Mediating Heat and Light: a Visualization-based Tool for the Analysis and Development of Dynamic Shading Control Protocols

Luis Santos[1], Christiane Berger[1]

[1]Department of Architecture, Design and Media Technology, Aalborg University, Aalborg, Denmark
lfds@create.aau.dk; chbe@create.aau.dk

Abstract. Operating Dynamic Shading Systems (DSS) is often an ill-defined task since it requires pondering design criteria that are often at odds with each other, e.g., visual comfort and building energy-efficiency. This work proposes a co-simulation approach to efficiently analyze the impact of controlling DSS in the daylight and the energy performance of indoor spaces to address this difficulty. The proposed workflow uses advanced daylight and building energy simulation tools to enable comprehensive comparative analyses by post-processing simulation output through queryable visualizations. Additionally, the approach allows designers to create or refine DSS control strategies by manipulating visualizations of hourly DSS operation schedules. The authors tested the workflow in designing and controlling a DSS in three different climates: a temperate, a hot, and a very cold climate. The proposed approach delivered valuable insights about the complex tradeoffs that emerge from controlling DSS.

Keywords: Building Performance, Solar Heat Gain, Visual Comfort, Building Operation

1 Introduction

Previous research has shown a significant impact of windows on buildings' heating and cooling demand (Grynning et al., 2013). Hence, it has been suggested that the application of external shading elements has a critical role in reducing buildings' cooling loads and controlling solar gains in buildings (Nielsen et al., 2011). Moreover, shading elements can potentially optimize daylight performance and ensure visual comfort in indoor spaces (Konstantzos et al., 2015), particularly Dynamic Shading Systems (DSS). DSS are shading systems composed by moveable parts that are controlled either directly by a building occupant or an intelligent system in response to different environmental stimuli in favor of comfort and energy efficiency (Al-Obaidi et al., 2019). Thus, DSS can effectively improve buildings' energy efficiency as well as occupants' comfort by means of controlling daylight (i.e., providing adequate illuminance levels and avoiding glare) and solar radiation in an efficient manner. However, designing and controlling DSS is difficult as it involves design criteria that are often at odds with each other, such as energy-efficiency and visual comfort. Currently DSS control protocols either aims towards energy efficiency in buildings (Huo et al., 2021) or the mitigation of visual discomfort (Luo et al., 2020). Hence, little research has been done on assessing the impact of operating DSS using standard shading control schemes for visual comfort (IESNA, 2012) in building energy performance and vice-versa. The lack of research on this topic is related either to the difficulty of spatially computing visual discomfort or conducting onerous lab or field studies. The subsequent section discusses exemplary instances of related work to this research field.

1.1 Related Work

The work of Tschakrow and Hellwig (2015) is one of the few that thoroughly analyzed the trade-offs between energy and daylight in DSS control optimization. However, the research focused solely on schools during summer and used limited predictive methods to assess visual comfort. De Vries et al. (2019) studied sensor selection for a sun-tracking control strategy for indoor roller blinds via a case study. The suggested strategy considered both daylight and energy performance and resulted in an overall improvement of building energy-efficiency. Recent developments in daylighting simulation (Jones and Reinhart, 2019) allowed the quick prediction of advanced glare metrics (i.e., Daylight Glare Probability), therefore facilitating the study of controlling DSS using either building energy performance or visual comfort criteria.

Moreover, in current standards, guidelines, and codes related to the visual domain, shading control schemas for visual comfort are commonly included. For example, the LM-83 standard (IESNA, 2012) includes DSS operation protocols in the calculation of Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE). The control protocol, known as the 2% rule, determines that a DSS should be deployed if 2% of the occupied area receives ≥1000 lux caused by direct beam (direct sunlight). In most standards related to the thermal domain, DSS control is provided in a rather marginal manner. Typically, minimum and maximum thresholds are related to solar radiation (W/m2), illuminance levels (lux), temperature (°C/°F), and cooling load rates (W or kW).

Current building simulation tools, such as ClimateStudio, use DSS control schemes defined in sustainable rating systems, like BREEAM and LEEDv4. Such control schemes are based on international daylight standards and norms, e.g., EN 17037 (CEN, 2021) and LM-83 (IESNA, 2012). For example, in LEEDv4, ClimateStudio applies the 2% rule as a default for DSS operation. Regarding building energy software, there is no embedded control protocols for DSS, leaving up to the energy modeler their definition.

1.2 Research Goals

Given the lack of integration between DSS control schemes designed either for daylight or energy-efficiency, this study aims to: (i) observe in which conditions current shading protocols conflict, and (ii) develop a computational approach that supports designers to examine the impact of DSS control schemes on daylight and building energy performance and specify custom DSS operation protocols. To that end, the proposed approach aims to assess the DSS impact on daylight and building energy performance via on-demand visualizations.

2 Methodology

This work imparted two phases: (i) development of the proposed design and analysis framework, and (ii) framework application. In the first phase, we developed and implement a framework for assessing the annual energy and daylight performance of DSS through a range of queryable visualizations. The second phase emulated a potential use of the framework and reflects on the complex tradeoffs between daylight and thermal performance of buildings while specifying DSS control protocols.

2.1 Design and Analysis Framework

The framework combines whole building energy simulation with climate-based daylight analysis in a seamless modeling and analysis workflow for the Rhino/Grasshopper Computer-Aided Design ecosystem. The framework implementation integrates ClimateStudio and Honeybee, popular front ends to Radiance (LBNL, 2022) and EnergyPlus (DOE, 2022), as well as custom-tailored Python programs that extend their modeling and visualization capabilities. The framework articulates four modules: the modeling, simulation, visualization, and control schedule design modules.

In the modeling module, the user describes the space to be analyzed, i.e., the geometry and the optical and thermal properties of static building elements and DSS. The user can either manually or parametrically model all design components. This module is supported by different ClimateStudio and Honeybee functionalities and a custom-developed program that interfaces with Radiance's *genblinds* and *genbsdf* routines to generate bidirectional scattering distribution functions (BSDF) to parametrically describe DSS based on venetian blinds. The BSDF describe how light is transmitted and scattered by the DSS.

The simulation module processes the previously described model to automatically simulate the annual daylight and energy performance of three scenarios: (i) baseline, i.e., without any DSS, (ii) the daylight-based (Db) shade control, where a control strategy solely based on daylight criteria controls the DSS, and (iii) the thermal-based (Tb) shade control, which applies thermal criteria to control operable shades. Although the user can specify the Db and

Tb control protocols, the default Db shade control applies the 2% rule defined in LM-83-12 standard (IESNA, 2012). Regarding the Tb shade control, the default protocol deploys shades whenever the incident irradiance in the window group is above 200 W/m^2, and there is a significant cooling load rate (0.5 KW). EnergyPlus and Radiance support the calculations performed in this module.

The visualization module enables users to compare simulation results through bar charts and paired queryable hourly heatmaps. The bar charts compare the annual performance of the different scenarios using different energy end-uses, sDA, and ASE results. They also report on mismatch events (i.e., hours where the different control strategies diverge) and their type. Additionally, users can request, pair, and stack hourly heatmaps of several output data on demand including: (i) hourly cooling and heating loads, (ii) windows transmitted irradiance, (iii) shades operation schedule, and (iv) labeled mismatch events.

Finally, the control schedule design module allows designers to specify alternative control schedules for the modeled DSS. This module supports the development of control strategies either from scratch or by editing Db or Tb shade controls. After prompting the new schedule, the framework assesses its impact on energy and daylight performance using modules 2 and 3.

2.2 Framework Application

We tested the proposed analysis and design workflow in a simple south-facing test cell in three locations: (i) Oakland, a warm/temperate climate, (ii) Phoenix, a hot climate, and (iii) Umeå, a very cold climate. In each location, we tested three blind angles in an equally spaced venetian blind DSS: (i) Tilt 0°, (ii) Tilt 30°, and Tilt 60°. The tilt angle follows the WINDOW software convention, where 0° is perpendicular to the window and positive tilts are in the counter-clock direction. The slats' depth and spacing are 0.1m.

Figure 1 and Table 1 describe the test cell's optical and thermal properties. The optical properties of the different surfaces are fixed. However, the assumed thermal transmittance (U-value) changes depending on location by following the ASHRAE guidelines for mass construction types in different ASHRAE climate zones. Hence, for Oakland, we assigned the construction assemblies for climate zone 3 (warm), for Phoenix, the ones specified for climate zone 2 (hot), and for Umeå, the ones recommended for the most similar ASHRAE climate zone, 7 (very cold).

Concerning building energy simulations, the test cell consists of a single thermal zone that uses an ideal loads air system as its heating, ventilation, and air conditioning (HVAC) system. The cooling thermostat was set to 24°C while the heating to 21°C. Regarding the annual climate-based daylight simulations, the illuminance threshold for sDA calculations is 300 lux. The design criteria for sDA and ASE is sDA ≥ 50% and ASE ≤ 20% of the occupied area. All simulations used hourly data of each location's typical meteorological year

(TMY) file. The shade control protocols were the default ones described in the previous section.

The framework's application imparted two stages. The first stage compared overall data on energy, daylight, and divergency of shade operation modes. Based on the discussion of the first stage results, the second stage entailed a thorough hourly comparison. The pairing of queryable heatmaps supported such comparison, detailed analysis, and even the hypothetical development of new control schedules for the proposed DSS in this stage.

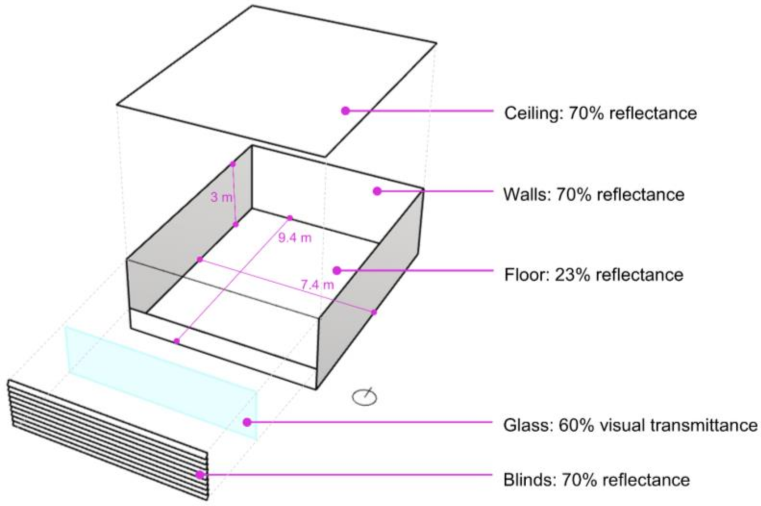

Figure 1. Exploded axonometric of the south-facing test cell labelled with surfaces optical properties (i.e., reflectance and visual transmittance) for all locations.

Table 1. U-values for external wall, roof, glass, and floor.

Location	U-values in (W.m^{-2}.K^{-1})			
	Ext. wall	U_{roof}	U_{glass}	U_{floor}
Oakland, CA	0.60	0.21	1.66	0.52
Phoenix, AZ	0.76	0.21		
Umeå, Sweden	0.37	0.15		

3 Results

This section presents the results of the two stages of our framework application. All the results are further discussed in the discussion section.

3.1 First Stage of Application

The following compares different combinations of tilt angles and DSS control protocols, i.e., scenarios, per location. Figures 2, 4, and 6 provide an overview of annual energy consumption, sDA, and ASE with and without DSS deployment. Figures 3, 4, and 7 measure the percentage of change in different energy end-uses of each scenario relative to the base case.

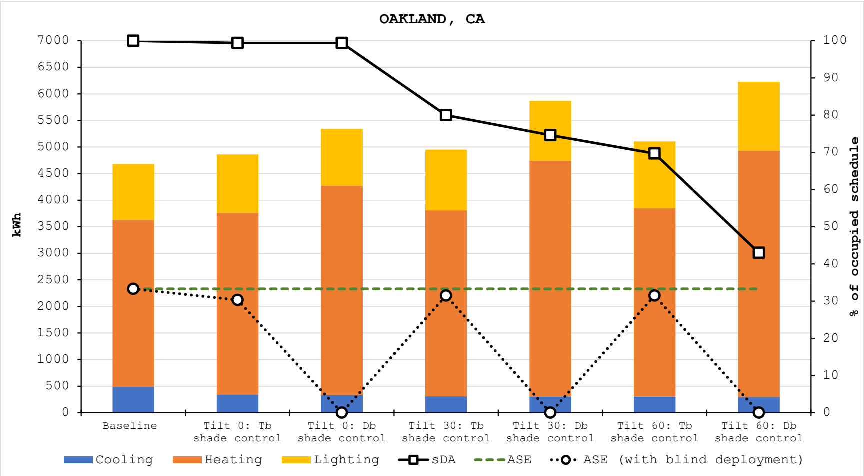

Figure 2. Energy loads per end-use (kWh), sDA, and ASE (with and without blind deployment) measured in percentage of occupied schedule for each shading strategy in Oakland, CA.

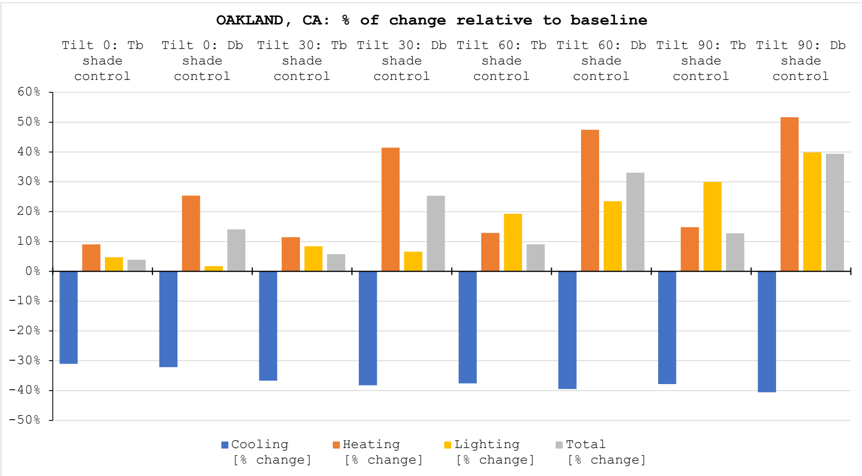

Figure 3. Percentage of change in relation to the baseline scenario for each shading strategy in Oakland, CA.

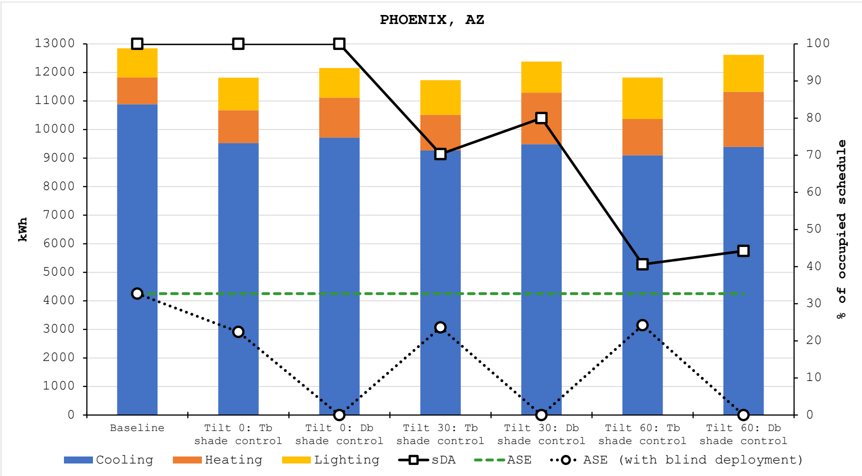

Figure 4. Energy loads per end-use (kWh), sDA, and ASE (with and without blind deployment) measured in percentage of occupied schedule for each shading strategy in Phoenix, AZ.

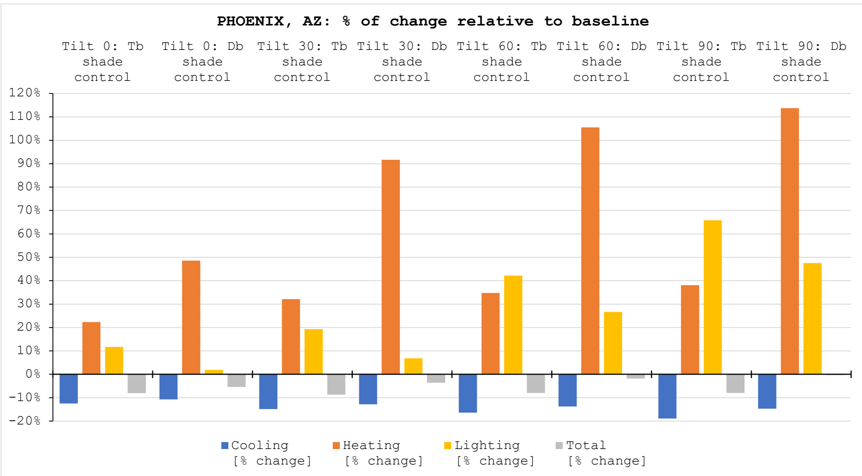

Figure 5. Percentage of change in relation to the baseline scenario for each shading strategy in Phoenix, AZ.

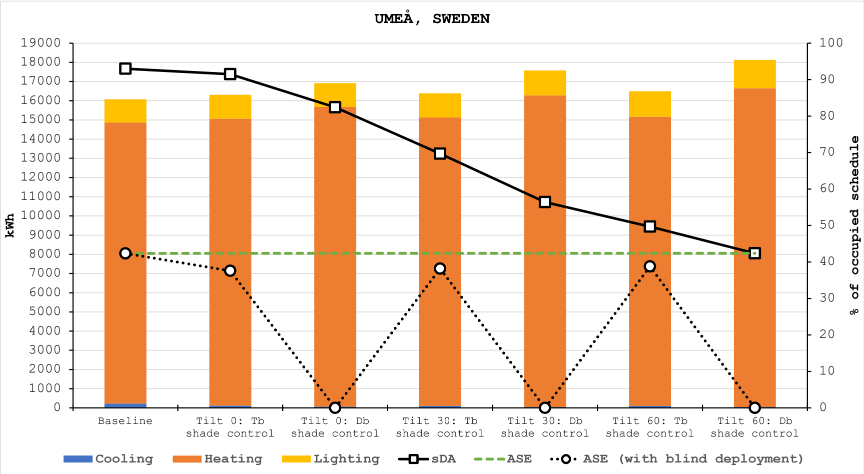

Figure 6. Energy loads per end-use (kWh), sDA, and ASE (with and without blind deployment) measured in percentage of occupied schedule for each shading strategy in Umeå, Sweden.

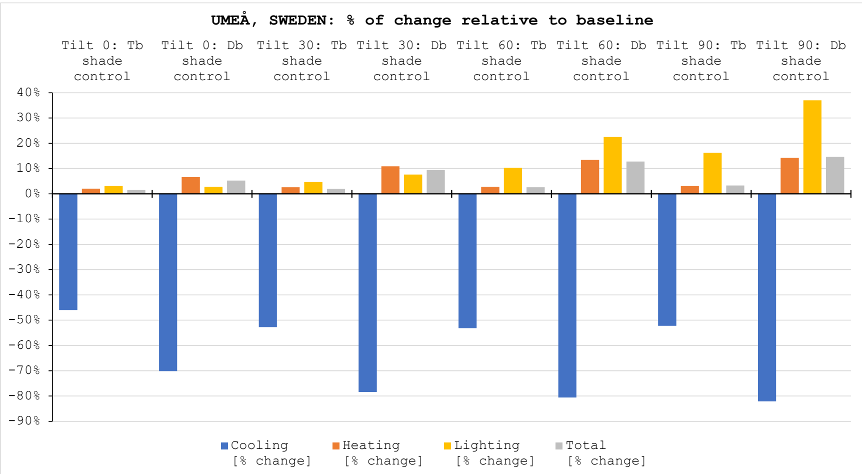

Figure 7. Percentage of change in relation to the baseline scenario for each shading strategy in Umeå, Sweden.

Figures 8 and 9 measure the misalignment of Db and Tb DSS control strategies for the following selected tilts: 0° for Oakland and Umeå, and 30° for Phoenix. Tilt selection was based on their performance, as argued in the discussion section. Figure 8 plots absolute and relative mismatching events, i.e., hours when the two control protocols diverge. Figure 9 maps the mismatching events into four categories: (1) Db shade protocols blocks useful solar heat gains (SHG), (2) Tb shade control blocks view, (3) Tb shade control potentially allows visual discomfort, and (4) Db shade control allows unwanted SHG.

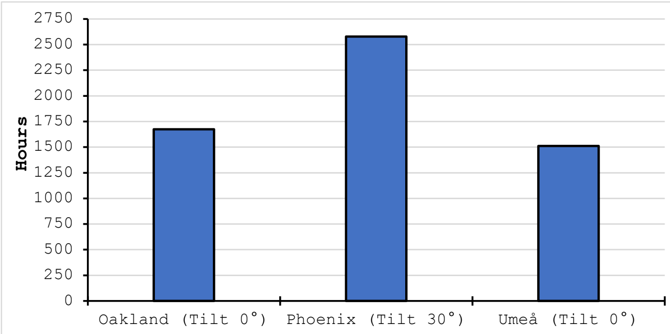

Figure 8. Total number of mismatching control events.

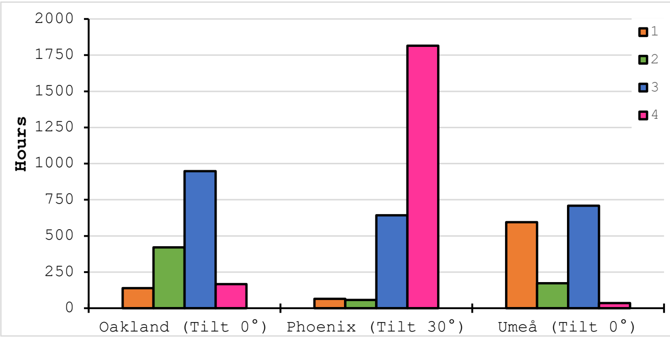

Figure 9. Distribution of mismatching control events type. The mismatching events legend key is as follows: 0 – no mismatch, 1 – Db shade control blocks useful SHG, 2 – Tb shade control blocks view, 3 – Tb shade control potentially allows visual discomfort, 4 – Db shade control allows unwanted SHG.

3.2 Second Stage of Application

Based on the information provided by the previous charts, users could use the framework to perform detailed hourly-based analysis. Due to space constraints, we only present the results of Umeå since it is the location where the Tb and Db shade control strategies are most conflicting. Figure 10 stacks three queryable heatmaps. The top two display the Tb and Db operation schedules, while the bottom one shows the mismatch of the above schedules. Figure 11 shows how the user can use the information provided by Figure 10 to improve one of the control strategies, in this case, the Db one, by prompting periods to be excluded or added. Compared with the Db control scheme, the new control schedule reduced the total annual heating load by 2.5% and overall energy consumption by 2% while maintaining acceptable sDA and ASE levels.

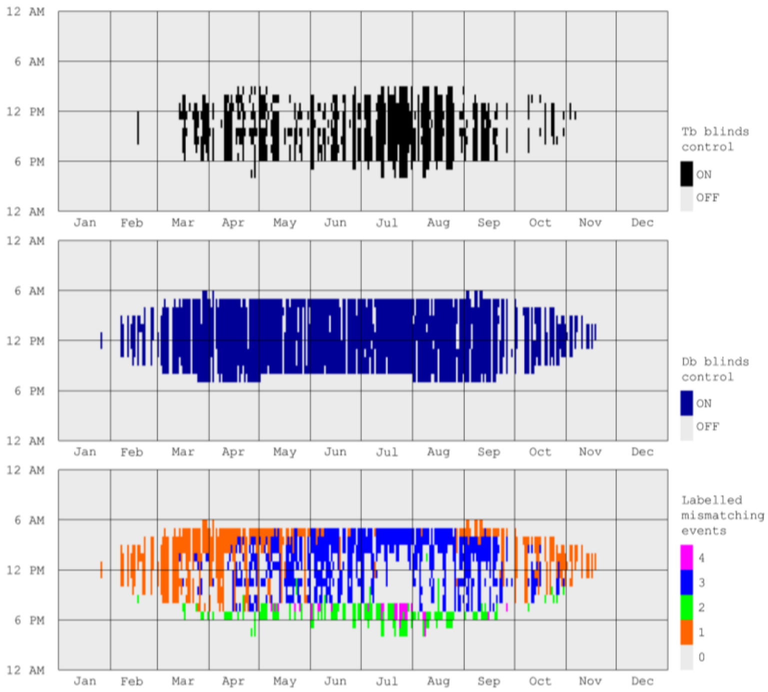

Figure 10. Hourly analysis of Tb and Db shade control strategies and their mismatching event type for Umeå, Sweden. The mismatching events legend key is as in Figure 9.

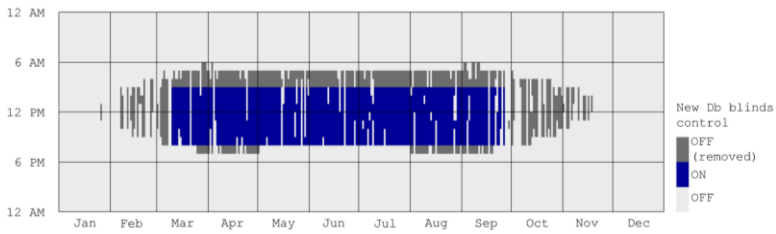

Figure 11. New shade control schedule designed for Umeå based on the Db shade control strategy derived for the same location.

4 Discussion

Figures 2 through 7 provide critical information about the most appropriated tilt angle for each location. The figures show that the DSS deployment using the Db and Tb control protocols significantly reduces cooling loads in all locations. Nevertheless, in Oakland and Umeå, such reduction does not offset the resulting increase in heating loads (Figures 2, 3, 6, and 7). Therefore, using

DSS for visual comfort purposes should impact as little as possible overall building energy performance. In the case of Oakland and Umeå, DSS with a blind tilt of 0° are the ones that least impact energy performance while yielding acceptable ASE and sDA scores. Figures 4 and 5 show that DSS deployment always results in overall energy reduction in Phoenix. Figure 5 indicates that the DSS with a blind tilt of 30° yields the most significant potential for energy savings in Phoenix. Hence, for Oakland and Umeå, the selected DSS blind tilt was 0°, while in Phoenix, it was 30°.

After selecting DSS' blind tilts, the proposed workflow compared the Tb and the Db control strategies to assess the benefits and limitations of using one over the other. Figure 8 shows that the two control strategies diverge in many hours. In Phoenix, using the Db control strategy would significantly increase cooling loads due to the admission of unwanted SHG (Figures 4, 5, and 9). An hourly analysis would show that most mismatching events occur during the cooling season when the sun altitude is higher and seldom causes visual discomfort. Thus, the designer could custom tailor a control strategy that adjusts the Db schedule to deploy the DSS only in the morning and evening summer hours. If we conduct an hourly analysis in Oakland, it is possible to reach to a similar conclusion (Figure 9).

In Umeå, the mismatch is due mainly to two competing factors: harvesting SHG and minimizing visual discomfort (Figure 9). In fact, the Db and Tb control strategies are often at odds mostly because the Db control strategy blocks SHG, which would reduce heating loads, while Tb allows it. Unfortunately, the hours of useful SHG yield a high potential for visual discomfort. Figure 10 presents the hourly comparative analysis of the two control strategies for this location. It shows several potential periods where the Db control strategy could allow the admittance of SHG to reduce heating loads with minimal impact on visual comfort. Such periods include the early hours of the annual occupied schedule, the period of October through December, and January through early March. Figure 11 illustrates the use of the proposed workflow to redefine the Db control schedule by excluding such periods. Compared with the original Db control scheme, the new DSS control strategy for Umeå reduced by 2.5% annual heating loads and by 2% the overall building energy consumption while scoring an sDA of 88% and maintaining an ASE < 20%.

5 Conclusion

This paper presents a new approach based on co-simulation for efficiently analyzing the tradeoffs of controlling DSS either for daylight or energy conservation in buildings. The application of the system shows that it can automatically simulate the daylight and energy performance of different DSS control strategies and provide useful on-demand visualizations to support analysis and design processes. The queryable visualizations inform about the convergence and divergence of diverse DSS operation modes, their causes, and potential opportunities for better integration. The framework can also be used to create or refine DSS control schedules. Future work will expand the approach by including annual DGP and testing it in more complex examples.

References

Al-Obaidi,K. M., & Al-Marasni, S. W. (2019). Dynamic shading systems: A review of design parameters, platforms and evaluation strategies. *Automation in Construction, 102,* 195-216. https://doi.org/10.1016/j.autcon.2019.01.014

De Vries, S., Loonen, R., & Hensen, J. (2019). Sensor Selection and Control Strategy Development Support for Automated Solar Shading Systems Using Building Performance Simulation. *Proceedings of BS2019, Rome, Italy*, 4855–4862.

CEN. (2021). *EN 17037:2018+A1:2021 Daylight in buildings*.

DOE. (2022). EnergyPlus (version 9.6). https://energyplus.net/

Grynning, S., Gustavsen, A., Time, B., & Jelle, B. P. (2013). Windows in the buildings of tomorrow: Energy losers or energy gainers? *Energy and Buildings*, *61*, 185–192. https://doi.org/10.1016/j.enbuild.2013.02.029

Huo, H., Xu, W., Li, A., Lv, Y., & Liu, C. (2021). Analysis and optimization of external venetian blind shading for nearly zero-energy buildings in different climate regions of China. *Solar Energy*, *223*, 54–71. https://doi.org/10.1016/j.solener.2021.05.046

IESNA. (2012). *LM-83-12 IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*. New York, NY, USA: IESNA Lighting Measurement. ISBN: 978-0-87995-272-3

Jones, N. L., & Reinhart, C. F. (2019). Effects of real-time simulation feedback on design for visual comfort. *Journal of Building Performance Simulation*, *12*(3), 343–361. https://doi.org/10.1080/19401493.2018.1449889

Konstantzos, I., Tzempelikos, A., & Chan, Y.-C. (2015). Experimental and simulation analysis of daylight glare probability in offices with dynamic window shades. *Building and Environment*, *87*, 244–254. https://doi.org/10.1016/j.buildenv.2015.02.007

Luo, Z., Sun, C., & Dong, Q. (2020). A daylight-linked shading strategy for automated blinds based on model-based control and Radial Basis Function (RBF) optimization. *Building and Environment*, *177*, 106854. https://doi.org/10.1016/j.buildenv.2020.106854

Nielsen, M. V., Svendsen, S., & Jensen, L. B. (2011). Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. *Solar Energy*, *85*(5), 757–768. https://doi.org/10.1016/j.solener.2011.01.010

LBNL. (2022). Radiance (version 5.4 a). http://radsite.lbl.gov/

Tschakrow, E., & Hellwig, R. T. (2015). *Comparison of control strategies of venetian blinds regarding visual and thermal comfort in summer in classrooms.* Healthy Buildings Conference Europe, 18-20 May 2015, Eindhoven, The Netherlands. Loomans, M. et al. (Eds.).