However, the study has some limitations. Some of the simulation parameters used were defined based on indicative values. Additionally, variables such as user behavior, interior arrangements, and real-time usage data were left outside the scope of the study. It is recommended that future studies integrate user-based data with simulation results and extend similar analyses in different building types.

5. Conclusions

This study aimed to evaluate the natural lighting performance of circulation areas in Building V at Istanbul Aydın University through a digital twin-based approach using skylights. Within this scope, the existing skylight system and an alternative design proposal were comparatively analyzed, and the effects of different glazing materials on performance were examined.

The findings demonstrate that skylight geometry plays a decisive role in natural lighting performance. In particular, it was determined that the proposed geometric arrangements provided more balanced and deep daylight penetration into the space, achieving an increase of 0.51-0.65% in average illuminance levels. Furthermore, the visible light transmittance values of the glazing material were shown to have a direct effect on illuminance levels and spatial distribution.

The study also reveals that natural lighting performance should be evaluated not only in terms of the amount of lighting but also with spatial homogeneity and distribution criteria. The results show that the alternative skylight design improved uniformity values and maintained the area ratio meeting the 100 lx reference illuminance level at 100% in all scenarios.

One of the most important contributions of this research is its focus on daylight performance in circulation areas, which are limitedly addressed in the literature. Considering that most existing studies concentrate on main usage areas, this study reveals that transition spaces are also important from a user comfort perspective.

In addition, the digital twin-based modeling approach used in the study allowed different design scenarios to be evaluated comparatively, and demonstrated the effectiveness of data-driven decision mechanisms in the design process. In this respect, the study presents an important example for the integration of digital twin technologies into sustainable architectural design processes.

It is recommended that future studies integrate user-based data (such as visual comfort perception and user satisfaction) with simulation results, conduct similar analyses in different climate zones, and evaluate skylight design together with energy performance. Additionally, using artificial intelligence-supported optimization methods together with digital twin models can contribute to developing higher performance solutions in design processes.

In conclusion, this study contributes to the development of sustainable and user-centered design strategies in educational buildings by revealing the effects of skylight design on natural lighting performance.

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Conflicts of Interest
The author(s) report no conflicts of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Institutional Review Board Statement
This study did not involve human participants or animals and therefore did not require ethics committee approval.

CRediT Author Statement
Ezgi Yilmaz: Conceptualisation; Methodology; Supervision; Writing - review & editing. Ayberk Pasaoglu: Methodology; Software; Formal analysis; Data curation; Writing - original draft. All authors have read and approved the final manuscript.

References

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. Automation in Construction, 114, 103179. https://doi.org/10.1016/j.autcon.2020.103179

Boyce, P. R. (2014). Human factors in lighting (3rd ed.). CRC Press.

CEN. (2018). EN 17037: Daylight in buildings. European Committee for Standardization.

Edwards, L., & Torcellini, P. (2002). A literature review of the effects of natural light on building occupants. National Renewable Energy Laboratory.

Heschong, L. (2002). Daylighting and human performance. ASHRAE Journal, 44(6), 65-67.

IES. (2012). IES spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). Illuminating Engineering Society.

Li, D. H. W., & Tsang, E. K. W. (2008). An analysis of daylighting performance for office buildings in Hong Kong. Building and Environment, 43(9), 1446-1458. https://doi.org/10.1016/j.buildenv.2007.07.002

Mardaljevic, J., Andersen, M., Roy, N., & Christoffersen, J. (2011). Daylighting metrics for residential buildings. Proceedings of the 27th Session of the CIE, Sun City, South Africa.

Reinhart, C. F., Mardaljevic, J., & Rogers, Z. (2006). Dynamic daylight performance metrics for sustainable building design. LEUKOS, 3(1), 7-31. https://doi.org/10.1582/LEUKOS.2006.03.01.001

Reinhart, C. F., & Wienold, J. (2011). The daylighting dashboard. Building and Environment, 46(2), 386-396. https://doi.org/10.1016/j.buildenv.2010.08.001

Roudsari, M. S., & Pak, M. (2013). Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. Proceedings of BS2013: 13th Conference of the International Building Performance Simulation Association, Chambery, France.

Tregenza, P., & Wilson, M. (2011). Daylighting: Architecture and lighting design. Routledge.

Baydoğan, M. Ç., & Özkantar, V. (2023). Evaluation of daylight performance metrics according to country guidelines: The case of educational buildings in Turkey. Energy and Buildings, 297, 113487. https://doi.org/10.1016/j.enbuild.2023.113487

Boje, C., Guerriero, A., Kubicki, S., Rezgui, Y., & Hadjidemetriou, L. (2023). A digital twin architecture for real-time and offline high granularity analysis in smart buildings. Sustainable Cities and Society, 98, 104795. https://doi.org/10.1016/j.scs.2023.104795

Eneyew, D. D., Capretz, M. A. M., & Bitsuamlak, G. T. (2022). Toward smart-building digital twins: BIM and IoT data integration. IEEE Access, 10, 130487-130506. https://doi.org/10.1109/ACCESS.2022.3229370

Fang, Y., Cho, S., Wang, Y., & He, L. (2024). Sensitivity analysis and multi-objective optimization of skylight design in the early design stage. Energies, 17(1), 219. https://doi.org/10.3390/en17010219

Hosamo, H. H., Nielsen, H. K., Kraniotis, D., Svennevig, P. R., & Svidt, K. (2023). Improving building occupant comfort through a digital twin approach: A Bayesian network model and predictive maintenance method. Energy and Buildings, 288, 112992. https://doi.org/10.1016/j.enbuild.2023.112992

Hraška, J., & Čurpek, J. (2024). The practical implications of the EN 17037 minimum target daylight factor for building design and urban daylight in several European countries. Heliyon, 10(1), e23297. https://doi.org/10.1016/j.heliyon.2023.e23297

Ko, W. H., Kent, M. G., Schiavon, S., Levitt, B., & Betti, G. (2021). A window view quality assessment framework. LEUKOS, 18(3), 268-293. https://doi.org/10.1080/15502724.2021.1965889

Ko, W. H., Burgess, I., Schiavon, S., Chung, S. T. L., MacNaughton, P., & Um, C. Y. (2024). Assessing the impact of glazing and window shade systems on view clarity. Scientific Reports, 14, 18392. https://doi.org/10.1038/s41598-024-69026-x

Kor, M., Yitmen, I., & Alizadehsalehi, S. (2023). An investigation for integration of deep learning and digital twins towards Construction 4.0. Smart and Sustainable Built Environment, 12(3), 461-487. https://doi.org/10.1108/SASBE-08-2021-0148

Li, X., & Wu, Y. (2025). A review of complex window-glazing systems for building energy saving and daylight comfort: Glazing technologies and their building performance prediction. Building Services Engineering Research and Technology, 46(1), 3-25. https://doi.org/10.1177/17442591241269182

Mangkuto, R. A., Wijaya, D., & Utami, S. S. (2024). Multi-objective optimisation of skylight design parameters for a low-rise building in the tropics. International Journal of Technology, 15(4), 1012-1025. https://doi.org/10.14716/ijtech.v15i4.5484

Hauer, M., Hammes, S., Zech, P., Geisler-Moroder, D., Plörer, D., Miller, J., van Karsbergen, V., & Pfluger, R. (2024). Integrating digital twins with BIM for enhanced building control strategies: A systematic literature review focusing on daylight and artificial lighting systems. Buildings, 14(3), 805. https://doi.org/10.3390/buildings14030805

Erdemir, G., & Köknel Yener, A. (2022). A study on daylight performance evaluation in primary school classrooms. Orclever Proceedings of Research and Development, 1(1), 257-270. https://doi.org/10.56038/oprd.v1i1.184

Shirzadnia, Z., Goharian, A., & Mahdavinejad, M. (2023). Designerly approach to skylight configuration based on daylight performance; Toward a novel optimization process. Energy and Buildings, 286, 112970. https://doi.org/10.1016/j.enbuild.2023.112970

Vojdani Fakhr, B., Mahdavinejad, M., Rahbar, M., & Dabaj, B. (2023). Design optimization of the skylight for daylighting and energy performance using NSGA-II. Journal of Daylighting, 10(1), 72-86. https://doi.org/10.15627/jd.2023.6

Wienold, J., Jain, S., & Andersen, M. (2022). Transmittance thresholds of electrochromic glazing to achieve annual low-glare work environments. E3S Web of Conferences, 362, 08001. https://doi.org/10.1051/e3sconf/202236208001