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TOWARD EMPIRICALLY-BASED MODELS OF PEOPLE'S PRESENCE AND ACTIONS IN BUILDINGS

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ABSTRACT

This paper presents the results of a recent study of people's presence and their interactions with the buildings' environmental systems in a number of buildings in Austria. The intention was to observe user control actions pertaining to building systems while considering the indoor and outdoor environmental conditions under which those actions occurred. The results of this study suggest that such interactions are difficult to predict at the level of an individual person. However, general control-related behavioral trends and patterns for groups of building occupants can be extracted from long-term observational data. Moreover, such trends and patterns show in many instances significant relationships to measureable indoor and outdoor environmental parameters. They can thus provide a reliable basis for occupancy and control action models in performance simulation applications.

INTRODUCTION

It is common knowledge that the presence and actions of building occupants have a significant impact on the performance of buildings (energy efficiency, indoor climate, etc.). Current practices in modeling the presence and actions of people in buildings do not display the necessary level of sophistication to reflect the complexity of people's passive and active impact on building performance: general information about building type (residential, commercial) and environmental systems (free-running, air-conditioned) as well as organizational information (working hours) can only provide rough directions regarding the far-reaching implications of user presence and actions in buildings.

More reliable people action models require extensive observational data based on empirical studies of control-oriented user behavior (as related to buildings' environmental systems) in a representative number of buildings. Thereby, possible relationships between control actions and environmental conditions inside and outside buildings can provide the underlying basis for predictive functions of user behavior for incorporation in building simulation applications.

In a recent study, we observed, over a period of 9 to 14 months, people's presence and their interactions with the buildings' environmental systems (lighting, shading, ventilation) in a number of buildings in Austria. The intention was to observe user control actions pertaining to building systems 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 was derived based on regularly taken digital photographs of the façade.

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 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.

The results of this study suggest that such interactions are difficult to predict at the level of an individual person. However, general control-related behavioral trends and patterns for groups of building occupants can be extracted from long-term observational data. Moreover, such trends and patterns show in many instances significant relationships to measureable indoor and outdoor environmental parameters. Thus, our observations underscore the need for typologically differentiated occupancy 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 reliable (representative) than most currently applied simulation input assumptions.

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. A number of such studies are briefly described in the following. Note that this review is not claimed to be comprehensive. Rather, the objective is to provide an impression of the kinds and scope of the relevant research efforts. As such, there are significant differences between individual studies in this set in terms of building size and type, relevant control devices (luminaires, shades, windows, etc.), duration of observation, measured environmental factors, and measurements' precision. Nonetheless, most of these studies share a common feature in that they attempt to establish a link between user control actions (or the state of user-controlled devises) and measurable indoor or outdoor environmental parameter.

Hunt (1979) introduced a function regarding the lighting conditions in offices and the probability that the occupants would switch on the lights upon their arrival in the office. According to this function, only illuminance levels less than 100 lx lead to a significant increase of the 'switching on' probability. Similar functions were subsequently suggested by Love (1998) and Reinhart (2001).

Pigg et al. (1996) 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 (Boyce 1980, Reinhart 2001). Boyce (1980) observed intermediate light switching actions in two open-plan offices and found that occupants tend to operate the lights more often in relation to the daylight availability given smaller lighting control zones. Reinhart (2004) 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 and Morel (2006) 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. (1978), Rea (1984), and Inoue et al. (1988) concluded that the blind operation rates varied greatly in relation to building orientation. Lindsay and Littlefair (1992) 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. (1978) suggested that occupants manipulate shades mainly to avoid direct sunlight and overheating. According to Inoue et al. (1988), 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 (2001). Once closed, shades seem to remain deployed until the end of the working day or when visual conditions become intolerable. Rea (1984) 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. (1988) observed a specific pattern concerning the relation between blind operation and incident illumination on the façade. Inoue concluded that occupants largely ignore short-term irradiance dynamics.

Herkel et al. (2005) 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 contrast to 10% in winter. The frequency of window operation 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. The windows were opened and closed more frequently 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.

Exploring an stochastic simulation approach toward consideration of occupant behavior in buildings, Nicol (2001), as Hunt (1979) before him, used probit analysis (Finney 1947) to examine correlations between outdoor temperature and the use of windows, heating, and blinds. The study suggested that information on solar radiation intensity would be necessary to establish correlations pertaining to light and blind usage.

Reinhart (2004) 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. (2007) 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 et al. (1990) in relation to window operation, Page et al. (2007) 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 (2005) attempted to bridge the gap between energy simulation and empirically-based information on occupant behavior via a selfcontained simulation module called SHOCC (Sub-Hourly Occupancy Control) that was integrated in ESP-r application (ESRU 2002).

Humphreys & Nicol (1998) introduced an adaptive approach to human thermal comfort stating that ‘people react in ways which tend to restore their comfort, if a change occurs such as to produce discomfort’.

Conducting a field survey, Rijal et al. (2007) concentrated on window opening behavior in naturally ventilated buildings with regard to indoor (globe) temperature and outdoor air temperature as trigger parameters. The resulting "adaptive algorithm" (Humphreys & Nicol 1998) was implemented in ESP-r toward a more realistic thermal comfort and building performance assessment.

The above studies – and other similar ones – have provided a number of valuable insights into the circumstances and potential triggers of occupancy control actions in buildings. However, given the complexity of domain, additional long-term and (geographically and culturally) broader studies are necessary to arrive at more dependable (representative) models of control-oriented user actions in buildings.

APPROACH

Within the framework of a recent cross-section study performed by the author and his associates in Austria, an attempt was made to systematically collect a large consistent set of observational data regarding building occupants' presence and control action patterns (Mahdavi et al. 2008a, 2008b, Mahdavi and Pröglhöf 2008). This study, given its large-scale, long-term, high-resolution nature, represents an appropriate case in point to demonstrate the potential, complexities, and challenges associated with the derivation of empirically grounded user presence and behavior models in buildings. The study was conducted in five office buildings in Austria (Mahdavi et al. 2008a). These buildings are referred to henceforth as VC, ET, FH, 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, the abbreviations VC-N and VC-S are used. Data collection was conducted on a long-term basis (9 to 14 months).

General information regarding these offices is provided in Table 1. The main intention of the study was to observe user control actions pertaining to lighting and shading systems (and in the case of one building, window operation) while considering the indoor and outdoor environmental conditions under which those actions occurred.

Indoor environmental data (room temperature, relative humidity, and illuminance) were monitored using data loggers distributed across 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. Position of shading and windows were 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% denotes no shades deployed, whereas 100% denotes

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 (15+14)	17	18	89	10
Orientation	N and SW	E	E	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

full shading). Measured outdoor environmental parameters included air temperature, relative humidity, and wind speed, as well as global horizontal irradiance. These parameters were monitored using weather stations, mounted either directly on the top of the building or the rooftop of a close-by building. With the exception of the shade and window states, which were monitored every 10 minutes, all the above data were monitored every 5 minutes. Vertical global irradiance incident on the façades was computationally derived based on measured horizontal global irradiance (see Mahdavi et al. 2006).

RESULTS

The above study generated an extensive quantity of data. The analysis of data provided a number of results, some of which are discussed below.

Figure 1 shows the mean occupancy level (i.e., presence in users' offices or at workstations) in VC, ET, FH, UT, and HB over the course of a reference day (representing the entire observation period). There can be considerable differences amongst the offices in the same building in view of occupancy patterns. To provide an statistically relevant sense of the fluctuations of such data, Figure 2 depicts, for UT, the mean occupancy level together with respective standard deviation values. Occupancy models in simulation applications must thus take into consideration the specific use types, functions, and associated presence hours of the respective occupants.

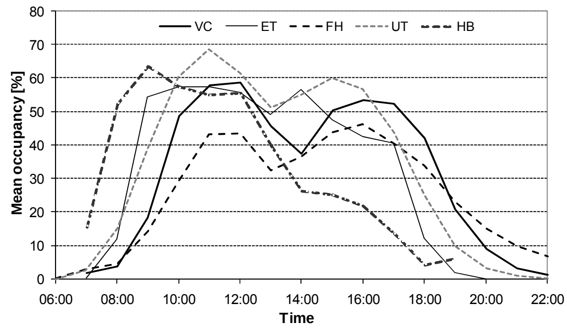

Figure 1 Mean occupancy level for a reference day in VC, ET, FH, UT, and HB

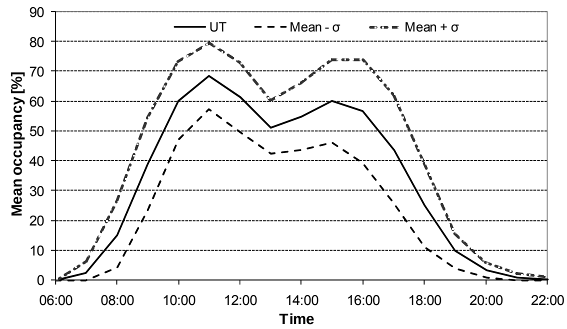

Figure 2 Mean occupancy level and standard deviation for a reference day in UT

Figure 3 depicts (as regression lines), for all time intervals during the working hours in the observation period (in VC-N, VC-S, FH, and HB), the relationship between mean presence level (in %) and effective electrical lighting operation level (in % of the installed maximum lighting load). The information captured in this Figure appears to imply a clear relationship between occupancy level and electrical light usage in the monitored offices. However, 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.). For example, no significant relationship between occupancy and light operation level could be observed in UT (Mahdavi and Pröglhöf 2008). This may be explained, in part, by this object's efficient use of daylight.

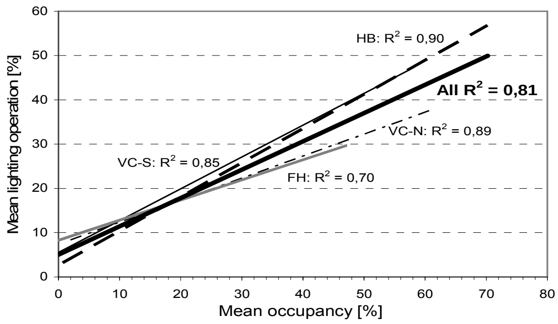

Figure 3 Lighting operation (in % of maximum installed load) in relation to mean occupancy for all time intervals of the working hours during the observation period in VC-N, VC-S, FH, and HB offices (shown is also the regression line for all observations)

Figure 4 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 VC and FH). In the most monitored offices, rather low workstation illuminance levels (measured horizontal task 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. This represents an interesting challenge in terms of the selection of appropriate (objective) visual performance criteria: Occupants' actions (in this case switching the lights on) is more likely to be triggered by the perceived general light conditions in the room, for which the horizontal task illuminance level may not be the appropriate indicator. The critical indicator value (for triggering actions) may shift considerably, if a different sensor position is selected. For example, Figure 5 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, 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.

In UT, where the daylight usage is relatively high, an unambiguous relationship could be discerned between switch on actions and the outside (vertical) illuminance (see Figure 6).

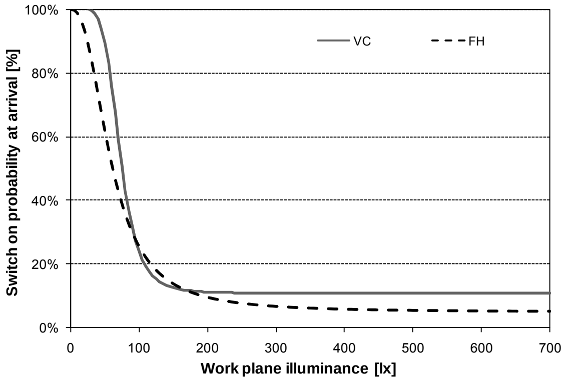

Figure 4 Probability of switching the lights on upon arrival in the office in VC and FH as a function of the prevailing task illuminance level

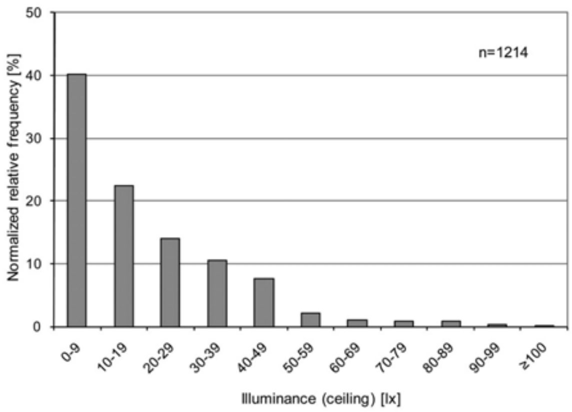

Figure 5 Normalized relative frequency of 'switch on' actions (0-500 lx) in UT as a function of ceiling illuminance (6:00 to 18:00, all shades open)

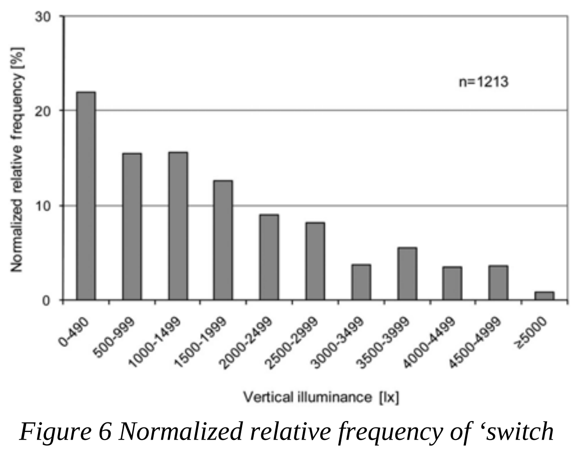

Figure 6 Normalized relative frequency of 'switch on' actions (0-500 lx) as a function of vertical illuminance (intervals between 6:00 and 18:00 with shades open)

Figure 7 shows the probability that an occupant (in VC, FH, 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. This finding is conform with the results of a number of previous studies (Pigg et al. 1996, Boyce 1980) concerning the dependency of probability of light switch off actions by occupants who leave their workstations on the duration of the time they stay away.

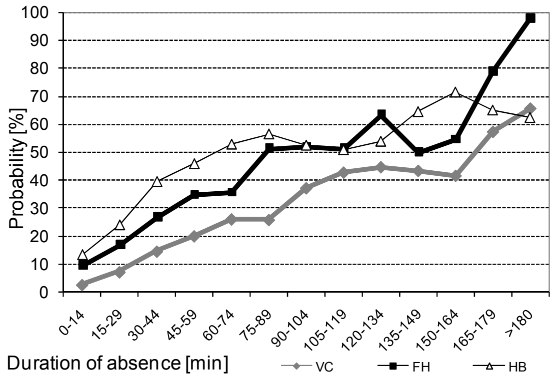

Figure 7 Probability of switching the lights off as a function of the duration of absence (in minutes) from the offices in VC, FH, and HB

The mean shade deployment levels (expressed as percentage of window area occluded due to shade operation) differ from building to building and façade to façade (see Fig. 8). In case of FH's 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 fluctuate 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).

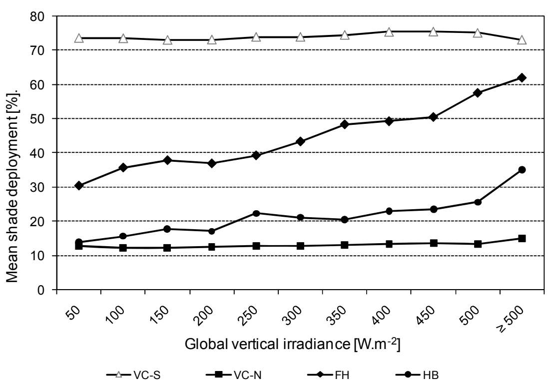

Figure 8 Mean shade deployment degree (VC-S, VC-S, FH, and HB) as a function of global vertical irradiance incident on the façade

As to natural ventilation operation, it has been suggested that the deviation of indoor air temperature from the "comfort temperature" can trigger window opening actions (when the rooms appear warm or hot) and window closing actions (when the room appears cool or cold). This conjecture appears to be partially corroborated by the data collected in HB and illustrated in Figure 9. Thereby, the frequency distributions of window opening and closing actions are plotted against the difference between indoor air temperature and the neutrality temperature (Auliciems 1981).

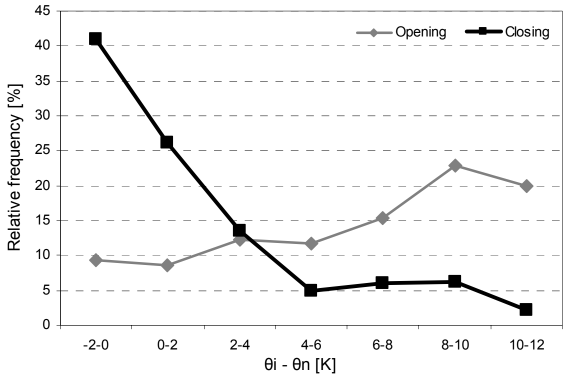

Figure 9 Relative frequency of window opening and closing actions as a function of the difference between indoor air temperature and neutrality temperature

Moreover, Figure 10 displays a clear relationship between window opening level and the difference between indoor temperature and neutrality temperature. The maximum mean window opening degree coincides with the minimum deviation of indoor temperature from neutrality temperature. As this temperature difference increases, the mean opening level decreases considerably.

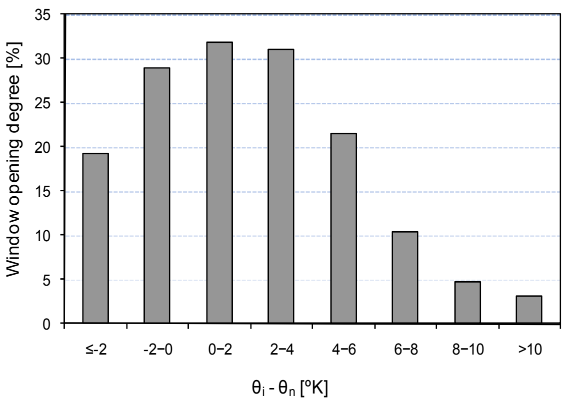

Figure 10 State of windows as a function of the difference between indoor air temperature and neutrality temperature

GENERAL MODELS

The previous section provided the example of a case study involving collection of observational data pertaining to user presence and control-oriented actions in buildings. Such studies can of course deepen the insights of building performance simulation specialists and enable them to better qualify the results they obtain from simulation given the kinds of user presence and action information they use in their models. However, beyond general "sensitization", it would be desirable to incorporate the result of such studies in a more direct way in the performance simulation process. Toward this end, the data must be properly evaluated, prepared, and processed. One possibility to utilize such data toward building performance applications is the derivation of generalized (aggregate) models.

For example, the relationships shown in the following figures (Figures 11 to 14) were derived by based on the research described in the previous section and represent examples of proposals for general simulation input models to capture occupancy and user-based control actions (office buildings, work days, Austria). Figure 11 shows the proposed model for mean occupancy. Figure 12 illustrates the proposed general light switch on probability model based on task illuminance level immediately prior to the onset of occupancy.

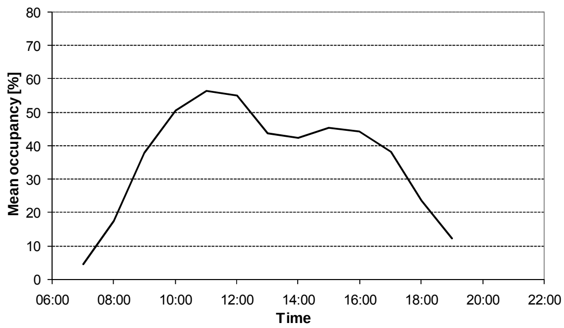

Figure 11 Mean occupancy input model for building performance simulation applications

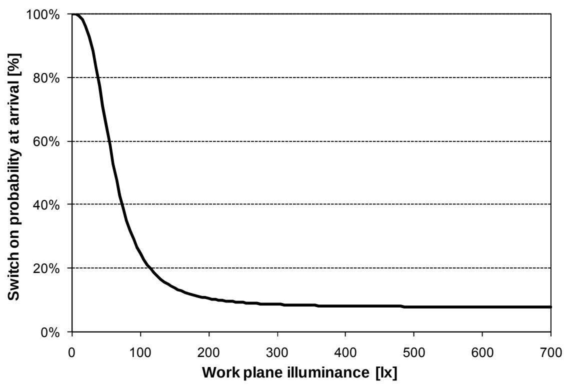

Figure 12 Light switch on probability model based on task illuminance level immediately prior to the onset of occupancy

Figure 13 shows the proposed light switch off probability model based on duration of absence from the workstation. Figure 14 shows the proposed general dependency model of shades deployment level (in %) as a function of façade orientation and the incident global (vertical) irradiance on the façade.

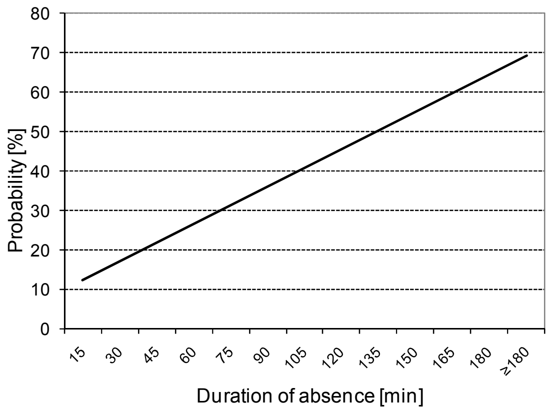

Figure 13 Light switch off probability model based on duration of absence from the workstation

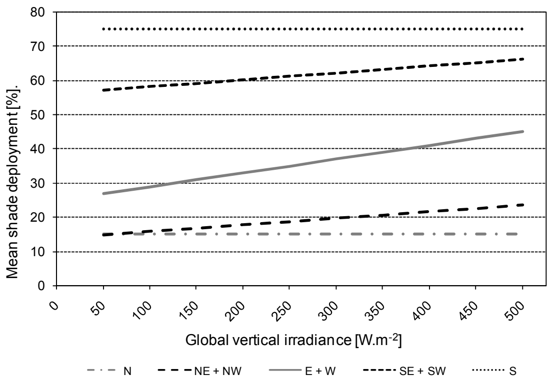

Figure 14 Dependency model of shades deployment level (in %) as a function of façade orientation (S: South, NE: North-East, NW: North-West, E: East, W: West, SE: South-East, SW: South-West, S: South) and the incident global (vertical) irradiance on the façade

Such aggregate models represent, of course, general trends and not specific conditions in any specific building. Consequently, their relevance is limited to the context (country, climate, culture, building type, etc.) from which their underlying observational data originate (in this case various office buildings in Austria). Nonetheless, they have a clear place and arguably fitting role in important areas of simulation-based building performance inquiry. Specifically, simulation-based assessment of design versions and design alternative (a presumably common activity in the initial phases of the building delivery process) is often required to provide concise statements as to the overall performance of the building "hardware" under "standardized" conditions pertaining to both external climate and internal (occupancy-related) processes.

CONCLUSION

The reliability of results obtained from building performance simulation applications depends not only on the validity of computational algorithms, but also on the soundness of input assumptions. While there has been significant progress concerning methods and practices for specification of building geometry, material properties, and external (weather) conditions, the resolution of input information regarding occupancy (i.e. people's presence and behavior in buildings) is still rather low. However, the importance of people's passive and active effects on building performance (e.g. indoor conditions, energy performance) has been recognized for some time. Accordingly, many recent and ongoing research efforts attempt to construct models for passive and active occupancy effects on building performance. Thereby, physiological and psychological descriptions of occupancy as well as empirically-based observational data provide the knowledge base. Specifically, long-term high-resolution empirical data on people's presence and control-oriented actions in buildings can support the generation of general patterns of user control behavior as a function of indoor and outdoor environmental parameters such as temperature, illuminance, and irradiance. These patterns can be expressed either as set of typologically differentiated standardized (aggregate) occupancy and control action models or realized in terms of emergent behavior of a society of computational agents with embedded stochastic features. Future developments in this area are expected to facilitate a detailed and dynamic simulation of environmental processes in buildings via comprehensive multiple-coupled representations that dynamically capture the states of occupancy, building, and context.

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