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Real-Time Multi-Objective Optimization Control of Partitioned Electrochromic Windows Using Neural Network

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Abstract. Optimizing daylight while controlling glare is essential in offices, yet existing electrochromic window (EC window) methods, while effective for glare prevention, remain limited in real-time and fine-grained control. This study proposes a real-time control strategy for partitioned EC windows, aiming to optimize daylight availability and glare control in office spaces. The EC window, divided into 6 partitions, uses a neural network surrogate model trained on simulation data from Grasshopper and Radiance to predict daylighting metrics (sUDI and DGP), incorporating features such as tint states, sun direction vectors, and façade illuminance to enhance prediction accuracy. By leveraging the NSGA-II algorithm for multi-objective optimization, the study achieved a balanced improvement in lighting performance, with partitioned control increasing sUDI by 50%-100% under high-glare conditions while simultaneously reducing DGP. The optimization process, accelerated by the neural network as a proxy model, reduced computational time by 97%, demonstrating the feasibility of real-time daylight optimization. These findings highlight the effectiveness of partitioned control in enhancing natural light utilization and minimizing glare, offering a scalable solution for smart building applications.

Keywords. Electrochromic window, Multi-objective optimization, Partitional control, Neural network, Visual comfort

1. Introduction

1.1. BACKGROUND

Today, the majority of the global workforce spends a significant portion of their day in

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office environments, where lighting comfort plays a crucial role in health and productivity(Casini, 2018). Natural light, in particular, is considered a healthy light source with benefits for mood enhancement and memory improvement (Wright et al., 2013). The dynamic nature of natural light, which changes with weather and time, helps regulate circadian rhythms and address imbalances in the body (Kim & Choi, 2012). Furthermore, utilizing daylight in office spaces can help reduce building energy consumption and carbon emissions (Bashir et al., 2024; Esquivias et al., 2018).

However, daylighting presents the challenge of glare, which can reduce comfort and productivity. To fully harness the advantages of daylighting, measures to mitigate glare are essential. While solutions such as external shading devices and blinds can partially address glare issues (Liu et al., 2024; Zheng et al., 2024), research has shown that non-automated shading systems often fail to maintain an optimal shading position, leading to reduced utilization of natural light (Koo et al., 2010). Additionally, blinds may result in uneven illumination in work areas, which is detrimental to lighting uniformity in offices.

1.2. RESEARCH CONCERNING EC WINDOWS

In recent years, electrochromic windows (EC windows) have gained increasing attention as an innovative shading technology and a type of smart window. EC windows can actively regulate the transmittance of daylight and infrared light by adjusting their transparency, with a visible light transmittance (VLT) range of 60% to 1%. Commercial energy-saving EC glass typically operates in four states: bleached, two intermediate states, and fully tinted (Casini, 2018). By darkening the glass, EC windows can significantly reduce glare, enhancing visual comfort. Conversely, they can be bleached to maximize daylight penetration, improving indoor illuminance levels.

Research has demonstrated that EC windows can serve as alternatives to traditional shading systems for controlling solar radiation (Zinzi, 2006). Users have shown high acceptance of EC windows (Clear et al., 2006). Further studies highlight the importance of automated control strategies for optimizing the performance of EC windows (Casini, 2018). Early research explored overall control methods for EC windows, employing semi-automated strategies based on predefined rules to prevent glare (Jonsson & Roos, 2010). More recent findings suggest that integrating sensors to collect light-related data and calculating the Daylight Glare Index (DGI) for controlling glass tinting can substantially improve glare prevention accuracy (Detsi et al., 2020).

Recent studies have indicated that partitioned control of EC windows can balance natural daylight utilization and glare reduction. EC windows are often divided into two or three segments, such as upper-lower or upper-middle-lower panes, with each segment independently controlled (Fernandes et al., 2013; Sun et al., 2023). However, in these studies, EC windows was primarily treated as a tool for glare mitigation, without fully leveraging its potential to enhance workplane lighting comfort. Other research has optimized segmentation methods for EC windows, enabling glare reduction while expanding the effective use of natural light (Han et al., 2023).

1.3. RESEARCH GAP

Existing research predominantly focuses on overall control or pre-set control methods for EC windows, failing to meet the multi-objective requirements of optimizing natural light availability and glare control in shared office spaces with multiple users in real time. Therefore, it is necessary to develop real-time partitioned control methods for EC windows. Previous studies have primarily employed single-point simulation methods (assuming only one occupant in the space) to assess glare, lacking comprehensive methods to evaluate glare conditions for multiple occupants. While many studies use glare conditions as the sole indicator to assess the lighting comfort of offices, factors such as illuminance and uniformity of lighting in work areas also significantly influence users' overall lighting comfort.

To address these gaps, this study proposes a parametric model of an office space with multiple occupants. The office's windows are composed of six independently controlled EC glass panels. A neural network was trained with simulated parameters to enable rapid predictions of lighting performance. Using a multi-objective optimization approach, the study set the office space's lighting performance as the objectives to optimize the states of the EC glass panels, developing a real-time EC window control method.

In summary, the contributions of this study include the following:

- Development of a method for evaluating lighting comfort for multiple occupants in offices.
- Introduction of a neural network-based approach for rapid assessment of glare and daylight availability.
- Proposal of a real-time glass state control method based on outdoor environmental conditions using a single illuminance meter, aimed at optimizing the indoor lighting environment.

2. Methods

2.1. RESEARCH WORKFLOW

This study consists of four main parts: constructing a parametric model using Grasshopper, calculating lighting comfort parameters using Ladybug Tools and Radiance, training and validating a neural network based on PyTorch, and optimizing and validating the control logic using the Wallacei plugin, as shown in Figure 1.

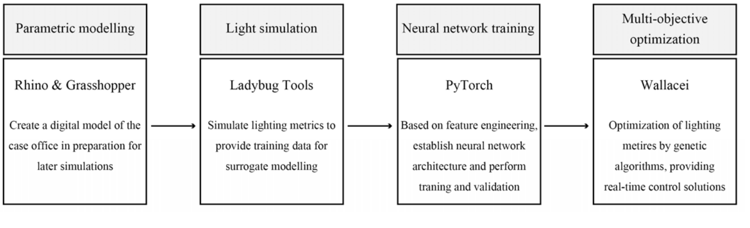

Figure 1. Research workflow diagram

Grasshopper is a parametric modelling software commonly used in the architectural field that allows designers to quickly adjust changes to the design by adjusting parameters(Eltaweel & Su, 2017). This facilitates this study to adjust the sunlight direction and the tint states of the EC windows conveniently. Ladybug can be inserted into grasshopper as a plug-into to help communicate with the building simulation software Radiance to simulate the lighting metrics(Turrin et al., 2012).

2.2. CONSTRUCTION OF THE PARAMETRIC MODEL

The study is based on a case located in Beijing, China, situated at 40°N latitude and an altitude of 55 m. Among China's five daylight climate zones (DCZs), Beijing falls within DCZ III. This indicates that the average annual natural daylight illuminance in Beijing ranges between 35-45 klx.

The office space under study, as shown in Figure 2, measures 5 m in width, 6 m in length, and 3.5 m in height, representing a typical office layout. The south-facing window is divided into six EC glass panes, each measuring 1 m in width and 0.8 m in height, with the windowsill positioned 0.8 m above the floor. The office accommodates two occupants, who are seated near the window along its side. This arrangement provides ample sunlight but increases the likelihood of glare under direct sunlight, potentially disrupting their work.

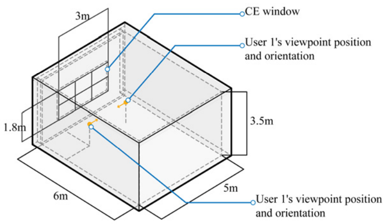

Figure 2. Model of the case study

The south-facing window is divided into a 2×3 grid of six identical EC glass panes, each individually controllable. The glass panes can transition among four transparency levels: 60%, 30%, 10%, and 1%.

2.3. METRICS CALCULATION

To comprehensively evaluate the comfort of the indoor lighting environment, Daylight Glare Probability (DGP) was selected as the metric for glare prevention. It was calculated based on the assumed working perspectives of two occupants, represented as DGP-E (facing east) and DGP-W (facing west). For sufficient illumination within the optimal range, spatial Useful Daylight Illuminance (sUDI) was used to describe the proportion of the office area with illuminance levels within the range of 300–3000 lux.

This study utilized the Ladybug Tools plugin on the Grasshopper platform in combination with Radiance software to simulate lighting metrics. To ensure the simulation parameters covered a wide range of time periods and sunlight angles, simulations were conducted on the 15th day of each month, at three specific times: 9:00 AM, 12:00 PM, and 3:00 PM, resulting in 36 simulation groups (12 months × 3 times).

For each group, 500 random states of EC glass panel configurations were generated, leading to a total of 18,000 simulations. The Colibri plugin was used to record both the input parameters and the simulation results.

2.4. NEURAL NETWORK TRAINING AND VALIDATION

A total of 18 input parameters were used to train the neural network. As shown in Figure 3, the first group consists of six parameters representing the tint states of the six EC glass panels, encoded as 0 for fully bleached, 3 for fully tinted, and 1 and 2 for intermediate states. The second group includes two parameters identifying which glass panel(s) intersect with the direct line of sight from the occupant to the sun, with values ranging from 0 to 5 for panels 0–5, and -1 if no panel intersects. The third group contains six parameters indicating the proportion of each panel's projection area on the work plane, calculated along the sun's direction, to reflect their relative influence on the work plane. The fourth group is a single parameter representing the façade illuminance at the given time, as outdoor light intensity significantly impacts work plane illuminance and glare. The fifth group consists of three parameters capturing the x, y, and z components of the sun's directional vector to assist the neural network in predicting work plane illuminance and glare.

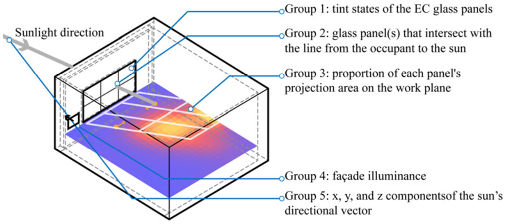

Figure 3. Data sources for each group of input parameters

The neural network model used in this study is a deep fully connected regression model consisting of six fully connected layers. The number of neurons in each layer decreases sequentially as follows: 256, 128, 64, 32, and 16. The final output layer matches the dimensions of the target variable. To stabilize and accelerate the training process, a Batch Normalization layer is added after each hidden layer. This normalizes intermediate feature distributions, thereby improving training efficiency.

The activation function employed is Leaky ReLU with a negative slope of 0.1, introducing nonlinearity to enhance the model's expressive capacity while mitigating the vanishing gradient problem. Additionally, Dropout layers are incorporated after each activation function to prevent overfitting and improve the model's generalization performance. The final output layer uses a linear activation function to generate regression predictions.

The training process optimizes the model using the Mean Squared Error (MSE) loss function, with the Mean Absolute Error (MAE) serving as an auxiliary evaluation metric. The optimizer used is AdamW with a learning rate of 0.001 and a weight decay coefficient of 1×10^{-5}, providing additional control over overfitting.

All simulated data are normalized and randomly split into training, validation, and test sets, accounting for 70%, 15%, and 15% of the total data, respectively. The neural network is trained for 400 epochs, with the model evaluated iteratively on the validation set. The epoch with the lowest MSE Loss on the validation set is selected as the optimal model for subsequent optimization.

2.5. CONTROL LOGIC OPTIMIZATION AND VALIDATION

2.5.1. Optimization Setup and Implementation

A surrogate model was deployed on the Grasshopper platform to perform real-time multi-objective optimization. The optimization aimed to maximize sUDI while minimizing DGP-W and DGP-E. The tint states of the six EC glass panels were used as design variables for optimization.

For the optimization algorithm, the Wallacei plugin in Grasshopper was employed, utilizing the NSGA-II algorithm to enhance performance. NSGA-II is an advanced multi-objective genetic algorithm capable of efficiently generating high-quality Pareto front solutions (Ghasemian & Ehyaei, 2018). NSGA-II improves traditional genetic algorithms by integrating non-dominated sorting, crowding distance, and elitism, ensuring both solution diversity and convergence (Deb et al., 2002). In this experiment, the optimization process was conducted over 20 generations, with each generation comprising 40 individuals.

2.5.2. Experimental Design

The optimization tests were conducted at 9:00, 12:00, and 15:00 during the spring equinox, summer solstice, autumn equinox, and winter solstice, aiming to evaluate the overall optimization performance across different times of the year (Sommese et al., 2024).

To validate the improvements in indoor lighting comfort provided by partitioned control of EC glass panels, a control group was set up with uniform tinting across all panels. In this setup, all panels shared the same tint level. Since the EC glass in this experiment supports four tint states, the control group had four feasible solutions. The performance of the control group was compared with that of the experimental group. This comparison involved analysing whether the solutions from the control group were dominated by those from the experimental group, and whether the experimental group provided consistently superior solutions across all performance metrics. This approach was used to demonstrate the advantages of partitioned control in enhancing indoor lighting comfort.

3. Results and Discussion

3.1. NEURAL NETWORK PERFORMANCE

As shown in figure 4, the optimal model was achieved at the 366th generation, with the MSE loss on the validation set recorded at 0.000194.

The predicted MSE losses for sUDI, DGP-W, and DGP-E were 0.000095, 0.000116, and 0.000149, respectively, with all three targets' prediction errors falling within acceptable ranges. The error distribution and regression analysis of the three targets further demonstrate the model's high reliability, with 99.94% of sUDI prediction errors within a 5% margin and 83.12% and 81.59% of DGP-W and DGP-E prediction errors having relative errors below 5%.

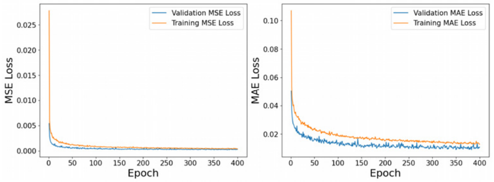

Figure 4. MSE Loss & MAE Loss over epochs

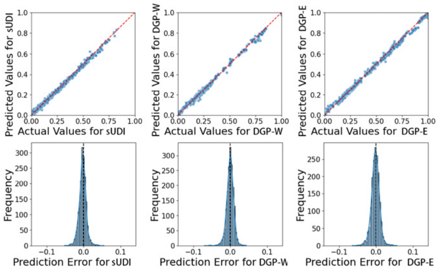

Figure 5. Residual regression and distribution

3.2. OPTIMIZATION CONTROL PERFORMANCE

3.2.1. Calculation Duration

Daylight simulations using Ladybug Tools and Radiance, even with GPU acceleration, require approximately 32 seconds per iteration. In contrast, predictions of sUDI and DGP parameters using the neural network take approximately 3 seconds per iteration. In an optimization task with a population size of 40 and 20 generations, numerical simulation-based calculations would take more than 7 hours to complete. However, using the neural network-based surrogate model reduces this time to approximately 40 minutes, representing a 97% reduction in computational time.

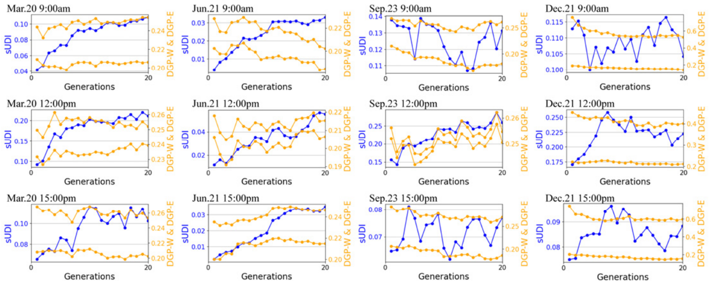

Figure 6. Mean values of performance objectives over optimization generations

Figure 6 illustrates the average values of the three performance objectives (sUDI, DGP-W, and DGP-E) across 40 individuals per generation as the optimization progresses. All three objectives improved in favorable directions during optimization: sUDI values increased, and DGP values were effectively constrained. However, in most cases, the average improvement in the final five generations tended to stabilize, suggesting that reducing the number of optimization generations in practical applications could further shorten computation time. This substantial improvement in computational speed makes real-time daylight optimization achievable.

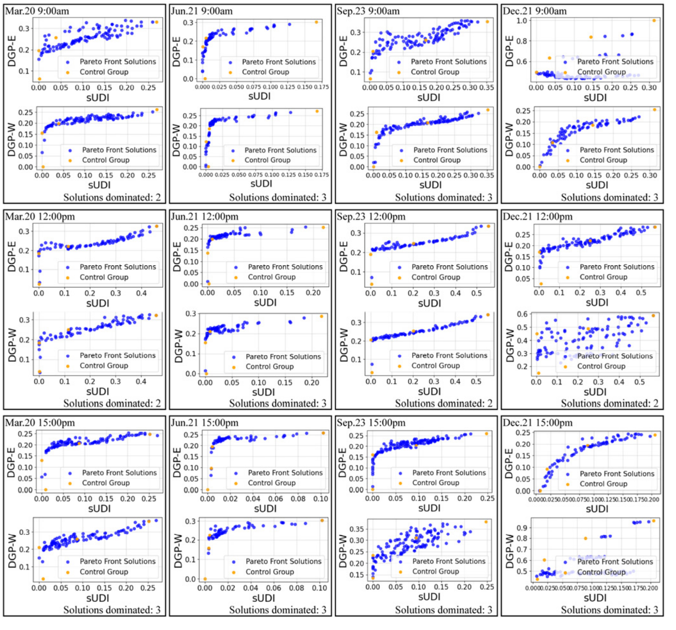

Figure 7. Scatter plot of experimental and control group results

3.2.2. Performance Gains from Partitioned Control

Compared to controlling the entire EC window uniformly, partitioned control significantly enhances the flexibility of managing the indoor lighting environment. In the 12 selected comparison scenarios, Pareto-optimal solutions were able to dominate 2–3 control group solutions in most cases. This result demonstrates that the partitioned control approach achieves a better balance across all performance objectives (sUDI, DGP-W, and DGP-E) in the majority of scenarios. Solutions not dominated by the Pareto front represent extreme cases, characterized by the EC windows being fully tinted. In such scenarios, natural daylight is almost entirely blocked, reducing the sUDI to its lowest value but simultaneously eliminating glare issues, resulting in optimal DGP-W and DGP-E values. However, such solutions are impractical for real-world office settings due to the lack of usable natural light.

Partitioned control proves especially effective in scenarios with pronounced glare, such as during early morning or late afternoon, especially during the winter months. For instance, on December 21 at 15:00 PM, using uniform control and setting the EC windows to intermediate tint levels resulted in DGP-W values of 0.8 and 0.6, indicating severe glare. In contrast, with partitioned control, the DGP-W value was reduced to approximately 0.5, while the sUDI increased by 50%–100%. This demonstrates that partitioned control can effectively suppress glare while simultaneously improving daylight availability in such challenging conditions, while uniform control cannot address the contradictions between multiple objectives.

4. Conclusions

This study, conducted on the Grasshopper platform using the Ladybug plugin integrated with Radiance, evaluated the daylight availability and visual comfort for multiple users in an office space. A neural-network-based method was developed to rapidly assess daylight comfort, and, leveraging this method in combination with a genetic algorithm, feasible control strategies for EC glass windows were proposed.

The results indicate that the combined evaluation method of sUDI and DGP at the workstations of two users effectively assesses the lighting comfort of office spaces. Issues such as overly bright or dark workplane or glare were successfully identified.

The neural network trained on simulation data demonstrated high reliability in predicting the comfort level of office lighting environments. Moreover, it significantly accelerated the evaluation process, making real-time control of EC windows feasible.

Compared to uniform control of EC windows, partitioned control proved to be more flexible, achieving a better balance between maximizing daylight availability on work surfaces and minimizing glare.

The findings suggest that the proposed methodology is a viable approach for evaluating daylight availability and visual comfort in office spaces, and the proposed partitioned real-time control method for EC windows can significantly enhance the indoor lighting environment comfort. Future research may explore integrating other techniques, such as convolutional computing, to further improve prediction accuracy.

References

Bashir, F. M., Dodo, Y. A., Mohamed, M. A. S., Norwawi, N. M., Shannan, N. M., & Afghan, A. A. (2024). Effects of natural light on improving the lighting and energy efficiency of buildings: Toward low energy consumption and CO2 emission. *International Journal of Low-Carbon Technologies*, *19*, 296–305. https://doi.org/10.1093/ijlct/ctad130

Casini, M. (2018). Active dynamic windows for buildings: A review. *Renewable Energy*, *119*, 923–934. https://doi.org/10.1016/j.renene.2017.12.049

Clear, R. D., Inkarojrit, V., & Lee, E. S. (2006). Subject responses to electrochromic windows. *Energy and Buildings*, *38*(7), 758–779. https://doi.org/10.1016/j.enbuild.2006.03.011

Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, *6*(2), 182–197. https://doi.org/10.1109/4235.996017

Detsi, M., Manolitsis, A., Atsonios, I., Mandilaras, I., & Founti, M. (2020). Energy Savings in an Office Building with High WWR Using Glazing Systems Combining Thermochromic and Electrochromic Layers. *Energies*, *13*(11), Article 11. https://doi.org/10.3390/en13113020

Eltaweel, A., & Su, Y. (2017). Parametric design and daylighting: A literature review. *Renewable and Sustainable Energy Reviews*, *73*, 1086–1103. https://doi.org/10.1016/j.rser.2017.02.011

Esquivias, P. M., Moreno, D., & Navarro, J. (2018). Solar radiation entering through openings: Coupled assessment of luminous and thermal aspects. *Energy and Buildings*, *175*, 208–218. https://doi.org/10.1016/j.enbuild.2018.07.021

Fernandes, L. L., Lee, E. S., & Ward, G. (2013). Lighting energy savings potential of split-pane electrochromic windows controlled for daylighting with visual comfort. *Energy and Buildings*, *61*, 8–20. https://doi.org/10.1016/j.enbuild.2012.10.057

Ghasemian, E., & Ehyaei, M. A. (2018). Evaluation and optimization of organic Rankine cycle (ORC) with algorithms NSGA-II, MOPSO, and MOEA for eight coolant fluids. *International Journal of Energy and Environmental Engineering*, *9*(1), 39–57. https://doi.org/10.1007/s40095-017-0251-7

Han, S., Sun, Y., Wang, W., Xu, W., & Wei, W. (2023). Optimal design method for electrochromic window split-pane configuration to enhance building energy efficiency. *Renewable Energy*, *219*, 119405. https://doi.org/10.1016/j.renene.2023.119405

Jonsson, A., & Roos, A. (2010). Evaluation of control strategies for different smart window combinations using computer simulations. *Solar Energy*, *84*(1), 1–9. https://doi.org/10.1016/j.solener.2009.10.021

Kim, K.-S., & Choi, A. (2012). *A Preliminary Study using Literature Review on the Lighting Design Considering the Circadian Rhythm*. https://www.semanticscholar.org/paper/A-Preliminary-Study-using-Literature-Review-on-the-Kim-Choi/0d6bad97a1f3efc3268430165089d806994b26c2

Koo, S. Y., Yeo, M. S., & Kim, K. W. (2010). Automated blind control to maximize the benefits of daylight in buildings. *Building and Environment*, *45*(6), 1508–1520. https://doi.org/10.1016/j.buildenv.2009.12.014

Liu, P., Hussein, A. A., Alizadeh, A., Baghoolizadeh, M., Yan, G., Zargari Pour, M., & Alkhalifah, T. (2024). Multi-objective optimization of office building envelopes properties and Venetian blinds using NSGA-II to save energy consumption and enhance thermal and visual comfort. *Case Studies in Thermal Engineering*, *64*, 105484. https://doi.org/10.1016/j.csite.2024.105484

Sommese, F., Hosseini, S. M., Badarnah, L., Capozzi, F., Giordano, S., Ambrogi, V., & Ausiello, G. (2024). Light-responsive kinetic façade system inspired by the *Gazania* flower: A biomimetic approach in parametric design for daylighting. *Building and Environment*, *247*, 111052. https://doi.org/10.1016/j.buildenv.2023.111052

Sun, Y., Li, Y., Xu, W., Wang, W., Wei, W., & Zhang, C. (2023). A glare predictive control strategy for split-pane electrochromic windows: Visual comfort and energy-saving assessment. *Renewable Energy*, *218*, 119259. https://doi.org/10.1016/j.renene.2023.119259

Turrin, M., Von Buelow, P., Kilian, A., & Stouffs, R. (2012). Performative skins for passive climatic comfort. *Automation in Construction*, *22*, 36–50. https://doi.org/10.1016/j.autcon.2011.08.001

Wright, K. P., McHill, A. W., Birks, B. R., Griffin, B. R., Rusterholz, T., & Chinoy, E. D. (2013). Entrainment of the Human Circadian Clock to the Natural Light-Dark Cycle. *Current Biology*, *23*(16), 1554–1558. https://doi.org/10.1016/j.cub.2013.06.039

Zheng, Y., Wu, J., Zhang, H., Lin, C., Li, Y., Cui, X., & Shen, P. (2024). A novel sun-shading design for indoor visual comfort and energy saving in office space in Shenzhen. *Energy and Buildings*, 115083. https://doi.org/10.1016/j.enbuild.2024.115083

Zinzi, M. (2006). Office worker preferences of electrochromic windows: A pilot study. *Building and Environment*, *41*(9), 1262–1273. https://doi.org/10.1016/j.buildenv.2005.05.010

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