

USER CONTROL OF INDOOR-ENVIRONMENTAL CONDITIONS IN BUILDINGS: AN EMPIRICAL CASE STUDY

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ABSTRACT

As in most buildings windows, shades, luminaries, radiators, fans, and other control devices can be operated by building occupants, information on user control behavior is crucial toward accurate prediction of building performance (energy consumption, indoor environment). The present contribution describes an effort to observe control-oriented occupant behavior in an educational building over a period of one year. The observations regarding control behavior tendencies imply dependencies both on indoor and outdoor environmental conditions and contribute, thus, toward the derivation of realistic user action models for building performance simulation applications.

KEYWORDS

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

INTRODUCTION

Realistic building performance simulation requires, amongst other things, reliable assumptions regarding user behavior. As in most buildings windows, shades, luminaries, radiators, fans, and other control devices can be operated by building occupants, information on user control behavior is crucial toward accurate prediction of building performance (energy consumption, indoor environment). Thus, multiple studies have been (and are being) conducted internationally to collect data on building users' interactions with building control systems and devices (see, for example, Hunt 1979, Newsham 1994, Reinhart 2002, Mahdavi et al. 2006a). Such empirically-based data can bring about a better understanding of the nature, type and frequency 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 13 offices in an educational building 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 a digital

camera 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 horizontal global irradiance, status of electrical light fixtures, position of shades).

The results reveal distinct patterns in the collected data. Specifically, control behavior tendencies show dependencies both on indoor and outdoor environmental parameter. A summary of these tendencies will be presented and their principal potential as the basis of empirically grounded user action models in simulation applications explored.

APPROACH

Object

Data collection was conducted in 13 scientific staff offices in one of the buildings of Vienna University of Technology (Vienna, Austria). We refer to this Building henceforth in this paper as FH. All selected offices in FH face east, situated on the 4th, 5th and 6th floors. Ten offices are single-occupancy, two are double-occupancy, and one is triple-occupancy. Figure 1 provides, as an example for the selected offices, the schematic layout of two single-occupancy offices and one double-occupancy office in the 5th floor of the building. The working stations are equipped with desktop computers and in some cases with task lights. Both VDT-based and paper-based tasks are performed.

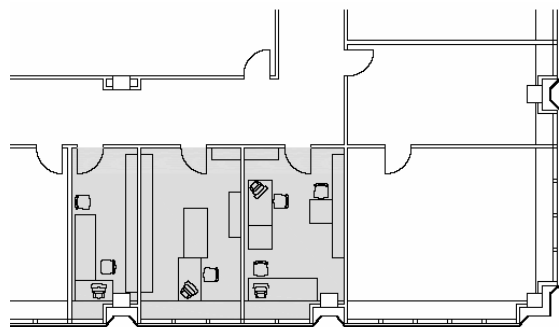


Figure 1 Schematic plan of sample offices in FH

Systems

The offices in FH are typically equipped with the following environmental control systems:

- i) Three luminaries (58W each), divided into two circuits manually controlled via switches near the office door;
- ii) External motorized screen shades operated by a switch mounted on a panel under the window;
- iii) Fan coil under the window for fine adjustment of temperature.

Monitored parameter

The intention was to observe user control actions pertaining to lighting and shading system while considering the indoor and outdoor environmental conditions under which those actions occurred. Occupancy and the change in the status of ambient light fixtures were captured using a dedicated sensor. 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. The images were processed with an originally developed shading detection software. The output of the program is the shade deployment degree, expressed in percentage terms (0%: no shades deployed, 100%: full shading).

The external weather conditions were monitored using a standard weather station, mounted on the top of a nearby university building.

Internal climate conditions (temperature, relative humidity, illuminance) were measured with autarkic data loggers (see Table 1 for sensor details) distributed across the workstations.

Table 1 Sensors of indoor data loggers

SENSOR	RANGE/ACCURACY
Temperature	-20 to 70 °C (±0.35 K at 25°C)
Relative humidity	5 to 95 % (±2.5 %)
Illuminance	1 to 30000 lx

To obtain information regarding user presence and absence intervals, occupancy sensors were applied, which simultaneously monitored the state of the luminaires in the offices. The loggers were mounted in the proximity of the luminaires, above the work places. The occupancy sensor utilizes PIR (passive infrared) technology for detection of occupancy and covers approximately a range of 14 m².

All of the above parameters were logged regularly every 5 minutes. Monitored indoor parameter included room air temperature (in °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) and wind direction, as well as horizontal global illuminance and horizontal global irradiance (in W.m⁻²). Vertical

global irradiance incident on the façade was computationally derived based on measured horizontal global irradiance using a method described in Mahdavi et al. 2006b.

Data processing

Collected data were stored and processed in a data base for further analysis. Thereby, the primary data structure follows a distinction between various types of "events" and "states" that occur at a certain point in time or persist over a certain time period (Mahdavi 2006a). This data structure and primary data types are summarized in Table 2.

For the purposes of the present analysis the range of data considered was limited to working days between the hours 8:00 to 19:00. The collected data was primarily 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.

Table 2 The structure of the collected data

DATA	TYPE	INSTANCES
Events (E)	System-related (E _s)	Switch lights on/off
		Pull shades up/down
	Occupancy-Related (E _o)	Entering into (or leaving) an office
States (S)	System-related (S _s)	Lights on /off
		Position of shades/windows
	Indoor environ. (S _i)	Air temperature
		Illuminance level
	Outdoor environ. (S _e)	Outdoor temperature
Global irradiance		
Occupancy-Related (S _o)	Office/workstation occupied/vacant	

RESULTS

Occupancy

Figure 2 shows the mean occupancy level over the course of a reference day (averaged over the entire observation period). Note that these values represent the presence at the users' offices/workstations, not merely the presence in the building. Moreover, as Figure 3 demonstrates, the occupancy patterns can vary considerably from office to office.

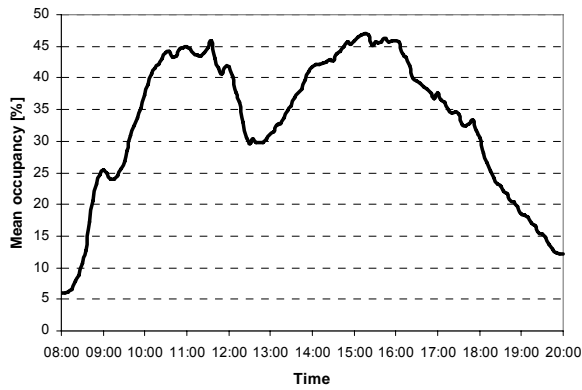


Figure 2 Mean occupancy level in FH for a reference day averaged over all offices observed

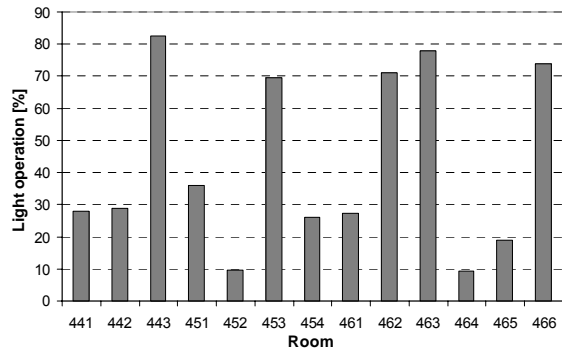


Figure 5 Duration of lighting operation (in percentage of respective overall occupied hours) in different offices of FH

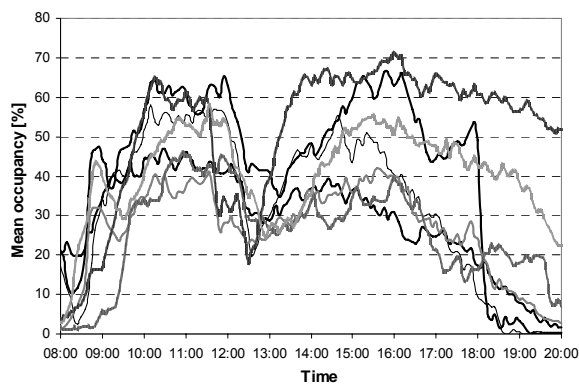


Figure 3 Observed occupancy levels in 7 different offices in FH for a reference day

Lighting

Figure 4 shows the observed effective lighting operation in the course of a reference day expressed in terms of effective electrical power. Obviously, the information in this Figure concerns the general light usage in all observed offices. To provide an impression of the differences amongst light usage in different offices, Figure 5 shows, for the entire observation period, the time (in percentage of the overall occupancy duration) in which at least a luminaire was operated in an office.

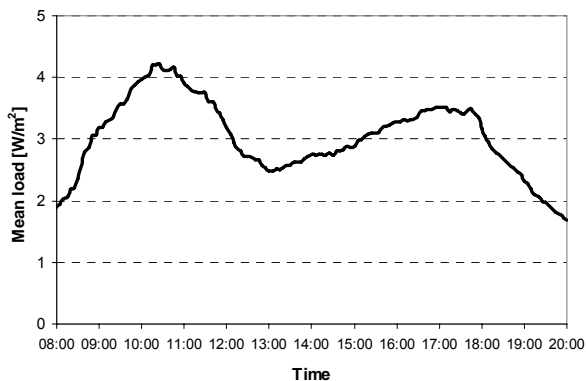


Figure 4 Lighting operation in FH offices

Figure 6 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 arrival. Probability is defined in this context as the number of times when an office user switched on the lights upon arrival in the office divided by the total number of arrivals.

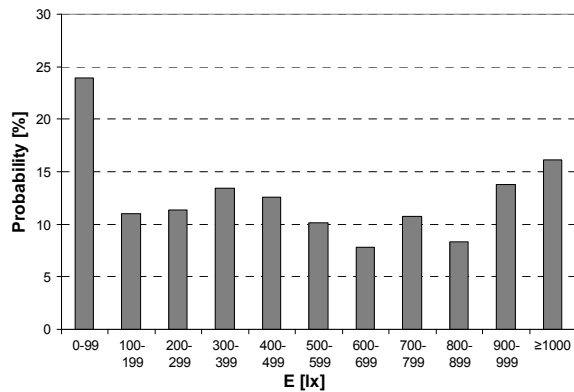


Figure 6 Probability of switching the lights on upon arrival in the office

Figure 7 shows the normalized relative frequency of (intermediate) actions "switching the lights on" (by occupants who have been in their office 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 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. In this case too, actions are normalized with regard to occupancy. Figure 9 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.

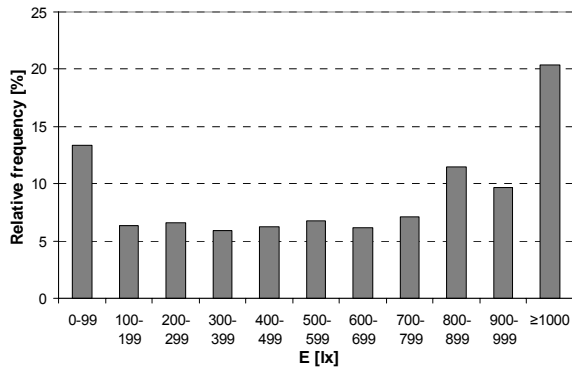


Figure 7 Normalized relative frequency of intermediate light switching on actions in FH

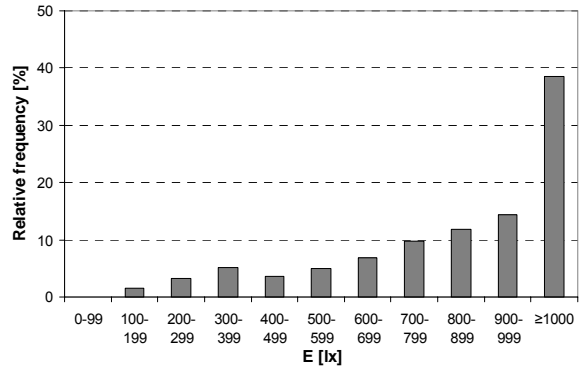


Figure 10 Normalized frequency of intermediate switching the lights off actions in FH offices

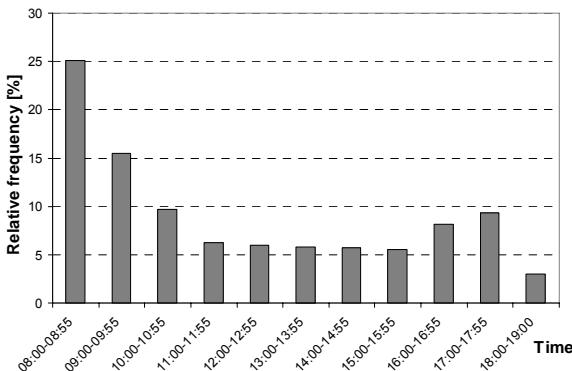


Figure 8 Normalized relative frequency of switching the lights on actions in FH over the course of a reference day

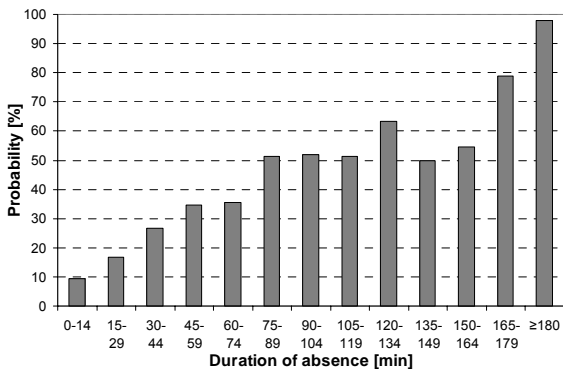


Figure 9 Probability of switching the lights off as a function of the duration of absence from the offices in FH

Figure 10 shows the normalized frequency of the (intermediate) "switching the lights off" actions as a function of the prevailing illuminance level immediately prior to the action's occurrence. Normalization denotes in this case the consideration of occupancy and the applicable durations of the respective illuminance bins while deriving the actions' frequency.

Shades

Figure 11 shows the mean and seasonal shade deployment degrees for a reference day, averaged over the entire observation period and for each season. Thereby, 100% denotes full shades deployment, whereas 0% denotes no shades deployed.

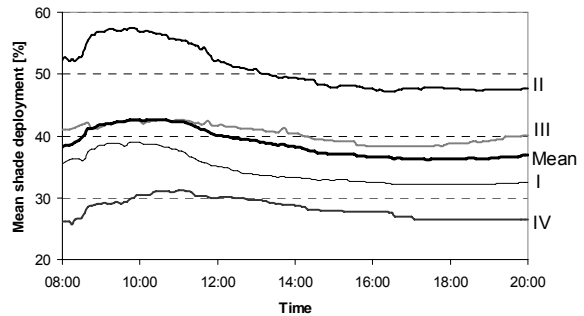


Figure 11 Mean shade deployment over the course of reference days (I: January to April; II: April to July; III: July to October; IV: October to January)

Figure 12 represents the mean monthly shade deployment degree together with the mean monthly measured global (vertical) irradiance.

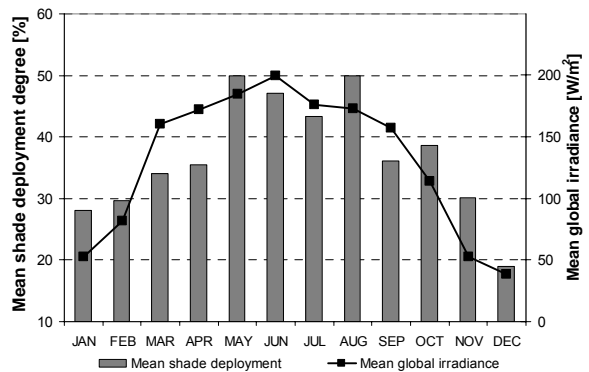


Figure 12 Mean monthly shade deployment degree

Figure 13 shows the mean shade deployment degree as a function of the incident global vertical irradiance on the façade.

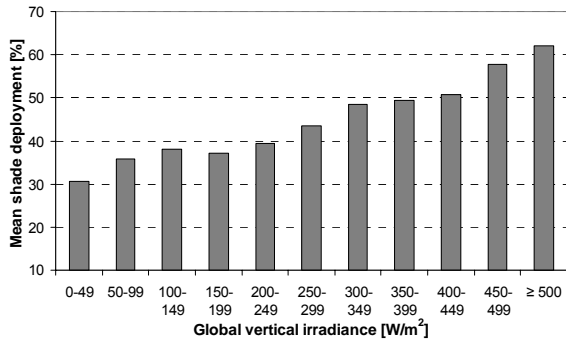


Figure 13 Mean shade deployment degree as function of global vertical irradiance

Figure 14 shows the normalized relative frequency of the actions "opening shades" and "closing shades" as a function of global vertical irradiance incident on the facade. Figure 15 shows the normalized relative frequency of the same actions as a function of outdoor air temperature. Likewise, Figure 16 shows the normalized relative frequency of the actions "opening shades" and "closing shades" as a function of the "sol-air temperature" (ASHRAE 2001). Normalization means that the frequency of actions (opening and closing shades) is related here to both occupancy and the duration of times in which the prevailing irradiance was within a certain range (bin).

Note that in Figures 14 to 16 opening/closing actions are not limited to actions resulting in fully opening/closing the shades. Rather, they denote a relative occupant-driven change in the position of the shades. This means that even an incremental change (e.g. changing from 80% to 40% or changing from 20% to 40%) is considered to be an opening/closing action.

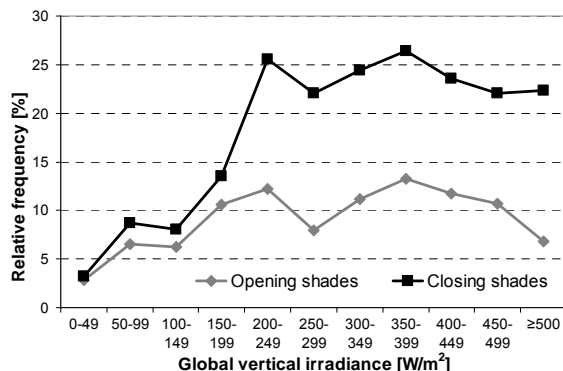


Figure 14 Normalized relative frequency of opening/closing shades as a function of global vertical irradiance

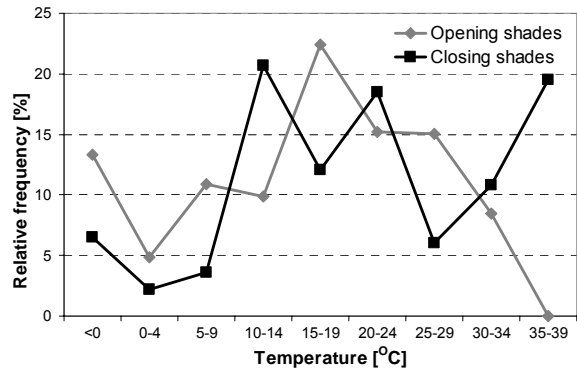


Figure 15 Normalized relative frequency of opening/closing shades as a function of outdoor air temperature

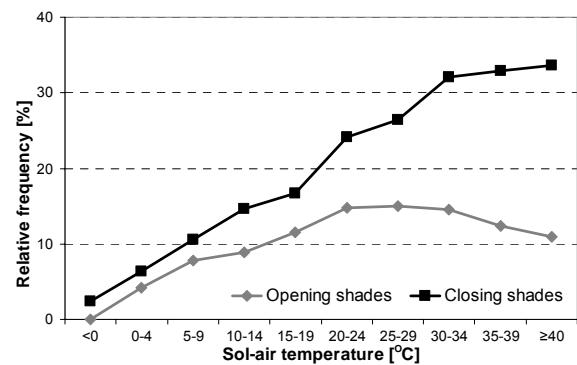


Figure 16 Normalized relative frequency of opening/closing shades as a function of sol-air temperature

DISCUSSION

The monitored occupancy in FH (Figure 2) and the obviously related people and lighting loads (see 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 (see Figures 17 to 19). Such simulations can be used, for example, to explore the impact of thermal improvement measures on the building's energy use). However, the maximum occupancy level is, in this case, comparatively low. This may be due to the circumstance, that our case study deals with offices of teaching and research staff, who spend a considerable amount of time in classrooms and laboratories. This underscores the need for typologically differentiated occupancy patterns for different buildings. Moreover, the differences in the both occupancy levels (see Figure 3) and lighting operation (Figure 5) in various offices of FH suggest the possibility of a more realistic simulation scenario using software agents to represent occupancy states in different offices in probabilistic terms.

On a more general level, our observations regarding this building suggests that the environment systems

in a considerable number of office buildings may in fact be "over-designed", in a sense that they are dimensioned for occupancy levels that seldom occur.

Concerning the dependency of the action "switching on the lights" on prevailing illuminance levels, no clear pattern emerges (see Figures 6 and 7). However, our data suggests that only illuminance levels below 100 lx are likely to trigger actions at a non-random rate. Moreover, 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 8).

As to the action "switching the lights off", a clear relationship to the subsequent duration of absence is evident (see Figure 9). Moreover, the respective intermediate actions appear to occur at a noticeably higher rate once the illuminance level in the office rises above 1000 lx (see Figure 10).

The position of the shades is, in this case, clearly related to the orientation of the offices observed (east). This explains the higher deployment level in the morning hours (see Figure 11). Moreover, the mean monthly shade deployment levels over the course of the year show a discernibly related the corresponding mean global (vertical) irradiance incident on the façade (see Figure 12).

An evident relationship between shade deployment and the magnitude of solar radiation is demonstrated in Figures 12 and 13. The latter provides a very effective basis for modeling the state of shades for this building (see Figure 20). Our observation did not reveal a clear relationship between "opening shades" actions and the incident radiation on the façade. However, the corresponding analysis of the "closing shades" actions shows a significantly higher action frequency once the incident radiation rises above 200 $W \cdot m^{-2}$ (see Figure 14).

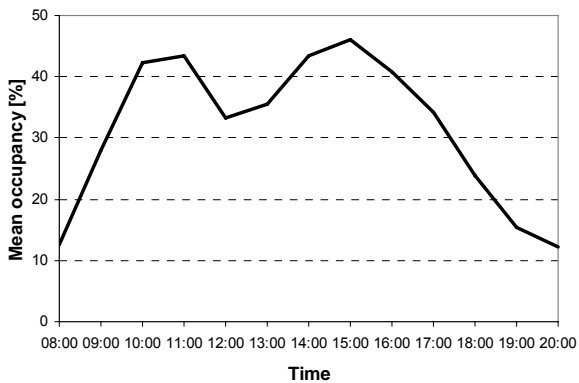


Figure 17 Illustrative simulation input data regarding mean hourly occupancy level for FH

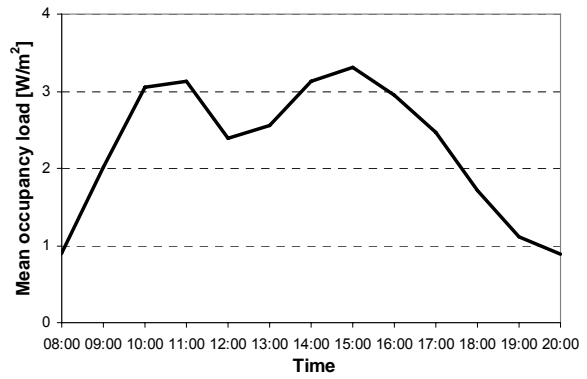


Figure 18 Illustrative simulation input data regarding mean hourly people (sensible) load for FH

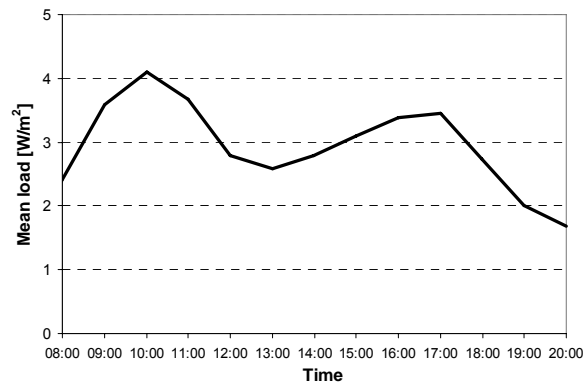


Figure 19 Illustrative simulation input data regarding mean hourly lighting load for FH

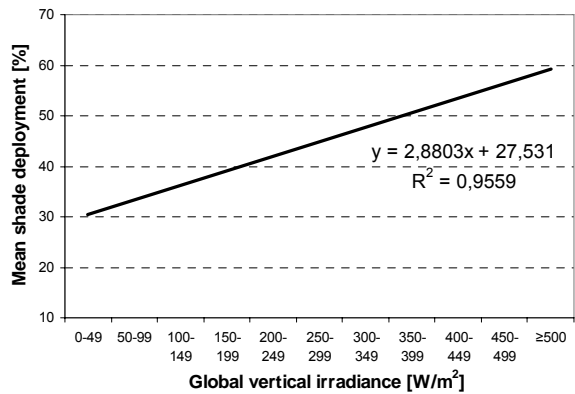


Figure 20 Illustrative model of shade deployment as a function of incident irradiance on FH's Facade

The occupant actions "opening shades" and "closing shades" do not display a clear relationship to the relevant outdoor air temperature values (see Figure 15). However, these actions seem to display an apparent dependency on the combined effect of solar radiation and air temperature as expressed in terms of the sol-air temperature (see Figure 16).

CONCLUSION

We presented a case study concerning user control actions in a university staff office building in Vienna, Austria. The results imply the possibility of identifying general patterns of user control behavior as a function of indoor and outdoor environmental parameters such as illuminance and irradiance. The compound results of the ongoing case studies are expected to lead to the development of robust occupant behavior models that can improve the reliability of computational building performance simulation applications.

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REFERENCES

- ASHRAE 2001. ASHRAE Handbook Fundamentals (SI) 2001, ASHRAE, Atlanta, GA, USA.
- Hunt D. 1979. The Use of Artificial Lighting in Relation to Daylight Levels and Occupancy, *Bldg. Envir.* (1979), 14: 21–33.
- Mahdavi A, Lambeva L, Pröglhöf C, Mohammadi A, and Kabir, E. 2006a. Integration of control-oriented user behavior models in building information systems. Proceedings of the 6th European Conference on Product and Process Modelling (13-15 September 2006, Valencia, Spain): eWork and eBusiness in Architecture, Engineering and Construction. Taylor & Francis/Balkema. ISBN 10: 0-415-41622-1. pp. 101 – 107.
- 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 GR. 1994. Manual Control of Window Blinds and Electric Lighting: Implications for Comfort and Energy Consumption, *Indoor Environment* (1994), 3: 135–44.
- Reinhart C. 2002. *LIGHTSWITCH-2002: A Model for Manual Control of Electric Lighting and Blinds*, Solar Energy (2002), v.77 no. 1, 15-28.