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ELEMENTS OF A SIMULATION-ASSISTED DAYLIGHT-RESPONSIVE ILLUMINATION SYSTEMS CONTROL IN BUILDINGS

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ABSTRACT

This paper presents a simulation-assisted daylight-responsive illumination control system. The controller application in this system can dynamically adjust the position of window blinds and the status of the room luminaires to achieve user-specified performance levels. In its main mode of operation, the control application considers in regular time intervals a set of alternative combinations of the states of control devices (e.g. position of window blinds, dimming levels of luminaires) for an immediate next time step. Subsequently, this set of alternatives is subjected to the lighting simulation, resulting in corresponding performance indicators. These results are then compared and ranked according to the objective function (preferences) set by the users. The controller application then updates the status of the pertinent control device(s) accordingly.

INTRODUCTION

Previous publications have elaborated on the concept and prototypical implementations of simulation-based building systems control strategies (for an overview see, for example, Mahdavi 2001). In a nutshell, a simulation-assisted control system aims at the behavioral description of the reaction of a controlled entity to alternative states of relevant control devices for a given context (i.e. climate, occupancy). Behavioral descriptions may be based on simple rules, self-adaptive algorithms (Guillemin and Morel 2002), or they may rely on numeric simulation. As Figure 1 illustrates, a simulation-based control process may be described in terms of four phases:

i) Multiple potential control device states are considered; *ii)* The resulting device state space is mapped to the corresponding control zone state space via multiple real-time simulation runs; *iii)* Simulation results (predicted control zone states) are evaluated and ranked according to applicable objective functions; *iv)* the control device is adjusted to mach the most desirable state.

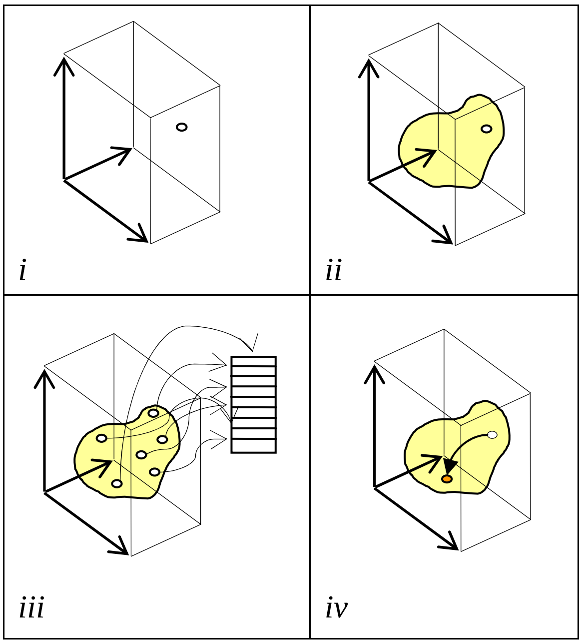

Figure 1
Simplified illustration of a simulation-based control process: i) system control state at time t_i; ii) candidate control options for time t_{i+1} (i.e. alternative states of control devices); iii) computational prediction and evaluation (ranking) of the performance implications (zone states) of alternative control states; iv) transition to the new control state.

In the present paper, we describe the elements of an actual implementation effort toward a simulation-assisted daylight-responsive illumination control system. The controller application in this system can control the position of window blinds and the status (on/off, dimming level) of the room luminaires. To arrive at control decisions, the controller application possesses an internal digital representation that encompasses: *i)* a room model; *ii)* a sky model; and *iii)* an occupancy model. The room model encapsulates the geometric and semantic information as needed for lighting simulation. Such information include, for example, room dimensions, reflectance of room surfaces, location and size of windows, transmittance of glazing, furniture location and properties, as well as the position of virtual sensors that monitor pertinent performance parameter (such as illuminance levels or glare indices). The sky model is generated on a real-time basis via calibrated digital imaging (using a digital camera with a fish-eye converter). The occupancy model captures mainly two pieces of information. One pertains to the presence of people in the space. The second relates to user settings (e.g. desirable illuminance levels). Ideally, all these three models should be self-updating. The manual updating scenario would involve a severe bottleneck and thus severely limit the practical applicability of simulation-based building systems control strategies.

ELEMENTS OF A PROTOTYPE

Overview

In the following, we discuss the elements of a test implementation of the simulation-based control approach. The room, sky, and occupancy models are mentioned, as well as the control system presentation, control objectives, and the control process.

Room model

As the test space, we selected a double-occupancy office (Figure 2) in a university building (Vienna University of Technology). The two windows of the office are equipped with automatically controllable blinds. Artificial illumination is provided by two free-standing luminaires. This room is equipped with a location-sensing system, which automatically tracks changes in the position of moveable furniture elements (including the aforementioned luminaires).

Sky model

Reliable prediction of daylight availability in indoor environments via computational simulation requires reasonably detailed and accurate sky luminance models. As past research has demonstrated (Roy et al. 1998, Mahdavi and Spasojević 2004), relatively low-cost sky luminance mapping via digital imaging could provide an alternative to high-end research-level sky scanners and thus support the provision of information on sky luminance distribution patterns on a more pervasive basis. A digital camera, equipped with a fisheye converter and pointing toward the sky zenith, has been placed on the roof of a building in which the test space is located. Images of the sky have been continuously taken and analyzed real-time to provide the sky model (sky luminance distribution pattern) to the simulation application.

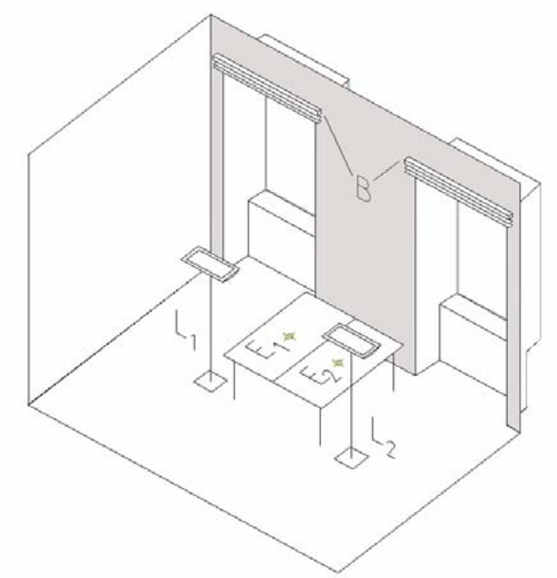

Figure 2
Illustration of the test space at the Vienna University of Technology (B: blinds; E_1, E_2: virtual illuminance sensors; L_1, L_2: luminaires)

Occupancy model

Presence of the people in the room (at the workstations) can be monitored with occupancy sensors. Preferences regarding desirable illuminance levels can be communicated to the lighting control application via users' laptops.

Control system representation

Figure 3 illustrates the control system scheme, as relevant to the test scenario considered in the present contribution. E_1 and E_2 represent the virtual illuminance sensors, for which the simulation program calculates the expected values as a result of various control device states. Three control devices are considered, namely the two luminaires (L_1, L_2) and the window blinds (B). Since in the control scenarios considered in this paper the two blinds are controlled simultaneously, they are represented in Figure 3 as one device. Blinds can be moved up and down, and the slats can be set into horizontal and vertical positions.

As all these devices affect both E_1 and E_2, a central control instance (C) is required to coordinate the three devices toward the most preferable control state. To each device, we allocate a discrete number of possible states. The luminaires can be in any of 10 possible dimming positions (see Table 1). The blinds can be in one of seven possible positions (see Figure 4).

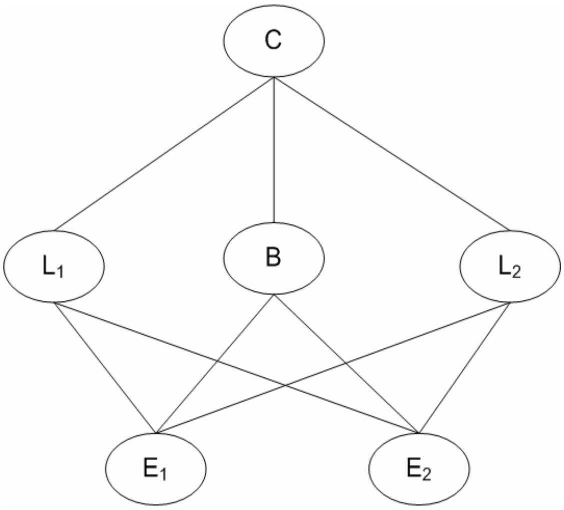

Figure 3
Control system scheme

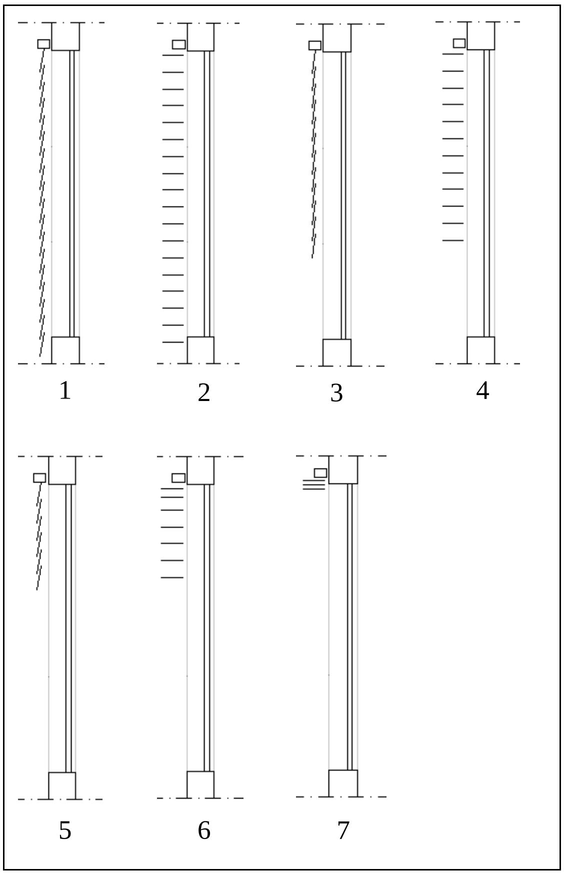

Figure 4
States of the blinds

TABLE 1
STATES OF THE LUMINAIRES

Dimming level	Power output [%]
1	0
2	20
3	30
4	40
5	50
6	60
7	70
8	80
9	90
10	100

Control objective

To demonstrate the working of the control system, we considered a simple control objective. For each workstation a user-specified illuminance preference (P_E) was assumed (see Figure 5). The target values (and maximal deviations) for task illuminance levels were derived based on corresponding CIE recommendations for normal visual tasks. One objective of the control operation is to minimize the deviation of the workplace illuminance levels from the user settings. The second objective is to reduce the electrical energy consumption. The corresponding preference function (P_L) is shown in Figure 6. It was derived by the "inversion" of the luminaire's dimming curve (luminous flux as a function of electrical energy input).

The overall behavior of the control system may be influenced by the formulation of a utility function (UF). The objective of the control process is to maximize the utility function. Equation 1 provides an example for such a utility function:

$$UF = w_{E1} \cdot P_{E1} + w_{E2} \cdot P_{E2} + w_L \cdot P_L \qquad (1)$$

In this equation P_{E1}, P_{E2}, and P_L are the preferences for illuminance levels (E_1 and E_2) and electrcial energy consumption. The corresponding weights are represented by w_{E1}, w_{E2}, and w_L.

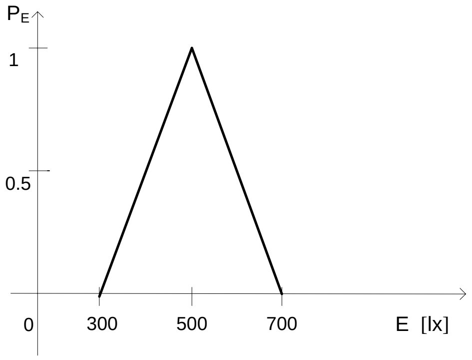

Figure 5
An illustrative user preference function for illuminance levels

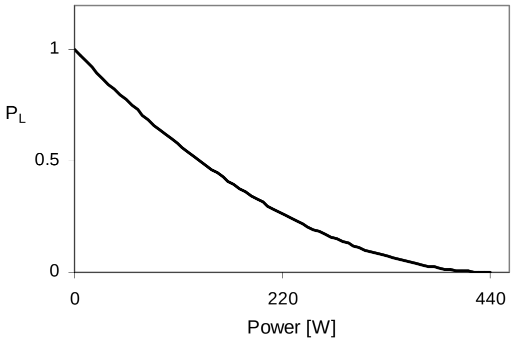

Figure 6
Preference values for electrical energy consumption of the two luminaires

DEMONSTRATION

Control process

Consider the following control process. At the time step t_i, each device (i.e. L_1, L_2, B) submits to the control application C a list of candidate device states. In the present case, each device submits four alternative options. These options are: the device's current position, the two neighboring device states, and a fourth – randomly chosen – option from the rest of the device's control state space. The control application considers the resulting overall option space involving a maximum of 64 combined options. To predict the illuminance levels at E_1 and E_2 due to these options, the control application uses a combination of rules (tables or functions) and simulation. The contributions of the two luminaires are predicted based on functions resulting from measurements. As an example of such a function, Figure 7 illustrates the relationship between the dimming position of L_1 and the resulting Illuminance levels at E_1 and E_2.

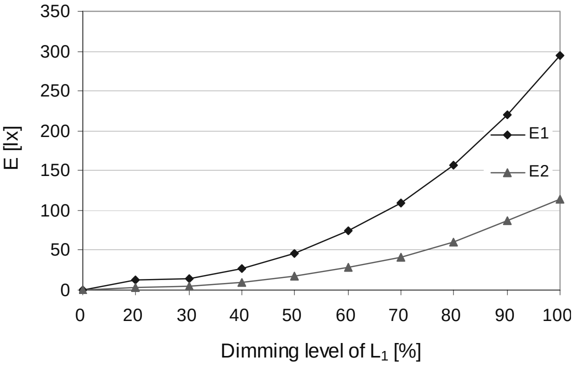

Figure 7
Illuminance levels at points E_1 and E_2 due to Luminaire L_1

The contribution of the windows to illuminance is a function of prevailing sky conditions and the position of the blind and is predicted using numeric simulation. For this purpose, we integrated the lighting simulation application LUMINA (Pal and Mahdavi 1999) in the control application.

Given the partial contributions of each device, the resulting illuminance levels at E_1 and E_2 are computed at each time step for the 64 device state configurations. Based on this information and the associated electrical energy consumption values, the utility function values can be derived using equation 1. Thus, the control state with the maximum utility function can be identified at each time step.

Illustrative results

To illustrate the control process, we documented the operation of the system in the course of a day. The external global horizontal illuminance level for this day is shown in Figure 8.

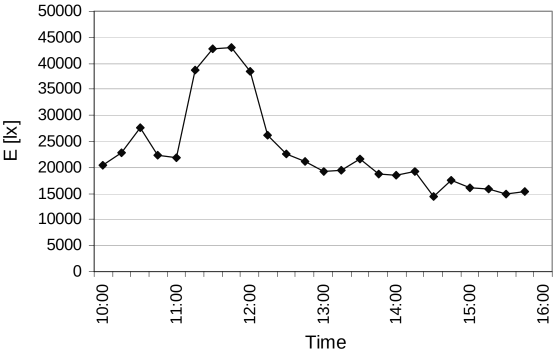

Figure 8
External global horizontal illuminance during the test day

The first set of illustrative results pertains to the following weight assumptions in Eq. 1: $w_{E1} = w_{E2} = 0.4$; $w_L = 0.2$. For this set, Figures 9 and 10 show the recommendations of the control application for dimming positions of the two luminaires and the blind position. Figures 11 to 13 illustrate the resulting illuminance levels at E_1 and E_2, the electrical energy power requirement, and the utility function.

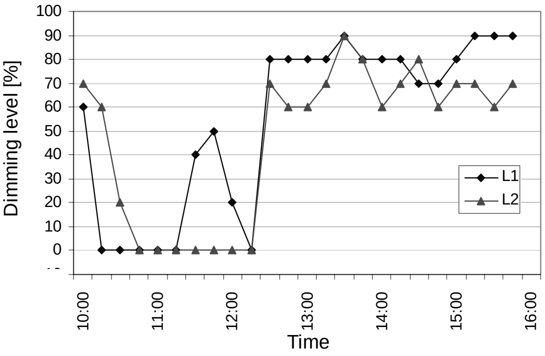

Figure 9
Control system recommendations for the luminaire dimming positions (first set)

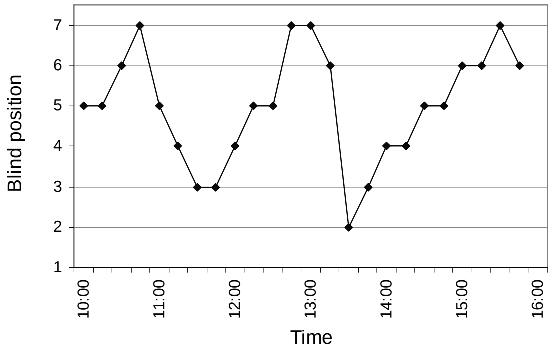

Figure 10
Control system recommendations for the blind position (first set)

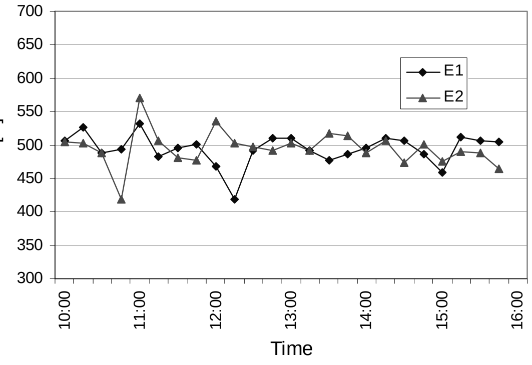

Figure 11
Resulting illuminance levels for E_1 and E_2 (first set)

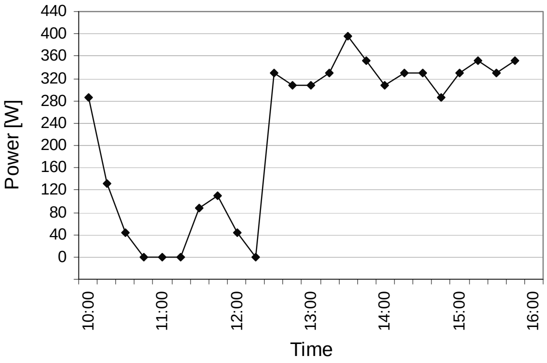

Figure 12
Resulting power values (first set)

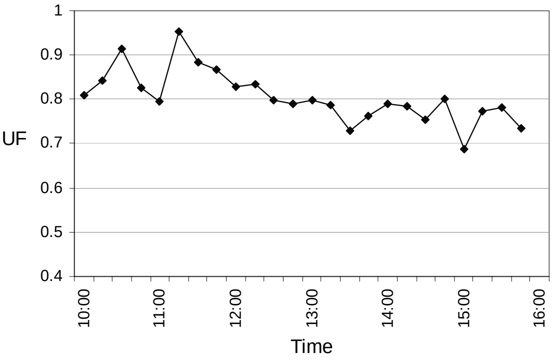

Figure 13
Resulting utility function values (first set)

The second set of illustrative results pertains to the following weight assumptions in Eq. 1: $w_{E1} = w_{E2} = 0.35$; $w_L = 0.3$. For this set, Figures 14 and 15 show the recommendations of the control application for dimming positions of the two luminaires and the blind position. Figures 16 to 18 illustrate the resulting illuminance levels at E_1 and E_2, the electrical energy power requirement, and the utility function.

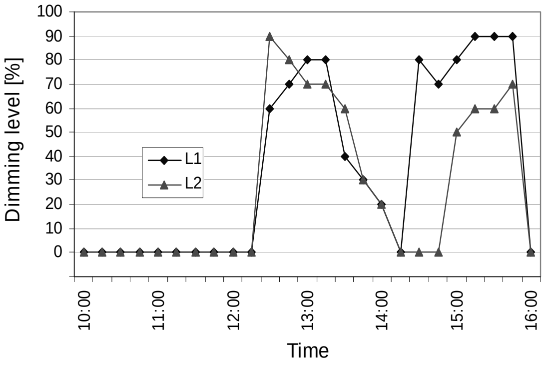

Figure 14
Control system recommendations for the luminaire dimming positions (second set)

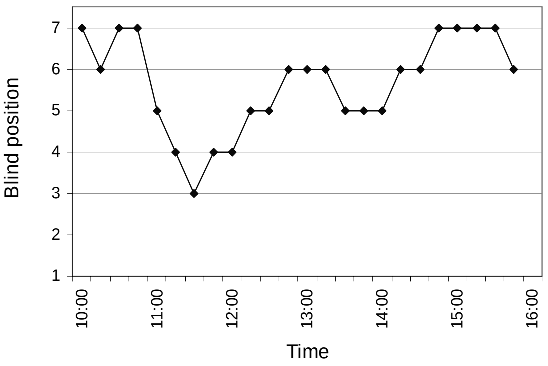

Figure 15
Control system recommendations for the blind position (second set)

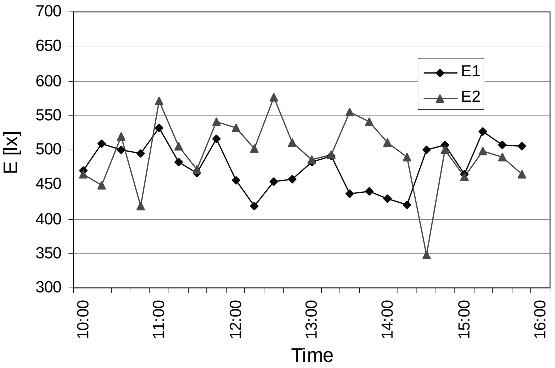

Figure 16
Resulting illuminance levels for E_1 and E_2 (second set)

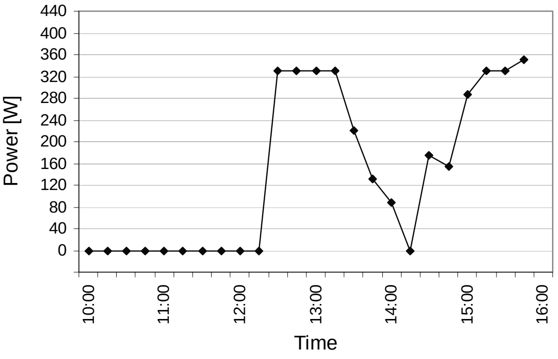

Figure 17
Resulting power values (second set)

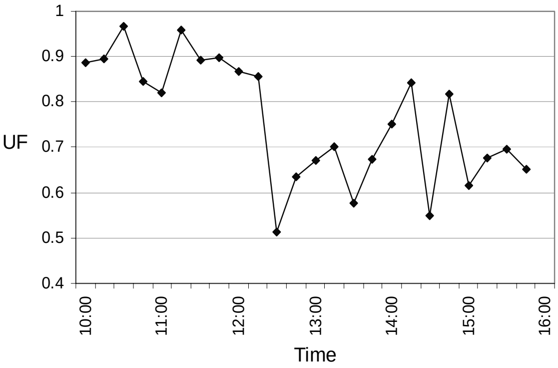

Figure 18
Resulting utility function values (second set)

Table 2 contrasts the two sets in terms of:

i) mean deviation (ΔE_m) of the resulting illuminances from the user-based set-points averaged over E_1 and E_2 throughout the test day;

ii) electrical energy consumption (q) by the two luminaires (for one day);

iii) mean value of the utility function (UF_m).

These results confirm the intuitively expected circumstance that a higher emphasis on energy saving in set 2 leads to a somewhat higher deviation from the illuminance set-points.

TABLE 2
COMPARISON OF THE TWO ILLUSTRSATIVE CONTROL RECOMMENDATIONS

	Set one	Set two
ΔE_m [lx]	17	33
q [kWh]	1.34	0.85
UF_m	0.8	0.76

CONCLUSION

We described the concept and a prototypical implementation of a simulation-assisted illumination systems control in buildings. Work is under way to extend the functionality of this system towards the integrated control of buildings lighting and thermal systems. Moreover, the scalability of the system and its self-updating capability is being improved via ongoing implementation activity involving larger objects and multiple environmental systems.

ACKNOWLEDGMENT

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