EXPLORING THE ENERGY PERFORMANCE OF SIMULATION-POWERED LIGHTING AND SHADING SYSTEMS CONTROLS IN BUILDINGS

Ardeshir Mahdavi and Sokol Dervishi
Department of Building Physics and Building Ecology
Vienna University of Technology, Vienna, Austria

ABSTRACT
This paper compares the performance of a predictive simulation-supported lighting control system with four conventional approaches. All five options are virtually implemented and tested in an office building. The performance comparison considers electrical energy use for lighting as well as visual comfort criteria. The results of the virtual implementation of these scenarios demonstrate the significant potential of the simulation-assisted lighting systems control method toward reducing electrical energy use for lighting in office buildings, while offering preferable visual performance.

INTRODUCTION
Advanced lighting systems and associated optimal control strategies could contribute not only to reduction of luminaires' electrical energy use, but also reduce buildings' cooling energy demand. In this context, the present contribution specifically focuses on the energy efficiency implications of a computationally-based energy performance analysis of a predictive simulation-supported approach to lighting systems control in buildings. Using real-time sensing and embedded numeric lighting simulation capability in the control logic, this system can dynamically control the position of window blinds and the status (on/off, dimming level) of the luminaires.

In the present contribution, we not only expand and substantiate previous descriptions and implementations of this simulation-assisted control strategy (Mahdavi 2008, 2001), but we address in detail its energy efficiency potential in the lighting control domain. Toward this end, five different control scenarios were considered and virtually implemented in an existing office building. The first scenario considers the continuous use of luminaires during the office hours, independent of daylight. The electrical lights are switched on during the working hours and no shading is deployed. The second scenario is similar to the first. However, in this case, shades are deployed according to a fixed schedule. The third scenario involves the use of daylight-responsive dimmable luminaires to achieve target task illuminance. The fourth scenario is similar to third, but with shades deployed according to a fixed schedule. The fifth scenario uses simulation-assisted lighting and shading systems control (described below). The performance of these scenarios was compared in view of electrical energy use for lighting as well as visual comfort criteria.

Generally speaking, the simulation-assisted control provides more advanced options to maintain visual comfort: not only a larger number of performance indicators (such as multiple indices for glare and lighting distribution uniformity) can be integrated in the control process, but also the weights associated with these indicators can be dynamically adjusted by the users to account for changes in operational requirements. The virtual implementation of the above mentioned scenarios allows specifically for the computational exploration of the potential of the simulation-assisted lighting systems control method toward reducing electrical energy use for lighting in office buildings.

APPROACH
The simulation-assisted control method
The predictive simulation-assisted lighting control method works as follows. At time \( t_i \), a sub-set of the control state space (i.e., the corpus of all possible positions of the relevant control devices, such as shades and luminaires) is taken into considerations as possible candidates for the control state at the future time point \( t_{i+1} \). To create this subset, different methods can be used. For the purposes of the present study, a combination of greedy search and stochastic jumps was applied (Mahdavi 2008). The reduced set of options is then virtually enacted for the future time point using a lighting simulation application. In the present study, the application RADIANCE (Ward Larson and Shakespeare, 2003) is deployed. In previous publications, we reported on our encouraging experiences in view of validation (and calibration) of this simulation application toward reliable prediction of indoor illuminance and luminance levels (Mahdavi and Dervishi 2009).

Using the lighting simulation engine, the values of multiple building performance indicators (e.g., horizontal illuminance at various locations in the space, illuminance distribution uniformity, different glare indicators, and electrical energy use for lighting) can be computed and used for the identification of the most desirable control action. In the present case, we focus on the following...
performance indicators: mean workstation horizontal illuminance ($E$), unified glare ratio ($G$) for a reference position in the room, and required power ($W$) for electrical lighting. The numeric values of these indicators can be translated into values of corresponding preference functions (see illustrative examples of Figures 1 to 3, with $P = 1$ indicating highest and $P = 0$ lowest preference). These in turn can be weighted in terms of an aggregate utility function ($UF$). $UF$ can be applied to compare and rank alternative control options (see Equation 1):

$$UF = \omega_E \cdot P_E + \omega_W \cdot P_W + \omega_G \cdot P_G \quad (1)$$

In this equation, $P_E$, $P_W$ and $P_G$ are the preferences for illuminance ($E$), electrical power ($W$) and glare index, ($G$). The corresponding weights are represented by $\omega_E$, $\omega_W$, and $\omega_G$.

The preference functions and weights can be defined in a flexible manner to account for the specific circumstances and constraints of concrete system control situations and scenarios. Moreover, such preference functions need not be static, but can be dynamically manipulated by users to facilitate transient changes in operational requirements.

Note that, in the present implementation, we have not addressed in detail the interrelationships between lighting and thermal performance aspects. To systematically demonstrate the control system's potential, we have focused in this paper on visual performance and energy use requirements for electrical lighting. The working assumption for this implementation implies that reduction of electrical energy use for lighting is desirable not only when the building is in a cooling mode, but also in cases where the lighting energy use reduction would lead to increase in heating load: space heating via electrical lighting use is undoubtedly inefficient. Independent of this assumption, however, the proposed method allows in principle for the explicit incorporation of a thermal performance simulation engine and a set of thermal performance criteria (e.g., predicted heating and cooling energy use, thermal comfort criteria) in the control system's kernel and utility function.

Test space and devices
To compare the energy performance of the proposed innovative simulation-assisted lighting and shading control method with the conventional approaches, we selected six rooms in a floor of an existing office building in Styria, Austria (see Figure 4 and 5) for a schematic floor plan and a 3-dimensional illustration. The relevant control devices for the present virtual implementation are suspended dimmable luminaires and window blinds. For each device, a discrete number of possible states is taken into consideration. The luminaires can be in any of 10 possible dimming positions (see Table 1). The blinds can be in one of seven possible positions (Figure 6).
Sky model
The prediction of daylight availability in indoor environment requires appropriate sky luminance distribution maps. Toward this end, we extracted the necessary horizontal global irradiance values from the applicable weather file information. Using this information, the corresponding diffuse radiation components are derived using an algorithm described in (Reindl et al. 1990). Given the resulting horizontal direct and diffuse irradiance values, corresponding horizontal direct and diffuse illuminance values were derived based on a luminous efficacy model developed by (Perez et al. 1990). These in turn provided the input information for the generation of the sky luminous distribution maps according to (Perez et al. 1993). The maps were subsequently used as input to the lighting simulation application.

Scenarios
To evaluate the energy performance of the predictive simulation-assisted lighting systems control, five different control scenarios are considered (see the overview in Table 3) and virtually implemented in the above-mentioned office building (see Figure 4 and 5). The scenarios considered are as follows:

i) Scenario 1 assumes luminaires are always switched on during the office hours, independent of daylight availability. Shades are not deployed.

ii) Scenario 2 is similar to scenario 1, other than in this case shades are deployed (fully closed) according to the schedule shown in Table 2.

iii) Scenario 3 involves the daylight-responsive dimming of the luminaires so that a minimum...
task illuminance levels of 500 lx is maintained (including daylight contribution) during the office hours.

iv) Scenario 4 is similar to scenario 3, other than in this case the shades are deployed according to the aforementioned schedule (Table 2).

v) Scenario 5 involves the predictive simulation-assisted lighting and shading systems control. Thereby, for each room the most desirable state of the devices, namely dimming level of the luminaires (10 possible positions) and the state of the shades (7 possible positions), is identified according to the previously described procedure. As explained above, the overall behavior of the simulation-assisted control system is guided through a utility function (UF). This function can include one or more performance indicators (e.g., illuminance level, electrical power, and glare index) together with their corresponding weights.

Table 2
Shading deployment schedule for scenarios 2 and 4

<table>
<thead>
<tr>
<th>Shades position</th>
<th>East façade</th>
<th>West façade</th>
</tr>
</thead>
<tbody>
<tr>
<td>closed</td>
<td>8:00-12:00</td>
<td>12:00-18:00</td>
</tr>
</tbody>
</table>

Experiments

Two sets of virtual experiments were conducted, whereby control states and resulting performance were simulated for 12 reference days representing the 12 months of the reference year.

The first set of experiments included the entire office floor including six rooms. In this case, the simulation-assisted method (scenario 5) applied a utility function that involved two performance indicators, namely illuminance levels and electrical power (equally weighted). The second set of experiments involved only one office space (a single-occupancy east-oriented room as highlighted in Figure 5). Thereby, we looked more closely at the implications of alternative weighting schemes for the energy performance of the simulation-assisted control strategy. Toward this end, three versions of scenario 5 (namely 5a, 5b, and 5c) were considered, each defined in terms of a distinct weighting scheme as per Table 4: scenario 5a assigns weights to all three performance indicators. Scenario 5b considers only illuminance level and energy use (similar to scenario 5 in the first experiment). Scenario 5c considers only illuminance and glare.

Table 4
Overview of the three weight schemes for simulation-assisted control

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>( \omega_I )</th>
<th>( \omega_W )</th>
<th>( \omega_G )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5a</td>
<td>0.5</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>5b</td>
<td>0.5</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>5c</td>
<td>0.5</td>
<td>-</td>
<td>0.5</td>
</tr>
</tbody>
</table>

RESULTS

To illustrate the working of the above-described control method functionality, we documented the operation of the system in the course of twelve days (one for each month of the year). The climatic data (specifically, irradiance values) from the local weather file (year 2009) was used as the applicable boundary condition information. For all scenarios, the state of the control devices was updated regularly (every 15 minutes).

To exemplify the operation of the simulation-assisted control system, Figures 7 shows detailed data (15 minute intervals) for the reference day in May. Maintained indoor illuminance levels are within the range of 500 to 1600 lx. Shades are deployed to avoid excessive illuminance levels. In this particular day, electrical lighting was almost entirely unnecessary.

Figure 8 compares the scenarios in terms of projected annual electrical energy use [kWh.m.\(^{-2}\).a\(^{-1}\)] for the whole office floor. Figure 9 displays this same energy use data on a monthly basis. Figure 10 shows monthly mean values of maintained illuminance (office hours) over all offices. Figure 11 compares, for one office room, the annual electrical energy use for lighting for different control scenarios. Figure 12 compares the performance of the control methods in terms of the respective utility functions. Thereby, the three weighting schemes of Table 4 were considered.

Table 3
Overview of the scenarios

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>LUMINAIRIES</th>
<th>SHADING</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>On (illuminance ( \geq 500 ) lx independent of daylight)</td>
<td>Fully open</td>
</tr>
<tr>
<td>2</td>
<td>On (illuminance ( \geq 500 ) lx independent of daylight)</td>
<td>Deployed according to schedule (see Table 2)</td>
</tr>
<tr>
<td>3</td>
<td>Dimming mode (illuminance ( \geq 500 ) lx including daylight)</td>
<td>Fully open</td>
</tr>
<tr>
<td>4</td>
<td>Dimming mode (illuminance ( \geq 500 ) lx including daylight)</td>
<td>Deployed according to schedule (see Table 2)</td>
</tr>
<tr>
<td>5</td>
<td>Simulation-assisted systems control</td>
<td></td>
</tr>
</tbody>
</table>
Figure 7 Maintained indoor illuminance, external illuminance (y-axis values times 100), and corresponding positions of the blinds (1 = fully closed, 7 = fully open) for a reference day in May.

Figure 8 Comparison of scenarios in view of annual electrical energy use for lighting [kWh.m².a⁻¹].

Figure 9 Comparison of scenarios in view of monthly values of electrical energy use for lighting [kWh.m²].
Figure 10 Mean monthly values of maintained illuminance [lx] in the 6 offices (during office hours)

Figure 11 Comparison of scenarios in view of annual electrical energy use for lighting [kWh.m².a⁻¹] in an office (see highlighted room in Figure 5)

Figure 12 Comparison of the performance of the five control scenarios in terms of utility functions (UF-a, UF-b, and UF-c). The weighting schemes for these versions correspond to those shown in Table 4
DISCUSSION
The results clearly display the better performance of the simulation-assisted systems control approach. It has the best energy performance (see Figures 8, 9, and 11), with the exception of scenario 3, which—similar to scenario 1, permits rather excessive illuminance levels (see Figure 10). An attractive feature of the simulation-assisted control approach is the possibility to consider multiple performance indicators dynamically during the control process. The incorporated simulation engine allows for the real-time calculation of sophisticated performance indicator pertaining, for example, to visual comfort. Moreover, the importance that can be attached to each of these indicators can be modulated according to the interests and constraints of the building occupants and managers. In this context, Figure 11 provides an example of the energy use implications of weighting schemes that consider energy use (scenarios 5a and 5b) or only focus on visual comfort scenario 5c). Not surprisingly, the results of our study (see Figure 12), imply the superior performance of the predictive simulation-assisted suggest for all performance indicator weighting schemes we considered (see Table 4), as these involve visual performance criteria in addition to energy performance.

CONCLUSION
We demonstrated virtual implementation and operation of multiple lighting and shading systems control approaches in an office building. Thereby, the performance of an innovative predictive simulation-assisted control strategy was compared to a number of conventional methods. The results underline the promise of the proposed concept. The predictive method displays a better energy performance and can dynamically and effectively accommodate multiple performance criteria and associated weights in the course of the control process. The next step in our exploration of the potential of the predictive simulation-assisted lighting and systems control strategy will be its projected actual implementation and long-term testing in the same office building that provided the context for the present virtual implementation. Thereby, the lighting and shading control functionality shall be integrated with the already implemented predictive window operation system for passive cooling.

REFERENCES