169: Observation-based models of user control actions in buildings

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Abstract

This paper summarizes the results of a long-term effort to study control-oriented occupant behavior in a number of office buildings in Austria. Specifically, states and events pertaining to occupancy, systems (particularly lighting and shading), indoor environment, and external environment were monitored. The results were analyzed in view of potential patterns in lighting and shading control behavior. Such patterns allow for derivation of predictive models of user control behavior in buildings.

Keywords: user actions, environmental systems, building automation, behavioral models

1. Introduction

Empirically-based information on frequency and kinds of users' interactions with buildings' environmental control systems (for heating, cooling, ventilation, lighting, and shading) is valuable for multiple reasons.

Firstly, to generate reliable results, building performance simulation applications require not only sound algorithms, but also accurate input data. Asides from building geometry, construction details, and weather conditions, data on user presence and control actions can significantly affect the outcome of simulation runs. Better user action models will thus improve the accuracy of performance simulation applications toward effective design support.

Secondly, user behavior can affect both buildings' energy performance and indoor climate. Structured knowledge on occupants' control actions can provide feed-back in support of building management activities and processes toward more efficient building operation.

Thirdly, building systems' design, configuration, and operation can benefit from empirically-based user control action models. Especially, in buildings with sophisticated building automation systems a balance must be achieved between centrally controlled environmental systems operations and user-based interventions in the state of control devices such as HVAC terminals, luminaires, and blinds. User-systems interaction models can be incorporated in the control logic repertoire of such buildings, thus allowing for timely anticipation and proactive accommodation of occupancy needs and requirements, while considering the monetary and environmental implications of alternative operational strategies.

In this context, the present contribution describes a long-term effort to monitor, document, and analyze control-oriented occupant behavior in a number of office buildings in Austria. Specifically, states and events pertaining to occupancy, systems (particularly lighting and shading), indoor environment, and external environment were monitored. Weather stations, a number of indoor data loggers, and digital cameras were used to monitor such events and states. The results were analyzed in view of potential patterns (dependencies of action occurrence and frequency on indoor and outdoor environmental parameters) in lighting and shading control behavior. Such patterns allow for derivation of predictive models of user control behavior in buildings. Our observations underscore the need for differentiated behavioral models for different buildings as patterns obtained from one building cannot be transposed to other buildings without calibration measures considering differences in buildings' function, size, context, envelope, systems, etc. However, user action models that are based on the outcome of actual long-term observations and high-resolution measurements in typical office buildings are preferable to most currently applied assumptions in systems design, simulation, and operation.

2. Background

A large number of studies have been conducted in the past decades to understand how building occupants interact with buildings' environmental control systems such as windows, blinds, and luminaires. Hunt [1] found a function which was reproduced by later studies [2, 3]: illuminance levels less than 100 lx lead to a significant increase of the 'switching on' probability (Fig. 1).

Pigg et al. [4] found a strong relationship between the propensity of switching the lights off and the length of absence from the room, stating that people are more likely to switch off the light when leaving the office for longer periods. Similar relationships were found by other studies [3, 5].

Boyce [5] observed intermediate light switching actions in two open-plan offices and found that occupants tend to switch the lights more often in relation to the daylight availability given smaller lighting control zones. Reinhart [6] suggested that the intermediate 'switching on' events are more common at lower than at higher illuminance values. Based on a related study conducted in a small office building in Lausanne, Lindelöf et al. [7] suggested an illuminance threshold of 100 lx, above which the probability of intermediate 'switching on' events was very low, whereas under this threshold the probability increased significantly.

Rubin et al. [8], Rea [9] and Inoue et al. [10] concluded that the blind operation rates varied greatly in relation to building orientation.

Lindsay et al. [11] conducted a study of 5 office buildings in UK and found a strong correlation between the operation of Venetian blinds and the solar radiation intensity (and sun position). Moreover, blinds were operated more frequently on the south façade.

Rubin et al. [8] suggested that occupants manipulate shades mainly to avoid direct sunlight and overheating. According to Inoue et al. [10], above a certain threshold of vertical solar irradiance on a façade (50 $W.m^{-2}$) the deployment level of shades is proportional to the depth of solar penetration into a room. This conjecture was corroborated by Reinhart [2].

Once closed, shades seem to remain deployed until the end of the working day or when visual conditions become intolerable. Rea [9] observed a rather low rate of blinds operation throughout the day, implying that occupants' perception of solar irradiance is a long-term one. Inoue et al. [10] observed a specific pattern concerning the relation between blind operation and incident illumination on the façade (Fig.2). Inoue concluded that occupants largely ignore short-term irradiance dynamics.

Herkel et al. [12] observed window operation in 21 south-facing single offices in Freiburg, Germany (with smaller and larger window units). Parameters such as window status, occupancy, indoor and outdoor temperatures, as well as solar radiation were regularly recorded. The analysis of the results revealed a strong seasonal pattern behind the window operation. In summer, 60 to 80% of the smaller windows were open in summer, in contrast to 10% in winter. The frequency of window opening/closing actions was observed to be higher in swing seasons spring and autumn. A strong correlation was found between the percentage of open windows and the outdoor temperature. Above 20 °C, 80% of the small windows were completely opened, whereas 60% of the large windows were tilted. Concerning the relationship to the time of the day, the windows were more frequently opened/closed in the morning (9:00) and in the afternoon (15:00). Moreover, window operation occurred mostly when occupants arrived in or left their workplaces. At the end of the working day, most open windows were closed.

Reinhart [6] developed LIGHTSWITCH 2002 using a dynamic stochastic algorithm. Based on an occupancy model and a dynamic daylight simulation application, predicted manual lighting and blind control actions provided the basis for the calculation of annual energy demand for electrical lighting.

Page et al. [13] hypothesized that the probability of occupancy at a given time step depends only on the state of occupancy at the previous time step. As suggested by Fritsch [14] in relation to window operation, Page explored the use of Markov chains toward occupancy prediction. Most studies of user-system interactions are conducted for individual building systems (lighting, shading, etc.). Bourgeois [15] attempted to bridge the gap between energy simulation and empirically-based information on occupant behavior via a self-contained simulation module called SHOCC (Sub-Hourly Occupancy Control) that was integrated in ESP-r application [16].

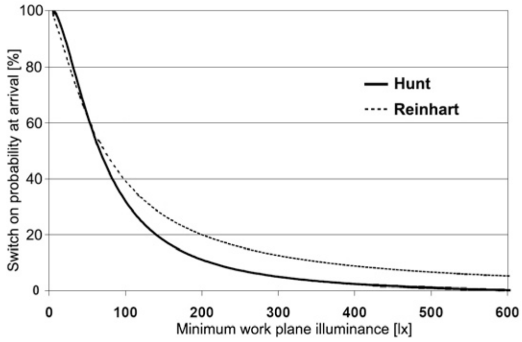

Figure 1. Probability of switching the lights on at arrival in the office

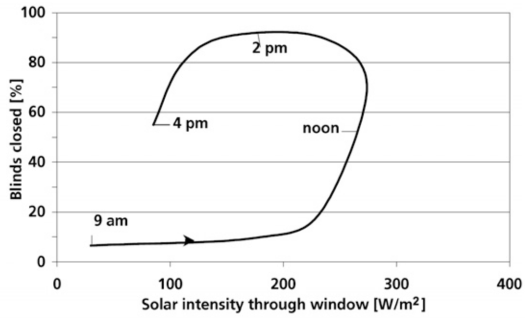

Figure 2. Percentage of blinds closed for SSW façade in relation to the vertical solar irradiance

3. Approach

3.1 Objects

To systematically collect a large consistent set of observational data regarding building occupants' presence and control action patterns, we concentrated on five office buildings in Vienna, Austria [17]. We refer to these buildings henceforth as VC, FH, ET, UT and HB. In some cases the data analyses for VC included a differentiation between office groups facing North and South-West. To denote this, we use the abbreviations VC-N and VC-S. Data collection was conducted on a long-term basis (9 to 14 months).

General information regarding these offices is provided in Table 1. The intention was to observe user control actions pertaining to lighting and shading systems while considering the indoor and outdoor environmental conditions under which those actions occurred.

Table 1: Summary information on selected office buildings

Code	VC	FH	ET	UT	HB
Location	Vienna	Vienna	Eisenstadt	Vienna	Hartberg
Function	International Organization	University	Telecom. services	Insurance	State government
Data collection	12 month	12 month	9 month	14 month	9 month
Work places observed	29	17	18	89	10
Orientation	N and SW	E	W	All	NW
Glazing to façade ratio	52 %	34 %	54 %	89 %	34 %
Glazing to floor ratio	26 %	18 %	20 %	51-80 %	18 %
Glazing transmittance	79 %	65 %	60 %	65 %	75 %
External Shades	-	Blinds (motorized)	Blinds (motorized)	Blinds (automated)	Blinds
Internal Shades	Blinds	-	Vertical louvers	Indoor screens (motorized)	curtains
Windows	Not operable	Not operable	Operable	Operable	Operable
HVAC	Air-conditioned	Air-conditioned	Mix mode	Mix mode	Naturally ventilated

3.2 Monitored parameters

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. In UT, the above mentioned parameters were continuously registered by the building's automation system. The external weather conditions were monitored using a weather station, mounted either directly on the top of the building or the rooftop of a close-by building. Monitored outdoor environmental parameters included air temperature, relative humidity, wind speed and wind direction, as well as global horizontal illuminance and global horizontal irradiance.

Internal climate conditions were measured with data loggers distributed across the workstations. To obtain information regarding user presence and absence intervals, occupancy sensors were applied, which simultaneously monitored the state of the luminaries in the offices. Collected data were stored and processed in a data base for further analysis.

4. Results

Figures 3 to 12 show selected results of the data analysis.

i) Occupancy

Figure 3 shows the mean occupancy level (i.e., presence in users' offices or at workstations) in VC, FH, ET, UT and HB over the course of a reference day (averaged over the entire observation period).

As Figure 4 exemplifies (using FH data), occupancy patterns can vary considerably from office to office.

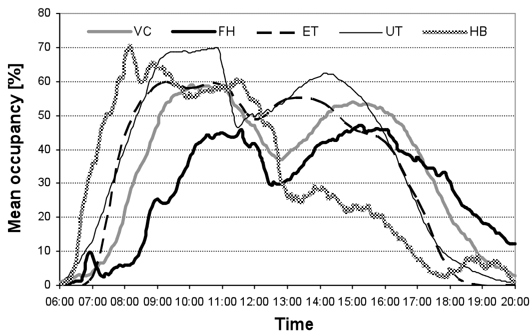

Figure 3. Mean occupancy level for a reference day in VC, FH, ET, UT and HB

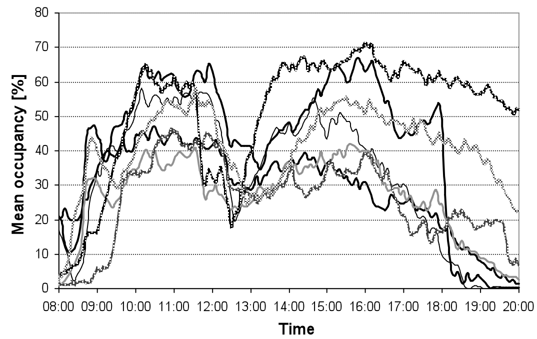

Figure 4. Observed occupancy levels in 7 different offices in FH for a reference day

ii) Lighting load and occupancy

Figure 5 shows lighting operation (in observed offices in FH, VC, UT, and HB) in the course of a reference day expressed in terms of effective electrical lighting load.

Figure 6 depicts (as regression lines), for all time intervals during the working hours in the observation period (in FH, VC-N, VC-S, and HB), the relationship between mean presence level (in %) and effective electrical lighting operation level (in % of the installed maximum lighting load).

Figure 7 shows the relationship between the mean effective electrical lighting power (expressed as the percentage of installed lighting power) averaged for all zones in UT (for time intervals between 6:00 and 18:00) and the external global horizontal irradiance. Time intervals with and without shade deployment are shown separately, together with the function for all time intervals.

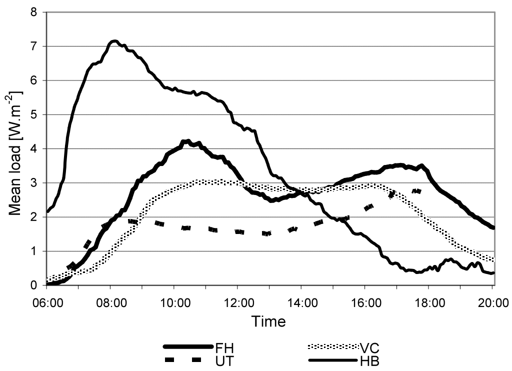

Figure 5. Lighting operation in FH, VC, UT, and HB offices

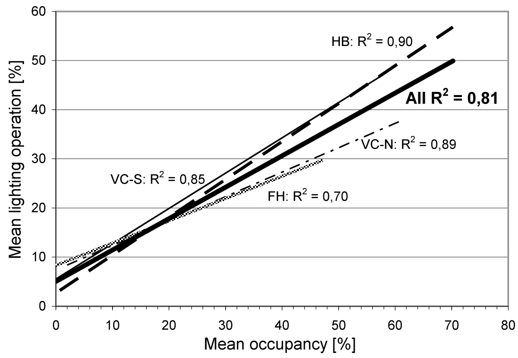

Figure 6. Lighting operation in relation to mean occupancy for all time intervals of the working hours during the observation period in FH, VC-N, VC-S, and HB offices (shown is also the regression line for all observations)

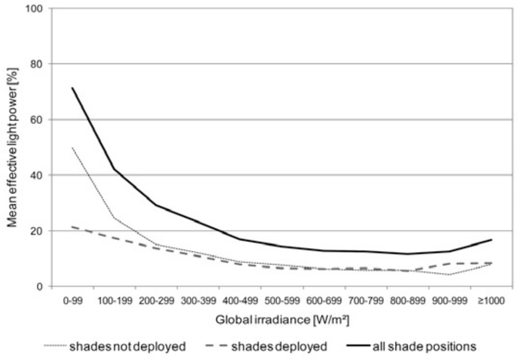

Figure 7. Mean effective electrical lighting power averaged for all zones plotted against external global horizontal irradiance (time intervals with and without shade deployment are shown separately)

iii) Lights switch on actions

Figure 8 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 (for FH and VC).

Figure 9 illustrates, for UT, the relationship between the normalized relative frequency of light switch on actions and indoor light levels (horizontal illuminance levels as measured by the building automation system's ceiling-mounted light sensors). Note that for this analysis, only those time intervals are considered where the shades were fully open. Moreover, in UT, the occupants turn the lights (change the setting from 0 lx to 500 lx) on via the desktop interface of the building automation system.

Figure 10 shows, again for UT, the normalized relative frequency of 'switch on' actions (0 lx to 500 lx) in the observed zones as a function of the vertical global irradiance incident on the façade measured for the orientation of the respective zones. For this analysis, only those time intervals are considered when all shades (internal and external) were open.

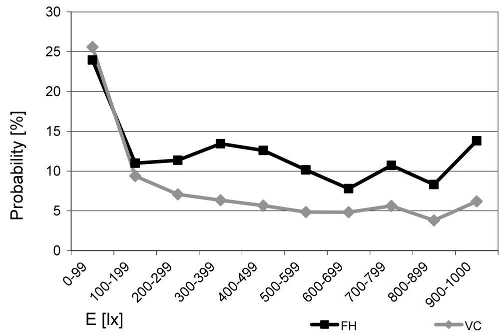

Figure 8. Probability of switching the lights on upon arrival in the office in FH and VC as a function of the prevailing task illuminance level prior to an action

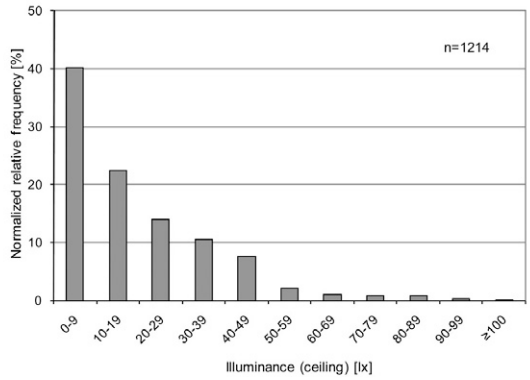

Figure 9. Normalized relative frequency of 'switch on' actions (0-500 lx) in UT as a function of ceiling illuminance (6:00 to 18:00, all shades open)

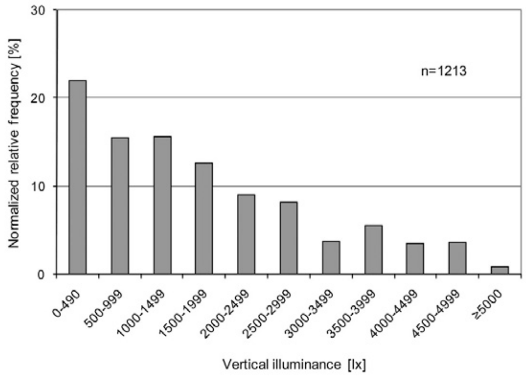

Figure 10. Normalized relative frequency of 'switch on' actions (0-500 lx) as a function of vertical illuminance (between 6:00 and 18:00, all shades open)

iv) Lights switch off actions

Figure 11 shows the probability that an occupant (in FH, VC, and HB) 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.

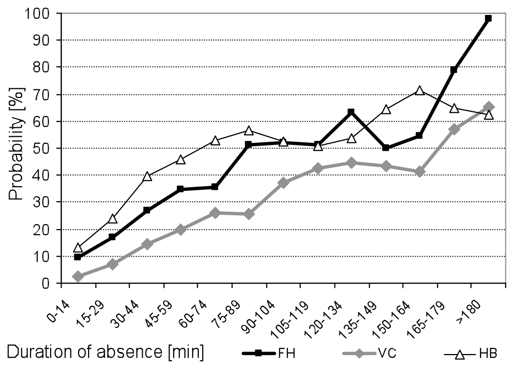

Figure 11. Probability of switching the lights off as a function of the duration of absence (in minutes) from the offices in FH, VC, and HB

v) Shade deployment and irradiance

Figure 12 shows the mean shade deployment degree (percentage of the shaded window area) for FH, VC-N, and VC-S as a function of global irradiance.

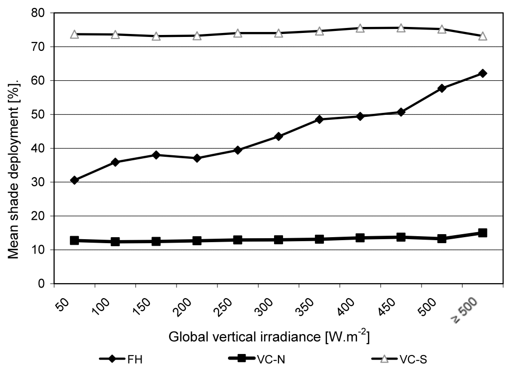

Figure 12. Mean shade deployment degree (FH, VC-N, and VC-S) as a function of global vertical irradiance

5. DISCUSSION

In the following, we summarize a number of reflections and interpretations concerning the study's results as presented in the previous section of the paper.

i) Occupancy

The mean fraction of office hours actually occupied by the users (Fig.3) is rather low (from 37% in FH to 49% in HB). In general, the differences between the extent and patterns of occupancy in offices buildings are quite considerable. Occupancy models of office buildings must thus take into consideration the specific use types, functions, and required working hours of the respective occupants. Inter-individual differences in occupancy patterns can be highly significant (Fig.4). Such differences can be important especially while simulating heating, cooling, and ventilation processes in buildings. Given sufficient observations, statistical methods can be used to generate individual occupancy patterns that, while unique – and realistic in their fluctuations – could represent, in toto, the mean occupancy level associated with a building.

ii) Lighting load and occupancy

The relationship between occupancy and the operation of electrical lighting can be highly complex (due to differences in buildings' location and orientation, floor, window area and glazing type, shading system, available view and daylight, etc.). Nonetheless, as Figure 6 demonstrates, there is a clear relationship between occupancy level and electrical light usage in the monitored offices. An exception in this regard was, in our study, UT, where no significant relationship between occupancy and light operation level could be observed. This may be explained, in part, by this objects efficient use of daylight, which is also reflected in the relatively low mean lighting load (see Fig.5 and 7).

iii) Lights switch on actions

In the most monitored offices, only rather low workstation illuminance levels (well below 200 lx) appear to trigger a non-random increase in probability of switching the lights on upon occupants' arrival in their offices/workstations (see Fig.8 and 9). A possible explanation for this circumstance may be the increasing portion of office time spent in front of computer displays. Note that in UT light levels were available not as horizontal workstation illuminance levels, but as illuminance levels monitored via ceiling-mounted illuminance sensors. Thus, given the complex relationship between measured illuminance at ceiling and at workstation, it is not possible to directly compare results shown in Figures 7 and 8. In UT, where the daylight usage is relatively high, a clear relationship between switch on actions and the outside illuminance (as represented by measured vertical illuminance on the facade) could be established (Fig.10).

iv) Lights switch off actions

Our data (Fig.11) confirms the results of a number of previous studies concerning the dependency of switching off probability of lights by occupants who leave their workstations on the duration of the time they stay away.

v) Shade deployment and irradiance

The mean shade deployment levels differ from building to building and façade to façade (see Fig.12). In case of FH, where we studied the east-facing façade, a relationship between shade deployment and the magnitude of solar radiation is observable. In case of VC-S and VC-N, the shade deployment level does not vary much, but there is a significant difference in the overall shade deployment level between these two facades (approximately 75% in the case of south-west-facing façade, 10% in the case of the north-facing façade). Overall, our data suggests that the shade deployment level in buildings cannot be predicted reliably on the basis of incident irradiance alone.

6. Conclusion

We presented the results of a study concerning user presence and control actions in a number of office buildings in Austria. The results imply the possibility of identifying certain patterns of user control behavior as a function of indoor and outdoor environmental parameters such as illuminance and irradiance. However, our observations also underscore the need for typologically differentiated occupancy and control action models for different buildings. Patterns obtained from one building cannot be transposed to other buildings without extensive calibration measures considering differences in buildings' use (function), size, context (physical, climatic, cultural), orientation, envelope, systems, etc. Nonetheless, efforts are justified to apply the collected data to date toward the generation of preliminary models of user presence and behavior. As these data are the outcome of actual long-term observations and high-resolution measurements in typical office buildings, they are more representative than most currently applied – highly simplified – models of user presence and behavior in buildings.

In future, more reliable people presence and actions models are expected to improve the accuracy of simulation studies (for example, to explore the impact of thermal improvement measures on the building's energy use) and to enrich the control logic in building automation systems.

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