MODELING USER CONTROL OF LIGHTING AND SHADING DEVICES IN OFFICE BUILDINGS: AN EMPIRICAL CASE STUDY

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ABSTRACT

Reliable information regarding user presence and behavior in buildings is crucial for building performance simulation applications (energy consumption, indoor environment). In this context, the present contribution describes an effort to observe control-oriented occupant behavior in 29 offices of a large high-rise office complex over a period of one year. The observations regarding control behavior tendencies suggest relationships to both indoor environmental conditions and outdoor environment parameters.

KEYWORDS

Building performance simulation, building control systems, user control actions, behavioral models

INTRODUCTION

Information on user control behavior is crucial toward accurate prediction of building performance (energy consumption, indoor environment), as in most buildings windows, shades, luminaries, radiators, fans and other control devices can be operated by building occupants. Thus, multiple studies have been conducted internationally to collect data on building users' interactions with building control systems and devices (see, for example, Bourgeiois et al. 2005, Newsham 1994, Hunt 1979, Mahdavi et al. 2006a). Such empirically-based data can bring about a better understanding of control-oriented user behavior in buildings and thus support the development of corresponding behavioral models for integration in building performance simulation applications.

The present contribution describes an effort to observe control-oriented occupant behavior in 29 offices of a large high-rise office complex over a period of one year. Specifically, states and events pertaining to occupancy, systems, indoor environment and external environment were monitored. A weather station, a number of indoor data loggers and two digital cameras were used to continuously monitor – and record every five minutes – such events and states (occupancy, indoor and outdoor temperature and relative humidity, internal illuminance, external air velocity and global horizontal irradiance, status of electrical light fixtures, position of shades).

APPROACH

Object

The measurements were conducted in 29 single-occupancy offices in a large high-rise office complex (referred to, in this paper, as "VC"). An important feature of VC is its use as one of the major seats of an international organization, resulting in a very diverse occupancy profile in cultural terms. From the selected offices, 15 face north (code: "VC_NO") and 14 face south-west (code: "VC_SW"). The offices are located on the 12thand 13th floor. A schematic layout of three offices in the 12th floor could be seen on Figure 1. The work stations are equipped with desktop computers and (in some cases) printers. Both screen-based and paper-based tasks are performend by the occupants.

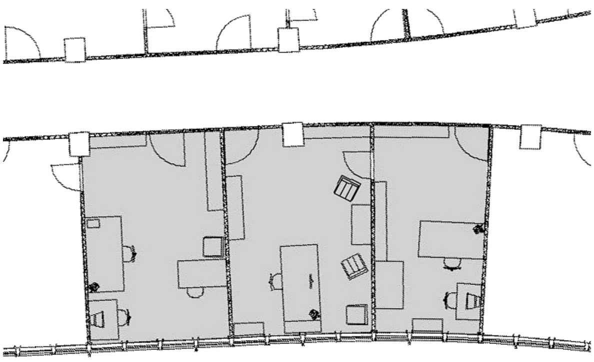

Figure 1 Example of offices in VC

The offices are typically equipped with the followings systems: Three rows of luminaries with 9 or 12 fluorescent lamps (36 W) divided into two circuits and manually controlled by two switches near the entrance door; internal manually operated shading; Three to four fan coil units under each window for fine adjustment of temperature.

Monitored parameters

The intention was to observe the actions of people toward lighting and shading as well as to monitor the indoor and outdoor conditions under which these actions occur. The change in the status of ambient light fixtures was captured using a sensor mounted under the luminaires. Shading was monitored via time-lapse digital photography. The degree of shade deployment for each office was derived based on regularly taken digital photographs of the façade. Shade deployment degree was expressed in percentage terms (0%: no shades deployed, 100%: full shading).

The external weather conditions were monitored using a weather station, mounted on the top of the building. Indoor climate conditions (temperature, relative humidity, illuminance) were measured with autarkic loggers distributed across the workstations. To obtain information regarding user presence and absence intervals, occupancy sensors were applied. All of the above parameters were logged regularly every 5 minutes.

Monitored indoor parameter included room air temperature (in ^{o}C), room air relative humidity (in %), ambient illuminance level at the workstation (in lx), luminaire status (on/off) and occupancy (present/absent). Monitored outdoor environmental parameter included air temperature, relative humidity, wind speed (in m.s^{-1}), as well as global horizontal illuminance and global horizontal irradiance (in W.m^{-2}). Global vertical irradiance incident on the façade was computationally derived based on measured global horizontal irradiance using a procedure described in Mahdavi et al. (2006b).

For the analysis, the range of data was reduced to working days and hours 8:00 till 20:00h (weekends and hours between 20:00 and 8:00 were excluded).

Data processing

The collected data was analyzed to explore hypothesized relationships between the nature and frequency of the control actions on one side and the magnitude and dynamism of indoor and outdoor environmental changes on the other side. Results were processed and visualized primarily in terms of probability and frequency (relative/normalized) distribution graphs.

Electrical energy saving potential for lighting

To estimate the saving potential in electrical energy use for office lighting, we started by monitoring the status quo in a sample of offices in each building. Subsequently, we considered three (cumulative) energy saving scenarios: i) lights are automatically switched off if the office is not occupied; ii) lights are switched off, if the daylight-based task illuminance level equals or exceeds 500 lx; iii) an automated dimming regime is applied, whereby luminaires are dimmed down so as to maintain a task illuminance level of 500 lx.

RESULTS

Occupancy

Figure 2 shows the mean occupancy level over the course of a reference day (averaged over the entire observation period). Note that this Figure represents the presence in the user's office and not the complex. Moreover, as Figure 3 demonstrates, the occupancy patterns in individual offices can vary considerably.

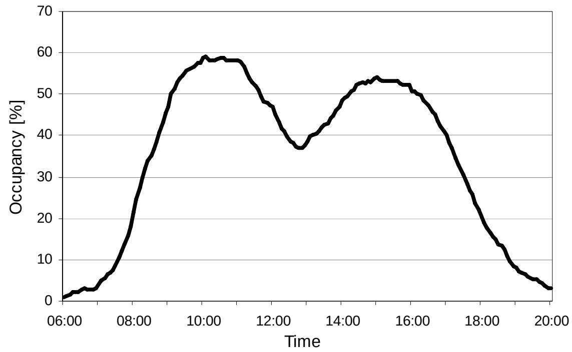

Figure 2 Mean occupancy level in VC_NO+VC_SW over the course of a reference day, averaged over all observed offices

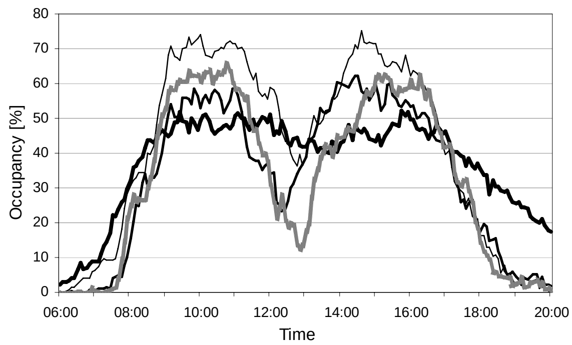

Figure 3 Observed occupancy levels in 4 different offices in VC_NO+VC_SW over the course of a reference day

Lighting

Figure 4 shows the observed effective lighting load in the course of a reference day. Obviously, the information in this Figure is about the general light usage tendency in all observed offices. To provide an impression of the differences amongst individual light usage profiles, Figure 5 and Figure 6 show the lighting operation in each observed office for the entire monitoring period expressed in terms of the ratio of the lighting operation duration to the overall working hours.

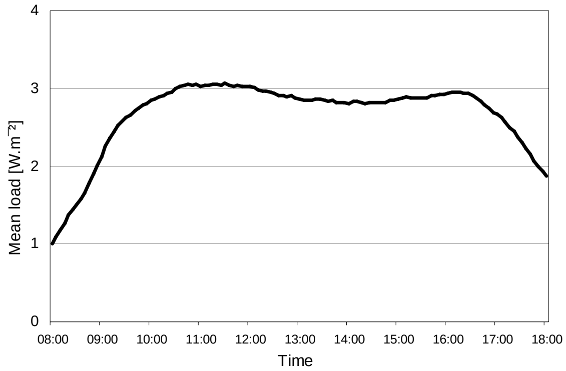

Figure 4 Lighting operation in VC_NO+VC_SW offices

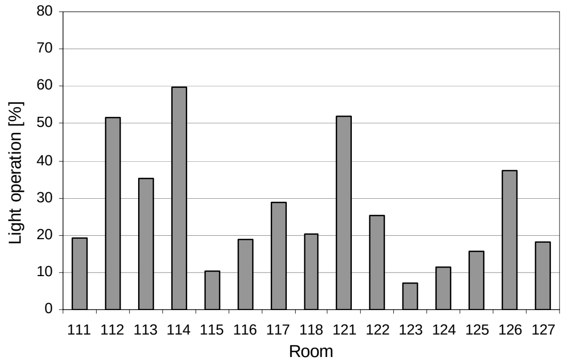

Figure 5 Duration of lighting operation (in percentage of respective overall working hours) in offices of VC_NO

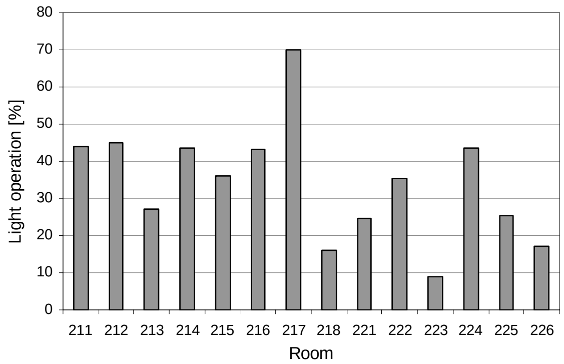

Figure 6 Duration of lighting operation (in percentage of respective overall working hours) in offices of VC_SW

Figure 7 shows the probability that an occupant would switch the lights on, upon arrival in his/her office as a function of the prevailing task illuminance level immediately before the arrival.

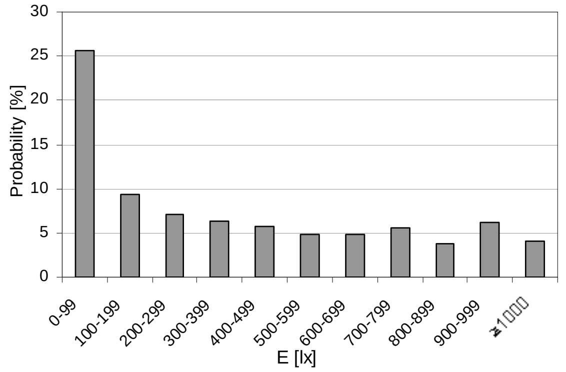

Figure 7 Probability of switching the lights on upon arrival in the office

Figure 8 shows the normalized relative frequency of (intermediate) actions "switching the lights on" by occupants who have been in their offices for about 15 minutes before and after the occurrence of the action as a function of the prevailing task illuminance level immediately prior to the action's occurrence. Normalization denotes in this context that the actions are related to both occupancy and the duration of the time in which the relevant illuminance ranges (bins) applied.

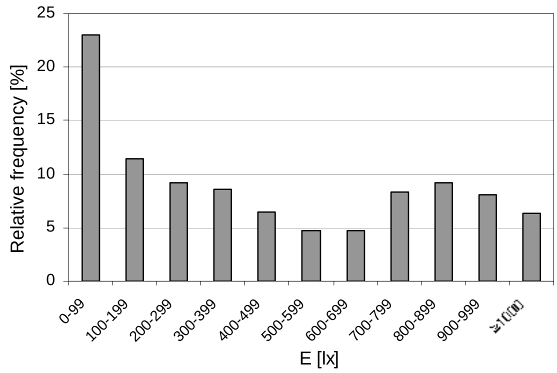

Figure 8 Normalized relative frequency of intermediate light switching on actions in VC_NO+VC_SW

Figure 9 shows the normalized relative frequency of all "switching the lights on" actions (upon arrival and intermediate) as a function of the time of the day together with mean global horizontal irradiance. In this case too, actions are normalized with regard to occupancy.

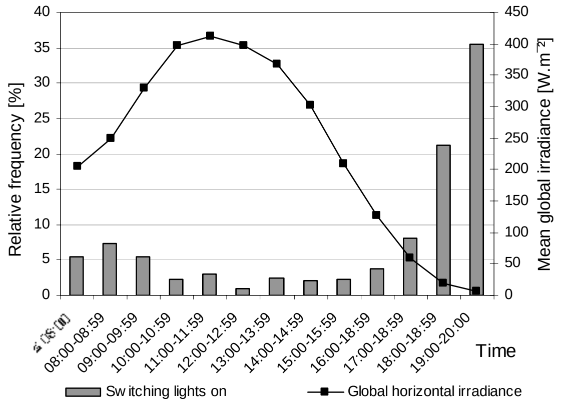

Figure 9 Normalized relative frequency of switching the lights on actions together with mean global horizontal irradiance in VC_NO+VC_SW over the course of a reference day

Figure 10 shows the probability that an occupant would switch off the lights upon leaving his/her office as a function of the time that passes before he/she returns to the office.

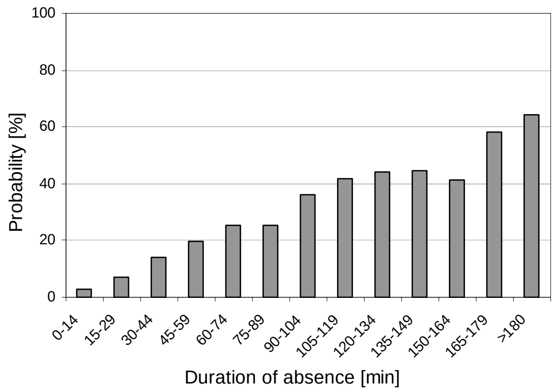

Figure 10 Probability of switching the lights off as a function of the duration of absence from the offices in VC_NO+VC_SW

Shades

Figure 11 represents the mean monthly shade deployment degree in VC_NO and VC_SW respectively.

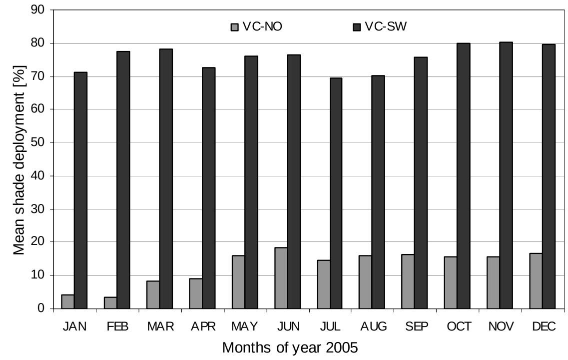

Figure 11 Mean monthly shade deployment degree in VC_NO and VC_SW

Figure 12 shows the normalized relative frequency of "opening shades" and "closing shades" as a function of the global horizontal irradiance in VC_NO+VC_SW. Figure 13 shows the normalized relative frequency of the same actions as a function of the global vertical irradiance. The number of actions is normalized with regard to occupancy and the time during which the respective irradiance bins applied.

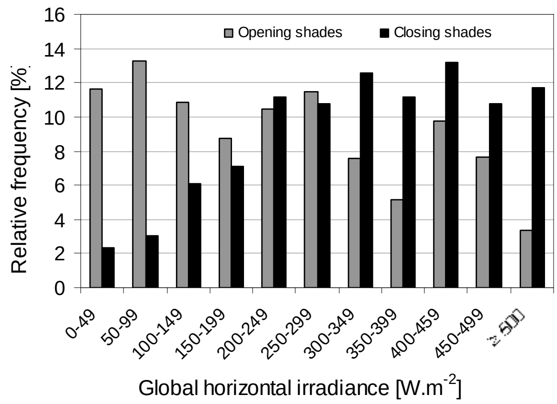

Figure 12 Normalized relative frequency of opening and closing shades in relation to global horizontal irradiance in VC_NO + VC_SW

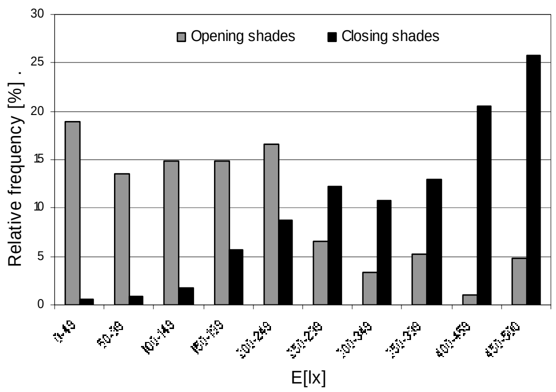

Figure 13 Normalized relative frequency of opening and closing shades in relation to the global vertical irradiance in VC_NO + VC_SW

Figure 14 and Figure 15 show the normalized relative frequency of "opening shade" and "closing shade“ actions together with mean global vertical irradiance over the course of a reference day in VC_SW.

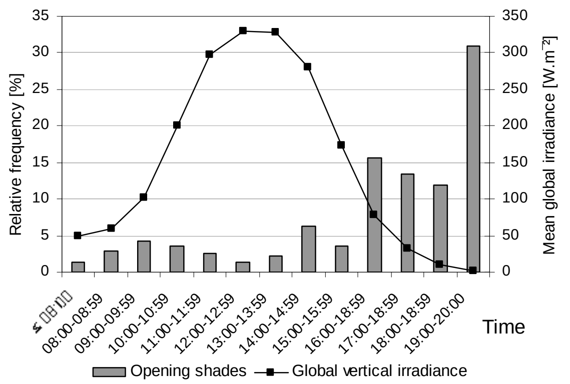

Figure 14 Normalized relative frequency of "opening shade” actions together with mean global vertical irradiance over the course of a reference day in VC_SW

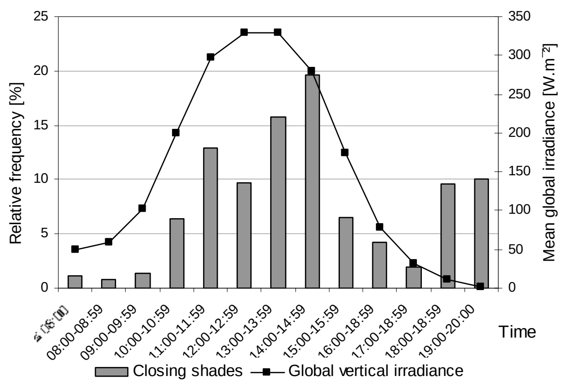

Figure 15 Normalized relative frequency of "closing shade” actions together with mean global vertical irradiance over the course of a reference day in VC_SW

Energy

Figure 16 and Figure 17 illustrate the potential for reduction of electrical energy use for lighting in VC_NO+VC_SW. Thereby, three (cumulative) energy saving scenarios are computationally derived. The first scenario requires that the lights are automatically switched off after 10 minutes if the office is not occupied. The second scenario implies, in addition, that lights are switched off, if the daylight-based task illuminance level equals or exceeds 500 lx. Finally, the third scenario assumes furthermore an automated dimming regime, whereby luminaires are dimmed down so as to maintain a task illuminance level of 500 lx while minimizing the electrical energy use for lighting.

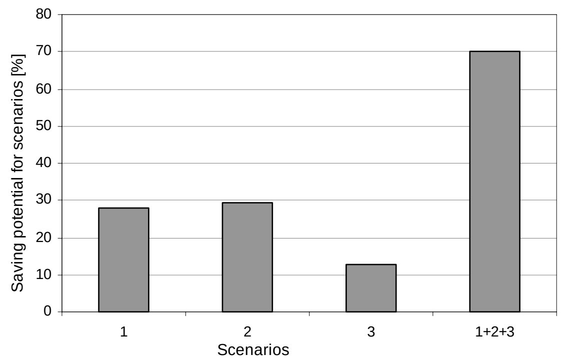

Figure 16 Electricity energy saving potential of luminaires in percentage by scenarios in VC_NO+VC_SW offices

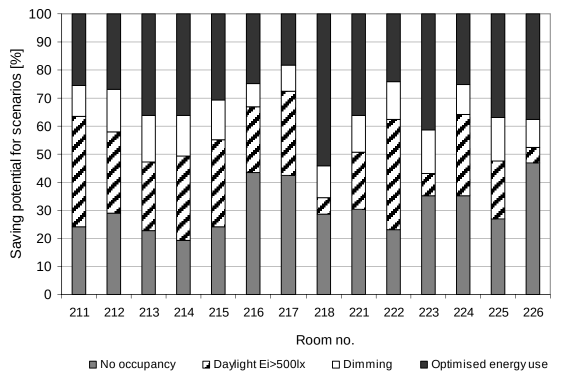

Figure 17 Saving potential in electrical energy use for lighting in 14 offices of VC_SW for the 3 scenarios

DISCUSSION

The monitored occupancy in VC_NO+VC_SW (Figure 2) and the obviously related people and lighting loads (Figure 4) reveal a pattern similar to that of many other office buildings and as such can be used for simulation runs in terms of corresponding hourly schedules (Figure 18 and Figure 19). Such simulations can be used, for example, to explore the impact of thermal improvement measures on the building's energy use. Moreover, the differences in the both occupancy levels (Figure 3) and lighting operation (Figure 5 and Figure 6) in various offices of VC_NO and VC_SW suggest the possibility of a more realistic simulation scenario using software agents to represent occupancy states in different offices in probabilistic terms.

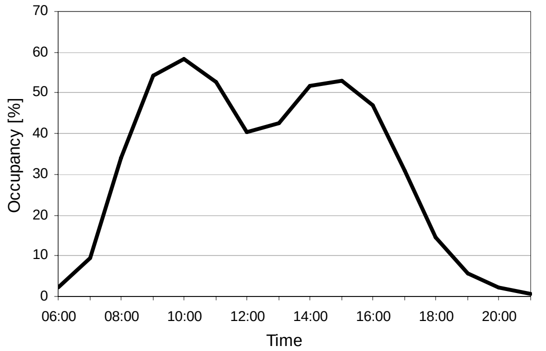

Figure 18 Illustrative simulation input data regarding mean hourly occupancy level for VC_NO+VC_SW

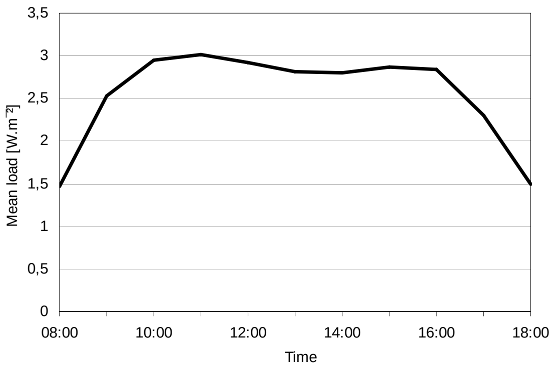

Figure 19 Illustrative simulation input data regarding mean hourly lighting load in VC_NO+VC_SW

Concerning the dependency of the action "switching on the lights" on prevailing illuminance levels (Figure 7 and Figure 8), the clear patterns suggest that only illuminance levels below 100 lx are likely to trigger actions at a non-random rate. However, if the frequency of the action is viewed in terms of the time of the day, a clear pattern is revealed that could be harnessed while modeling the respective behavior in a simulation program (Figure 9).

As to the action "switching the lights off", a clear relationship to the subsequent duration of absence is evident (Figure 10).

The mean monthly shade deployment for each façade depends on the orientation of the offices observed. This explains the higher deployment level of about 65 percent for VC_SW in comparison to VC_NO (Figure 11). Our observation reveals a clear relationship between the frequency of "opening shades" actions and incident radiation on the façade (Figure 13). The corresponding analysis of the "closing shades" actions shows a significantly higher action frequency once the incident radiation rises above 200 $W.m^{-2}$ (Figure 13). In VC_SW (Figure 14 and Figure 15), which has a south-west orientation, closing actions occur mainly mid-days, while opening actions occur mostly in the afternoons due to the incident radiation on the façade.

The estimated saving potential in electrical energy use for lighting of the sampled offices is significant (Figure 16 and Figure 17). The overall cumulative energy saving potential for all sampled offices is 70% for VC_NO+VC_SW. This would imply, that in the VC complex, annually roughly 127,000 € could be saved by a comprehensive retrofit of the office lighting system toward dynamic consideration of occupancy patterns and daylight availability. Note that a lighting system retrofit and the resulting electrical energy use reduction would increase the heating loads and decrease the cooling loads. However, as previous studies have shown, given the magnitude of required cooling loads in office buildings, the overall thermal implications of a lighting retrofit are positive both in energetic and monetary terms.

CONCLUSION

We presented a case study from an ongoing project concerning user control actions in an office complex in Austria. The results show that:

- Actual occupancy degrees are significantly below "design" assumptions, resulting in undifferentiated (and thus inefficient) provision of indoor environmental services;
- Only relative low workstation illuminance levels trigger actions of the type "switching on the lights" upon users arrival in their offices;
- The likelihood that occupants would turn off the lights in their offices is tightly correlated with the duration of the subsequent absent interval from the office;
- Given intelligent occupancy-sensitive and daylight-responsive lighting devices and control systems, about 70% of electricity energy use for lighting could be saved (in the observed office building).

In general, the results imply the possibility of identifying general patterns of user control behavior as a function of indoor and outdoor environmental parameters. The compound results of the ongoing case studies are expected to foster the development of robust occupant behavior models that can improve the reliability of computational building performance simulation applications.

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REFERENCES

Bourgeiois, D., Reinhart, C., Macdonald, I. A. 2005. Assessing the Total Energy Impact of Occupant Behavioural Response to Manual and Automated Lighting Systems, Proceedings of the IBPSA International Conference - Montreal, Canada (2005), 99 – 106.

Hunt, D., 1979. The Use of Artificial Lighting in Relation to Daylight Levels and Occupancy, Bldg. Envir. (1979), 14: 21–33.

Mahdavi A, Kabir E, Mohammadi A, Lambeva L and Pröglhöf C. 2006a. "User Interactions with Environmental Control Systems in Buildings"; in: "PLEA 2006 - 23rd International Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6-8 September 2006 - Clever Design, Affordable Comfort - a Challenge for Low Energy Architecture and Urban Planning", R. Compagnon, P. Haefeli, W Weber (Hrg.); Eigenverlag, Genf, Schweiz, 2006, 3-540-23721-6, S. 399 - 404.

Mahdavi A, Dervishi S and Spasojevic B. 2006b. Computational derivation of incident irradiance on building facades based on measured global horizontal irradiance data. Proceedings of the Erste deutsch-österreichische IBPSA-Konferenz - Munich, Germany (2006), 123-125.

Newsham, G. R., 1994. Manual Control of Window Blinds and Electric Lighting: Implications for Comfort and Energy Consumption, Indoor Environment (1994), 3: 135–44.