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DISSERTATION

USER INTERACTION WITH ENVIRONMENTAL CONTROL SYSTEMS IN AN EDUCATIONAL OFFICE BUILDING

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Doktors der technischen Wissenschaften unter der Leitung von

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Kurzfassung

Die Nutzer eines Gebäudes bzw. ihr Umgang mit den Gebäudesystemen für Innenklimasteuerung können die Energie-Performance signifikant beeinflussen. Diese Tatsache wird selten von den Gebäudeforschern berücksichtigt. Verbesserung der Energieeffizienz wird am meisten durch Umsetzung neuer nachhaltiger Baumaterialien sowie energiesparenden und umweltfreundlichen Technologien angestrebt. Die Menschen mit ihrem Nutzerverhalten sind in diesem Forschungsgebiet unterrepräsentiert, obwohl sie eine wichtige Rolle für die Energieeffizienz spielen. Diese Dissertation ist ein Beitrag zu dem besseren, empirisch begründeten Verständnis des Nutzerumgangs mit den technischen Gebäudesystemen in Bürogebäuden. Im Rahmen eines Forschungsprojekts wurde ein Universitätsbürogebäude in Wien langfristig untersucht um allgemeine Muster des Nutzersteuerungsverhaltens zu identifizieren. Der Fokus dabei war der Nutzerumgang mit den Gebäudesystemen für Beleuchtung und Beschattung. Der Inhalt der Dissertation erläutert die Untersuchungsmethoden und Abläufe, sowie die Datenbearbeitung, Analyse und Ergebnisse der gesammelten Daten im Rahmen dieser empirischen Studie.

Außen- und Innenraumbedingungen im Gebäude wurden ein Jahr lang erfasst. Die Messwerte schliessen Anwesenheit, Lichtein-/ausschalten, Beleuchtungsstärke, globale Solarstrahlung, Innen-/Außentemperatur und relative Feuchtigkeit ein. Die Postion der Beschattung wurde mit der Hilfe digitaler Fotografie registriert. Es wurden ein Jahr lang Digitalfotos in Abständen von 10 min. gemacht. Die Bilder wurden mit einer semi-automatisierten Applikation bearbeitet und in ein Tabellenkalkulationsformat zusammengefasst.

Die gemessenen Parameter wurden analysiert um angenommene Zusammenhänge zwischen Nutzeraktionen und Innen-/Außenbedingungen festzustellen. Die Ergebnisse weisen darauf hin, dass der Zustand und die Bedienung der Beleuchtung und Beschattung mit den Innen- und Außenklima-Parameter zusammenhängen. Die Nutzerverhaltensmuster können in realistische Verhaltensmodelle umgesetzt werden, die der Verbesserung von Gebäude-simulationssoftware dient. Die Information über das Nutzersteuerungsverhalten ist ausschlaggebend für die genaue Voraussage der Gebäude-Performance und des Energieverbrauchs. Weiters führt die tiefere Kenntnis des Nutzerverhaltens zur Entwicklung innovativer Produkte wie Nutzerschnittstellen für Innenklima-Steuerung und zu höherer Energieeffizienz.

Abstract

This thesis contributes to the better empirically grounded understanding of the occupants' interaction with the environmental control systems in office buildings. With the intention to identify general patterns of user control behavior, based on long-term measurements, a study has been conducted in an educational office building in Vienna, Austria. The thesis chapters include monitoring methods and procedures, as well as data processing, analysis, and results of the collected data. The main tasks were observation and analysis of control-oriented occupant behavior toward systems for lighting and shading. High-resolution data for occupancy, light on/off, internal/external illuminance, temperature and relative humidity was collected for the period of one year. The measured parameters were analyzed to determine hypothesized relationship between user actions and indoor/outdoor conditions. The results indicate that the status and operation of electrical lights and shades depend both on indoor and outdoor environmental parameters. These behavioral patterns can be translated into realistic user action models for improving building performance simulation applications. Information on user control behavior is crucial toward accurate prediction of building performance and energy consumption. Moreover, deeper knowledge of user control behavior can lead to the development of innovative products such as user interfaces for more effective environmental control and higher energy efficiency.

Keywords: occupant behavior, user interaction, manual lighting control, operation of shades

Acknowledgment

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Parts of the text in this dissertation are adopted from the papers, written in relation to the project “People as Power Plant”, with authors prof. Mahdavi and the project-team members.

I would like to express my special gratitude to prof. Mahdavi for making this dissertation possible, for his ultimate and highly professional support during the entire period of my studies. I very much appreciated his insistence on writing scientific papers and participating in international conferences, which enriched my personality and broadened my horizons.

Special thanks to my colleagues Claus Pröglhöf, Abdolazim Mohammadi, Elham Kabir, Josef Lechleitner, and Georg Suter, with whom I was working in a team for almost three years. We had nice and productive time, which will remain unforgettable to me.

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TABLE OF CONTENT

1 Introduction

1.1 Overview

In the time of global climate changes, natural resource tightness and increasing energy prices, improving energy efficiency of buildings becomes a main priority. Researchers and construction industry are looking for sustainable solutions through developing new construction technologies and materials; developing advanced systems for environmental control; improving the building simulation software for better prediction of energy performance and indoor climate. Into consideration are taken mostly indoor and outdoor environmental factors, as well as physical building characteristics (geometry, materials) and hardware. One factor, quite underrepresented, when talking about building energy efficiency, is the human factor, i.e. the occupants and specifically their interaction with the building components and systems for indoor environmental control. People and their actions regarding these systems can significantly influence the microclimate and energy consumption of buildings. The energy conscious interaction with building control systems can be beneficial and result in reduced energy consumption. In contrast, inappropriate interface designs or locations, as well as insufficient knowledge about the functionality of indoor systems, can cause increased energy expenditure. Thus, consideration of user attitudes and behavior toward the indoor climate control devices should be obligatory, when addressing the optimization of energy efficiency in buildings.

The driving force that triggers occupants' actions is rather complex, involving various physical and psychological factors. In traditional building physics terms these factors are related to the definition of comfort (visual, thermal). People become "active" in buildings when improvement of their comfort (visual/thermal, emotional and psychological) is necessary. This common interpretation is insufficient for solving the complexity of human motivation for certain actions. The individual behavior can be affected not only by environmental factors but by others like: temporal – biorhythmic patterns during the day, season of the year, day of the week; spatial – room characteristics, position in space, building systems and control devices; nationality and cultural background; age and gender; education and technology interest etc.; type of activity, specific tasks etc.

The present research intends to extract behavioral patterns pragmatically, based on observations in real buildings, relating action frequencies with indoor or outdoor physical parameters and their dynamical changes. The empirical evidence of such type is still insufficient, in spite of the numerous existing researches. The goal of this thesis is to extend the knowledge, considering the environmental factors, based on long-term, empirically grounded observations of user interactions with control systems for lighting and shading in one Austrian office building. Within a research project the control-oriented occupant behavior in 13 offices in an educational building in Vienna (Austria) was observed over the 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, internal illuminance, 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 is presented and their principal potential as the basis of empirically grounded user action models in simulation applications explored.

Chapter 1 gives motivation for choosing the research topic and then an overview of the existing approaches in the area of occupants' behavior in buildings. Chapter 2 describes the research design and methods used for the study, giving details about the building and selected offices, data collection, data processing and analysis. The results are presented in Chapter 3, divided into categories for occupancy, operation of electrical lighting and operation of shading. Chapter 4 comments the results from the previous chapter following the same category sequence, as well as includes several model inputs for performance simulation applications. Additionally to the conclusions about manual operation of electrical lighting, 3 energy saving scenarios are presented. The general conclusion from the study together with future research perspectives in the area of occupants' behavior is included in Chapter 5.

1.2 Motivation

The goal of this thesis is to enhance the knowledge about the nature, logic, types, and frequency of control-oriented user behavior in buildings. Such knowledge can bring benefits in several directions. On one side, it supports the development of reliable, empirically-based behavioral models (of user-systems interactions in buildings). Furthermore, integration of "high-fidelity user behavior models (either in terms of general tendency patterns of statistical nature, or in terms of stochastic agents) in building performance simulation applications" (Mahdavi 2007a) can contribute to the more accurate prediction of building energy performance (energy consumption, indoor environment). On the other side, the consistent analysis of control-oriented behavior can provide information on the energy implications of the user control actions. User information campaigns can be initiated to educate and inform users regarding these implications. Knowing the consequences of their control actions, the occupants may consciously modify their behavior, resulting in energy conservation and improved indoor climate.

Analysis of the user attitudes toward the functionality of the building control systems can provide ideas and suggestions toward the improvement of design, operation and user interfaces of buildings' environmental control systems and devices.

Another utilization aspect is improving the communication and interaction between the building management services and the building occupants, and so addressing more effectively users' problems with buildings' environmental control systems. Furthermore, the many-sided knowledge of user control-behavior can help to advance "the performance of building management and automation systems via integration of proactive and user-responsive control algorithms and methods" (Mahdavi 2007a).

The complex exploration of user control behavior can produce guidelines for successful design of built environment and sustainable occupant interactions with building systems, which will aim the improvement of indoor climate and user satisfaction on one side, and on the other side - minimize the energy penalties in buildings.

1.3 Background

There are numerous studies of occupants' behavior toward systems for electrical lighting and shading in office buildings. All explore the existence of patterns of switching on/off lights, opening/closing of shades, and possible relationships with internal/external climatic conditions. Some of the studies concentrate on other factors like occupancy sensor controls or automatic control systems and their influence on occupants' behavior and comfort. A third aspect is the energy implication – which control strategy (manual, automated or combined) is most effective in terms of energy consumption.

The main goal of this research area is to achieve better understanding of peoples' control behavior (patterns and energetic consequences) to be able to predict more accurately the performance of building systems as well as to improve user satisfaction.

The studies have been performed mostly in real or test spaces, where information is gathered on: presence/absence of people in the room; status of lighting (on/off), shading (% of occlusion); control actions (switch on/off lights, open/close shades, open/close windows), their frequency, and time of occurrence; indoor climatic conditions (illuminance (ambient, work plane), temperature); outdoor climatic conditions (solar radiation (horizontal, on the facade)), illuminance, temperature etc. Other factors like orientation, sun position, and surrounding environment (obstructions, reflections) are also taken into consideration.

Each field study uses individual observation strategy and research methods, and delivers results with different levels of precision, which makes the direct comparison between them inconclusive. Though, few research studies in the last years try to verify and validate already established behavioral patterns by applying similar methods of analysis (Reinhart 2001, Bourgeois 2005).

The following paragraphs describe the major findings of previous studies regarding the manual operation of electrical lighting and shading.

Manual operation of electrical lighting

The studies in this area began in the late 70's with the goal to explore the impact of human factor on artificial lighting use and energy consumption, and possible optimization strategies by applying occupancy sensors. The issue was to observe how people operate their electrical lighting, in relation to daylight levels and occupancy. The measurements were conducted in private, double occupancy offices, as well as open plan offices, with manual operation of lights.

The major findings in this area can be summarized as follows:

1) Switching on/off lights occurs mostly by entering or vacating the office.

Hunt (1979) monitored for 6 months via time-lapse photography 3 medium-sized, multi-person offices, 2 school classrooms and 2 open-space teaching spaces and observed that for continues occupation switching occurs mostly at the beginning and the end of the working day. He concluded that the cycle of occupation determines the operation of lights. In one study Reinhart et al. (2003a) observed that 86% of the switch-on events happen upon arrival.

2) The probability of switching the lights on at arrival depends on the working plane illuminance.

Hunt (1979) derived a "switching on at arrival" probability function in relation to the illuminance on the work plane. Hunt's function has been validated by Reinhart (2001) and other researchers (Love 1998). Both functions state that illuminance levels under 100 lx cause significant increase of the switching on probability (see Figure 1).

3) The probability of switching the lights off depends on the period of absence from the office.

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. This relationship is verified in other studies (Boyce 1980, Reinhart 2001, see Figure 2).

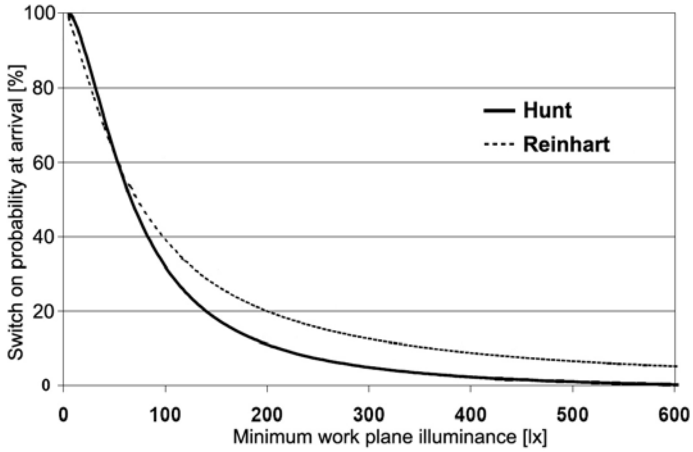


Figure 1. Probability of switching the lights on at arrival in the office

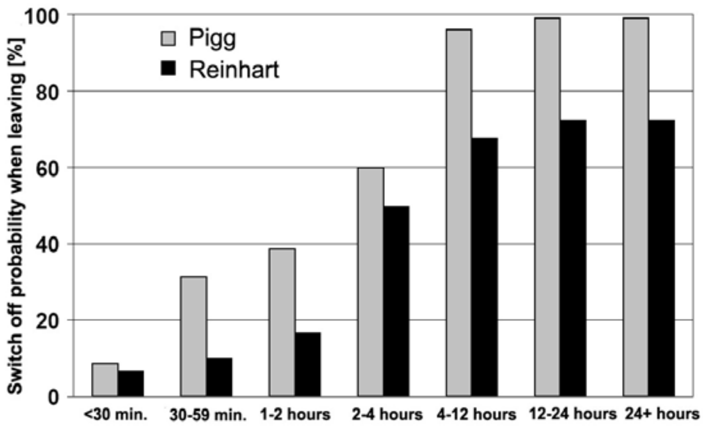


Figure 2. Probability of switching the lights off when leaving the office

Pigg also observed that in the presence of occupancy sensors people modify their behavior and are "about half as likely to turn out the lights when they left compared to those without occupancy sensor control" (Pigg et al. 1996, p. 8.164). Being conscious about the energy implication of this behavioral tendency, Pigg calculated that the saving potential from the occupancy sensors is reduced by about 30%.

4) “Intermediate” switching the lights is related to the daylight availability.

Switching the lights during the period of occupation, or so called “intermediate switching”, is another topic of research interest. Boyce (1980) observed intermediate switching in two open-plan offices and found that people tend to switch the lights more often in relation to the daylight availability if the lighting covers smaller size areas with lights switched on. Reinhart (2003a) suggested that the intermediate switch-on events are more common at lower than at higher illuminances. He defined an intermediate switching on probability function according to which, the probability is 2% if the minimum work plane illuminance is between 0 and 200 lx; at illuminance level higher than 200 lx the probability drops to 0,002%. Lindelöf et al. (2003) conducted a study in a small office building in Lausanne to verify Reinhart’s “intermediate switch on” probability function. The results determined an illuminance threshold of 100 lx under which the probability raised significantly, and above that threshold the probability was very low. Love (1998) observed the switching behavior in single occupancy offices in a building in Canada. He defined two groups of people, depending on their switching behavior. The first are people, who switch the light on during the entire working day including lunch time. The second group, supporting the intermediate switching concept, consists of the people who operate the electrical lighting when the daylight levels are low.

5) There are seasonal differences of lighting operation.

Several studies could establish dependency in lighting operation on the seasons. In a study about the manual switching of electrical lighting Boyce (1980) discovered that the total number of luminaires switched on was less in summer than in winter, corresponding to the considerable differences in daylight availability for the two seasons. Another study by Carter et al. (1999) established seasonal dependency in the average lighting load. The researchers recorded 53% lighting load in January and 43% in April and May.

Manual operation of shades

A limited number of studies concerning shade operation have been conducted until now. Generally, they explore how the occupants operate their shading devices, if there are certain patterns and dependencies on factors like solar radiation, orientation, time of the day, direct sun light and glare, seasons etc.

The major findings in this area can be summarized as follows:

1) The operation of shading depends on the façade orientation.

Rubin et al. (1978) investigated the operation of Venetian blinds in south and north facing offices in Maryland USA, by taking images. The results show that the blind occlusion was higher on the south façade (80%) than on the north façade (50%). Rubin concluded that people were “more likely to accept their blinds extraneously opened than closed”.

Rea (1984) conducted a pilot study in a 16 storey office building in Ottawa, Canada, about how the blinds are manually operated and if the operation depends on factors like window orientation, time of the day and weather conditions. The results show that on a clear day about 60% of each façade was occluded by blinds, while on a cloudy day the east façade was different from the others with 40% occlusion.

Inoue et al. (1988) investigated the manual operation of conventional Venetian blinds in 4 high-rise office buildings in Tokyo, Japan. Inoue noticed that the changes in the rate of blind operation varied greatly with the orientation of the buildings. He also observed that on the eastern façade the blinds that were closed in the morning were gradually opened in the afternoon!

Lindsay et al. (1992) found a strong correlation between the Venetian blind use and the amount of solar radiation and sun position. They conducted a filed study involving photographic surveys of 5 office building the UK over the course of 4 years. They concluded that: the blinds were adjusted more frequently on the south façade than on any other; the typical daily blind operating rate was 35-40%.

2) Occupants operate their shades mainly to avoid direct sun light and overheating.

This dependency was found by Rubin et al. (1978). Rea (1984) confirmed Rubin's statement that people used blinds mostly when direct sun light reached the working area.

Bülow-Hübe (2000) conducted a study with 50 people in 2 south-facing single occupancy offices and observed that the shades were closed as protection from sun glare. She couldn't establish correlation between indoor/outdoor illuminance and the degree of closing shades, nevertheless a slightly better relation could be determined between the action closing shades and the existence of sun patches in the room as well as the position of the shading device.

3) Above a certain threshold of vertical solar radiation the position of shades is proportional to the solar penetration depth into a room

Inoue et al. (1988) derived a threshold of 50 $W.m^{-2}$ vertical irradiance, above which the blind position was strongly related to the solar penetration depth. The same hypothesis was confirmed by Reinhart (2001) (see Figure 3).

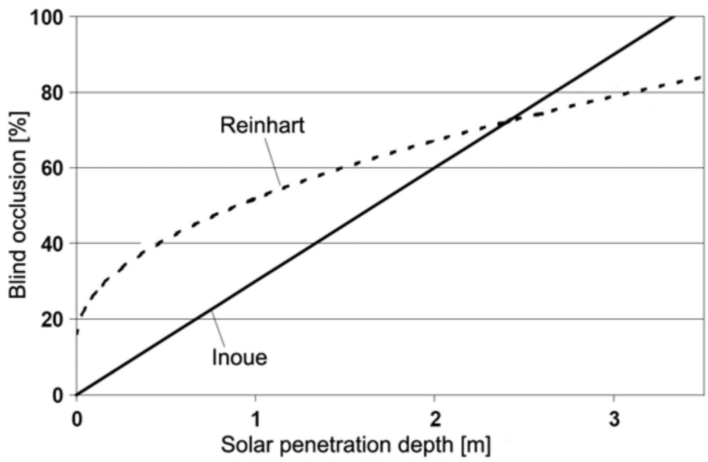


Figure 3. Mean blind occlusion in relation to the solar penetration depth on SSW façade, when the vertical solar irradiance is above 50 $W.m^{-2}$

Farber Associates (1992) found that a threshold of 300 $W.m^{-2}$ would trigger a change in the blind position by occupants in buildings in UK.

Newsham (1994) modeled with the help of the computer-based thermal model FENESTRA a typical single, south facing office-room in Toronto, Canada, and compared 4 blind control strategies: ‘permanent’ (always closed); ‘none’ (always open); ‘7 months’ (always closed April-October, and always open November-March); and ‘manual’. Newsham derived a threshold value of 233 $W.m^{-2}$ for solar radiation, above which the blinds were closed and remained so until the following morning.

4) Once being closed, the shades remain closed till the end of the working day.

Rea (1984) observed that throughout the day people rarely changed the position of blinds. Rea concluded in agreement with Rubin that people have a long term perception of solar irradiances.

Inoue (1988) observed that the relation between blind operation and incident illumination on the façade followed a curve (see Figure 4). His main conclusion was that when the incoming solar irradiance decreased, the number of blinds closed could still rise. The blinds were not fully reopened as vertical irradiance decreased, presumably because of the lost view to outside. Inoue concluded also that people considered long-term irradiance values, while short-time-step dynamics were largely ignored.

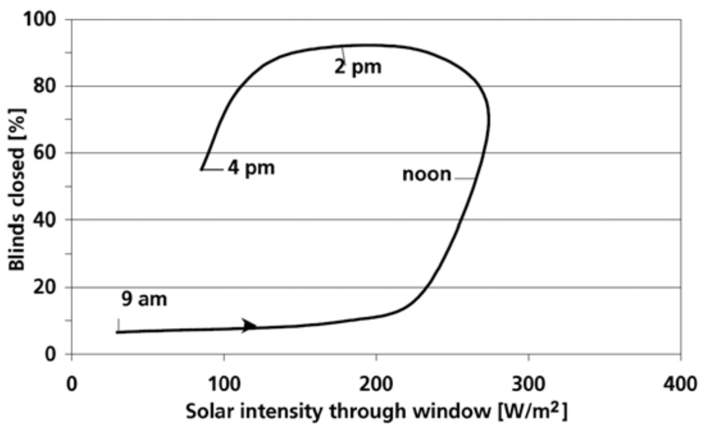


Figure 4. Percentage of blinds closed for SSW façade in relation to the vertical solar irradiance

In spite of the common conclusions, the research results from past studies reveal many discrepancies. Some of them observed blind operation on a daily basis, whereas others on a weekly, even monthly basis. Some results determine relationships between the shade operation and the incident vertical solar irradiance, time of the day and orientation, while others show weak or no dependencies on those. The reasons for the inconsistency are the different monitoring procedures and analysis methods, building types, rooms and shading systems. Another limitation is that the occupancy has not been recorded and considered in the analysis, which leads to uncertainty whether no or few opening/closing actions is due to tolerable outside/inside conditions or due to user absence from the investigated offices.

Future research in the area of people' behavior in buildings should consider extended set of building types in different climatic and cultural settings, as well as long-term monitoring and collection of high-resolution data. Another recommendation would be unifying the research design and methods (length of monitoring, logging intervals, building control systems, number of monitored offices, experimental equipment setup, methods of analysis), which would allow consistent comparison of the results.

2 Research methodology

2.1 Overview

13 scientific staff offices in one of the buildings of Vienna University of Technology were selected for the purpose of the study. Measurements of various indoor and outdoor parameters were conducted in these offices for the period of one year. Two types of indoor data loggers, combined with sensors, were distributed in the rooms, mounted near the work stations for measuring indoor parameters like temperature, relative humidity, illuminance, status of lights (on/off) and occupancy. Outdoor parameters like temperature, relative humidity, solar radiation, illuminance, wind speed and direction were measured by weather station, mounted in near proximity of the monitored building. Outdoor, indoor environmental parameters and occupancy were recorded simultaneously every 5 min. for the period of January to December 2005. Additionally the status of the external shading was captured by taking digital images of the façade every 10 min. The images were processed with semi-automated software application.

The indoor sensor for lighting required calibration, followed by procedure for converting vertical illuminance into horizontal working plane illuminance. The horizontal global irradiance values, measured by the weather station, were converted into vertical, using a method, developed by Mahdavi et al. (2006a). For the purpose of the analysis the various collected data ('.XLS' and '.TXT' files) were structured in a "5 min. step" matrix according to time. The structured data were then inserted in a specially developed database with built-in standard data queries. The data was analyzed using methods of descriptive statistics, trying to find "hypothesized relationships between the nature and frequency of occupants' control actions and the indoor/outdoor environmental parameters" (Mahdavi 2006b).

At the end of the measuring period the office occupants were asked to give a feed back in a form of interview about their perception of indoor environment. The interview was based on a questionnaire, especially developed for the project. The questions were divided into several groups: 1) personal information (gender, age, professional occupation etc.); 2) assessment of the indoor climate parameters and control systems – temperature, day-/artificial light, air-conditioning, heating etc.; 3) operation and accessibility of the systems and system controls; 4) awareness of the functionality of the building control systems and energy conscious behavior; 5) personal preferences in organizing the current/ideal working space followed by a closing question about the type and frequency of health complaints.

2.2 Object description

2.2.1 The building

The building, object of the study, has been constructed in the early 80es as a part of Vienna University of Technology, hosting scientific staff and administrative offices, canteen, as well as auditoriums and classrooms. The building has around 63.400 m^2 floor area, consisted of three tower-blocks (8, 9 and 12 floors) connected with each other. The building has a double-skin facade. The inner layer consists of a conventional envelope (concrete + thermal insulation) with manually operable windows. The outer layer consists of fire proof enamel glass, supported by aluminum raster frame. The peripheral columns have aluminum cladding and divide the façade into fields. On each floor the field between two columns consists of 5 rectangular transparent glass elements, of which the middle one is always operable (20% of the field). Figure 5 shows a general view of the building and the observed area (marked).

Figure 5. General view of FH

The building is air-conditioned using two independent systems: an air-based system with both supply and return air ducts located in the ceiling plenum and a hydronic system with fan coils below the windows. The settings of the fan coils can be controlled by the users within certain range. The electrical lighting is controlled manually via switches. The daylight is controlled via manually operated screen shades, located between the two façade layers.

2.2.2 The offices

The 13 selected rooms face east and are situated on the 4th, 5th and 6th floor. Ten offices are single-occupancy, two are double-occupancy, and one is triple-occupancy, corresponding to 17 monitored work stations (see Figure 6). The complete set of plans of the monitored offices is included in Appendix A (Figure 106, Figure 107, Figure 108). The area of the rooms is between 12 m^2 and 25 m^2. The walls have white color with reflectance 90%. The double ceiling consists of perforated white metal plates, with reflectance 77%. The “window to wall” ratio is between 30% and 60%.

The furniture includes desks, cupboards and book shelves, mostly bright colored. The work stations are equipped with desktop computers and in some cases with task lights. Figure 7 provides an interior view of one selected single-occupancy office in the 6th floor.

Figure 6. Schematic plan of sample offices in the 6th floor

Figure 7. View of a single-occupancy room in the 6th floor

The rooms are typically equipped with the followings system for environmental control: 3, 4 or 6 luminaires 58 W each, divided into two circuits manually controlled by two switches near the entrance door; external motorized screen shades, operated by button mounted on a panel under the window; fan coil under the window for fine adjustment of temperature, again operated by a button mounted on a panel under the window. View of the panel and the buttons can be seen in Figure 109, Appendix A.

2.2.3 The occupants

Twenty people participated in the experiment. They are university professors, scientific and administrative staff, performing screen-based as well as paper tasks. The majority completes more than 50% of their work on computer. 75% of the people are male, and the remaining 25% are female. Half of the occupants are younger than 35 years, 25% are between 35 to 45 years old and the remaining 25% are older than 55.

In total 17 work stations were observed. Within the monitoring period some of the work stations changed their occupants, resulting in a higher number of people, 20, being considered. There were “new comers”, occupants changing rooms as well as people that left before the end of the experiment.

2.3 Data collection

Our intention was to observe the actions of people toward lighting and shading as well as under which climatic conditions they occurred. For this purpose simultaneously internal and external parameters were measured. The goal of the project was to provide long-term and high-resolution data. Therefore, the monitoring took approximately one year starting from January to December 2005. The logging interval for all environmental parameters was 5 min. Photos were taken with digital camera every 10 min. The instruments recorded data which was downloaded on a regular basis every 30 to 40 days.

2.3.1 Indoor environment: Equipment and measured parameters

For measuring indoor environmental parameters we used autarkic data loggers, placed in direct proximity of the work stations (see Figure 8).

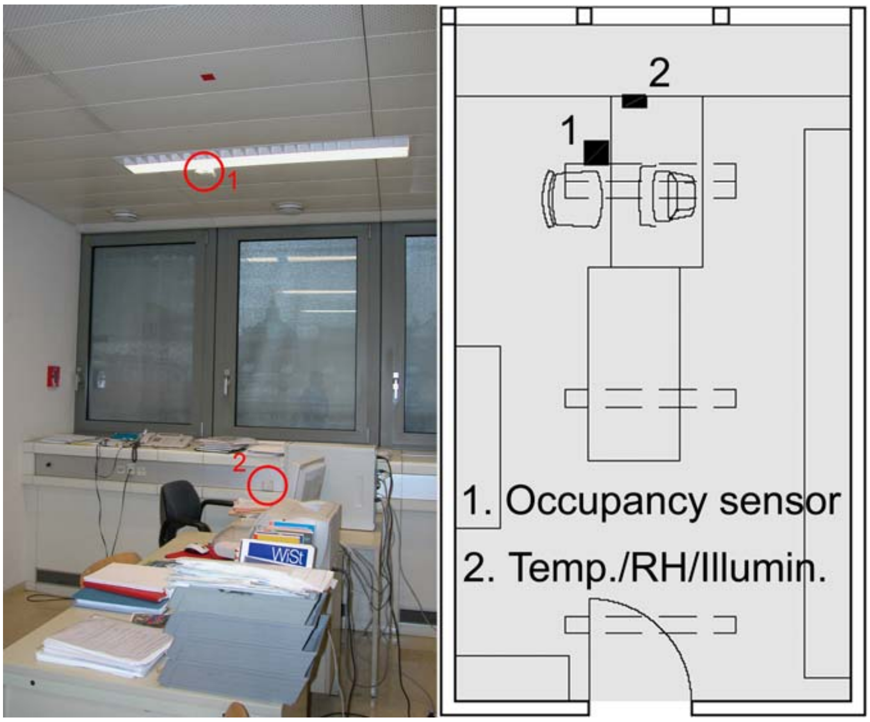


Figure 8. Position of indoor sensors

Temperature, relative humidity and light intensity were measured with HOBO® (U12-Temp/RH/Light/Ext. channel) data logger. The instrument combines sensors and data logger with capacity of storing up to 43.000 measurements. The loggers have been read out and set up for new measurements every 30 to 40 days with the help of a laptop computer and GreenLine® software. The program has an option to export the stored data as Excel text. The output is a '.TXT' file listing the logged data points in rows, each of which containing logging time (DD.MM.YY hh:mm) and the three measured indoor parameters. More information about the software and technical details of HOBO U12 data logger are listed in Appendix B.2. The positions of the loggers have been selected individually for each work station because of the different interior situations and occupants' acceptance. Nevertheless, they were mounted either on the side or in front of the tables, fixed vertically (wall, panel under the window) or horizontally (directly on the table or around 20 cm above the table surface). Care has been taken of placing the loggers so that they couldn't be reached by direct sunlight or easily covered by objects (paper, books, pots, plants etc.).

Occupancy and status of lights (on/off) has been registered with InteliTimer Pro® logger (IT-200), combining also in this case sensors (for occupancy and status of lights) and data logger in one device. The occupancy sensor uses passive infrared (PIR) technology for detecting motion. The time-out period of the occupancy sensor has been set to 5 min. The light sensor reacts to a sudden change of the illuminance level. To avoid false detection of light status in case of increased illuminance from direct sunlight, the sensors have been mounted in proximity of the luminaires. Following this recommendation and also considering the occupancy sensor coverage 14 m^2, we placed the loggers above the work stations with light pipes aiming to the nearest light fixture (see Figure 113). Specific for IT-200 is that it registers events. Similar to HOBO logger, the IT-200 were read out every 30 to 40 days with the help of a laptop computer and dedicated software ITProSoft®. The program has the possibility to save the collected data in '.XLS' format, listing in separate columns logging time (DD.MM.YY hh:mm), status of lights (Lit, Unlit) and occupancy (Occupied, Vacant). More detailed description of the logger and the servicing software is included in Appendix B.2.

2.3.2 External environment: Equipment and measured parameters

Outdoor climatic parameters like temperature (°C), relative humidity (%), global horizontal solar irradiance ($W.m^{-2}$) and global horizontal illuminance (lx) were measured with meteorological station, mounted on the roof top of the department of Building Physics and Building Ecology in near proximity (~100 m) of the monitored building. The measured data were recorded on a data server through the local network. More technical details about the weather station can be found in Appendix B.1. For the purpose of the analysis the outdoor parameters were structured in 5 min. steps, considering the time they have been recorded. The output is a table with several columns, the first of which is the time stamp (DD.MM.YYYY hh:mm), followed by the categories of the weather station data.

2.3.3 Position of shades

The position of shades has been recorded by taking images of the façade with digital camera, set up to take pictures automatically every 10 min. The camera has been mounted outdoors on the roof of our department, housed in a hermetically closed metal case with built-in power supply (see Figure 9). The box has been designed to protect from bad weather conditions like rain, wind, high (ventilator) or low temperatures (heating), and so to ensure faultless and long-term function of the electronic device. The images have been downloaded every week because of the limited memory card capacity.

Figure 9. View of the camera and the housing box

2.3.4 Interviews

At the end of the data collection period the occupants of the monitored rooms have been interviewed with the intention to get a feed back regarding the human subjective perception of the indoor environment. The questions were grouped in several chapters – personal information (gender, age, professional occupation etc.); assessment of the indoor climate parameters and control systems – temperature, day-/artificial light, air-conditioning, heating etc.; operation and accessibility of the systems and system controls; awareness of the functionality of the building control systems and energy conscious behavior; personal preferences in organizing the current/ideal working place, followed by a closing question about the type and frequency of health complaints. The full content of the questionnaires is included in Appendix C. 20 people in total have been interviewed and the results summarized in '.XLS' format.

2.3.5 Energy consumption and costs

Energy consumption information and energy bills were provided by the building technical and administrative services. The data was used to estimate the potential energy savings for electrical lighting in monetary terms (Chapter 4, Discussion). Summary of the energy consumption information is included in Chapter 3, Results.

2.4 Data processing

Five indoor parameters (light switch on/off, occupancy, illuminance, indoor temperature, relative humidity) of 17 work stations have been recorded for the period of one year. Simultaneously several outdoor parameters (global solar irradiance, global illuminance and outdoor temperature) have been logged. The shading positions of 29 window units have been registered parallel to the environmental parameters in 10 min. interval. The measured indoor and outdoor parameters together with the shading position data have been synchronized in accordance to time and structured in 5min. intervals.

A calibration procedure has been applied to the indoor sensors and illuminance measurements. For the purpose of the analysis, an algorithm has been developed, converting the measured vertical ("original position") indoor illuminance into horizontal on the work station. Another algorithm (Mahdavi et al. 2006a) has been applied for derivation of global vertical irradiance on the façade from measured global horizontal irradiance.

The process of synchronization between the various parameters, the algorithms for calibration and computational derivation of horizontal illuminance at the working place and global vertical irradiance are explained in this chapter.

2.4.1 Calibration of light sensors

The lack of technical information about the measurement accuracy and the assumption of possible accuracy drifts, required calibration of the indoor light sensor. For this purpose experimental illuminance measurements have been taken simultaneously with the HOBO indoor sensors and a high accurate instrument (Minolta T-10 illuminance meter, Konica 2007). Two rounds of measurements have been conducted: one for daylight and second for artificial light at fixed illuminance levels of 0, 40, 75, 225, 450 and 680 lx. After comparing the results linear correlations have been derived between the measurements of the indoor sensor and the illuminance meter. The equations for daylight and artificial light have been combined.

The resulting equation has been applied as correction for the indoor illuminance measurements that are above or equal to 28 lx. It has been experimentally proven that measurements under 28 lx are not reliable in terms of accuracy. After calibration the threshold varied up to 80 lx. This wide range was the reason for grouping the calibrated illuminance values lower than 100 lx together with the original values lower than 28 lx into one bin category '< 100 lx' later in the data analysis.

2.4.2 Derivation of horizontal illuminance from measured vertical illuminance

For analysis purposes it was necessary to convert the measured ambient (mostly vertical) indoor illuminance into a horizontal illuminance on the table. Illuminance measurements have been conducted for each work station for the period of approximately 48 hours with logging interval of 2 seconds. The equipment setup included 3 indoor loggers, mounted on the table, the original sensor position and head position (vertical, 50 cm above the table surface, see Figure 115). More detailed description of the experimental setup is included in Appendix B.1. A linear regression for daylight has been derived between the "original position" illuminance and the "table position" illuminance. The artificial light illuminance for all positions has been measured in a lack of daylight, with lights switched on, and considered as constant. Figure 10 shows one example of "original position" illuminance values, plotted against horizontal table illuminance values. The cluster of data points (shown as dark squares) and the linear equation represent the daylight algorithm, while the single circle data point represents the constant value for artificial light.

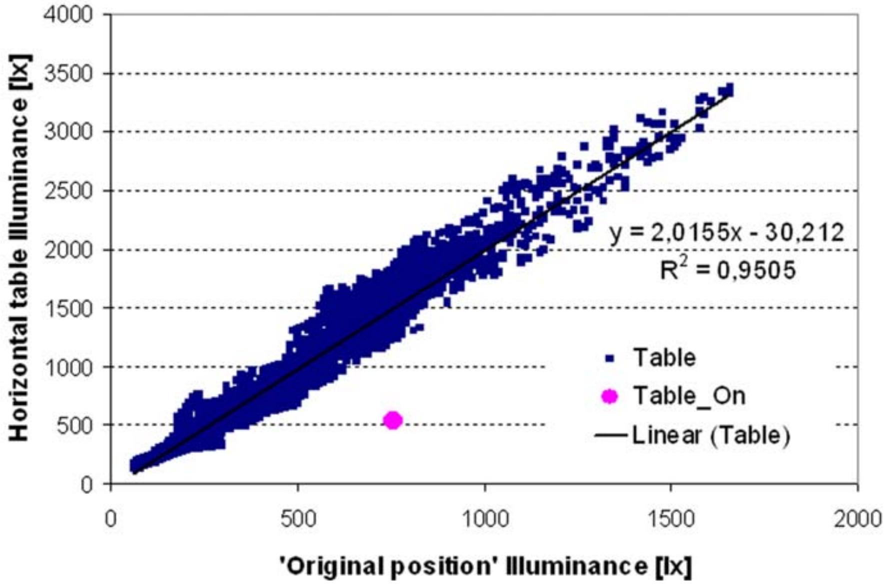


Figure 10. Original position illuminance plotted against horizontal table illuminance

Furthermore, the linear regression for daylight differs from the regression for mixed light (artificial + daylight). So, to convert the "original position" illuminance into a "horizontal table" illuminance two approaches have been used, depending on the status of lights (on or off). In case of lights switched off a linear equation $y=a*x+b$ has been directly applied to convert the measured values to horizontal, where: y is the "horizontal table" illuminance; x is the "original position" illuminance; a and b are coefficients, derived from the calibration measurements, unique for each sensor and working place. In case of lights switched on (mixed light) the horizontal illuminance (E_H) is calculated in 3 steps: first step is subtracting the artificial light component (E_{Va}) of the "original position" illuminance from the measured illuminance (E_{Vm}); second step is applying a linear regression equation for daylight to the arithmetic difference (actually the daylight component) calculated in the first step; third step is to sum the result from step 2 with the artificial light illuminance (E_{Ha}) of the "horizontal table" position (see Eq. 1).

$$E_H = a*(E_{Vm} - E_{Va}) + b + E_{Ha} \qquad \text{(Eq. 1)}$$

E_H derived horizontal illuminance

a, b equation coefficients

E_{Vm} measured illuminance of the “original (vertical)” position

E_{Va} ‘artificial light’ component of the “original (vertical)” position

E_{Ha} ‘artificial light’ component of the “horizontal table” position

The calculated horizontal table values adopted the time stamp and the 5 min. structure of the “original” measured illuminance values.

2.4.3 Derivation of global vertical irradiance from measured global horizontal irradiance.

The global vertical irradiance has been derived from the measured global horizontal irradiance using a method, developed by Mahdavi et al. (2006a). The method involves simulation in RADIANCE – advanced lighting simulation tool, using Perez all-weather sky model (Perez et al. 1993). Inputs for the sky model are diffuse horizontal and direct normal irradiance. The diffuse horizontal component is derived, following the method of Reindl et al. (1990), involving measured global horizontal irradiance, outdoor temperature and relative humidity, provided by the weather station. A geometry model of the building and its surrounding, including optical surface properties, has been generated in RADIANCE. Having geometry and sky model as input, the program calculates incident global irradiance on arbitrary oriented surfaces in various time steps. In case of FH the calculated global vertical irradiance values adopted the time stamp and the 5 min. structure of the “original” measured global horizontal irradiance values.

2.4.4 Image processing

The digital images taken between 21:00h and 05:00h as well as images with insufficient quality (blurry, foggy weather, obstacles in front of the camera objective etc.) have been excluded from the data set. Because of camera malfunctions during the first 5 months there has been around 40% data loss. The rest of the images have been processed with semi-automated shading detection software, specially created for the project by Josef Lechleitner, technical assistant of our department. Figure 11 shows the interface of the program.

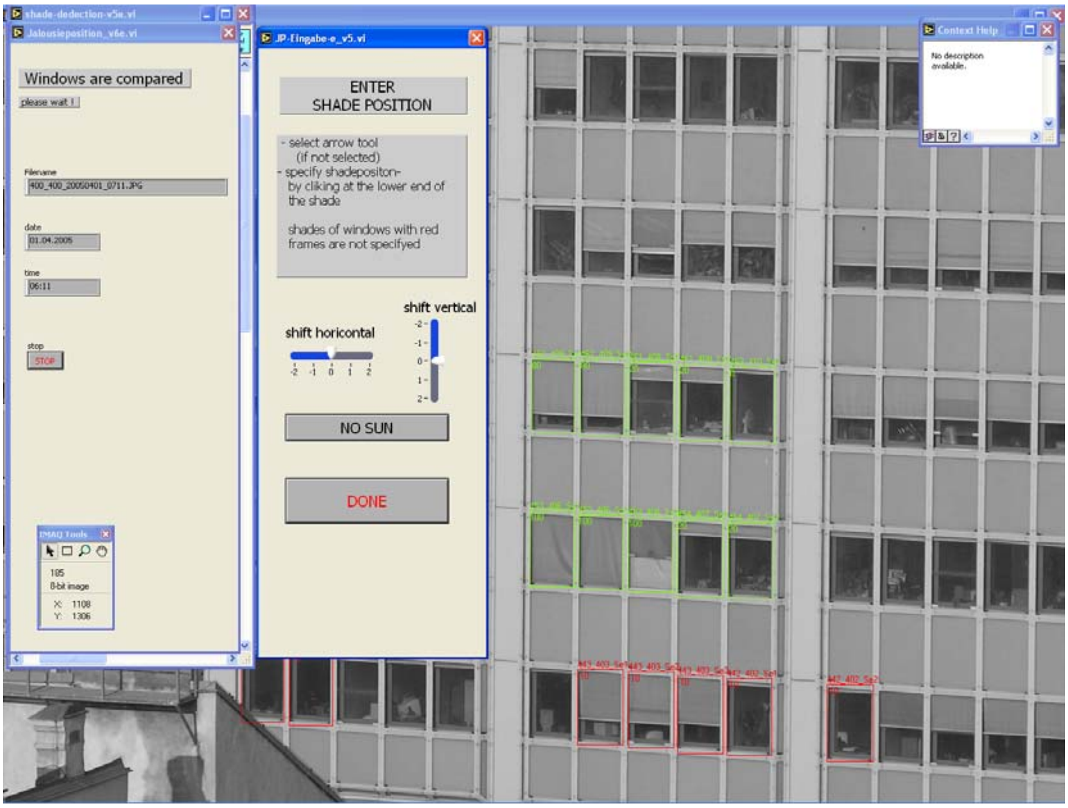


Figure 11. Graphical interface of application for semi-automated shading detection

The application, developed with LabVIEW (graphical programming language by National Instruments, USA), includes options for defining windows and shading positions, inspection of entire image set and output in '.XLS' format. The input is one '.TXT' file, listing the name of all windows in columns, followed by specification of a path to the folder containing the image set. The windows' geometry is defined via rectangles (rectangle tool). The position of shades for each window is specified by clicking at the lower edge of the shade. In total 6 shading positions have been considered; 0 (fully opened) to 1 (fully closed) in 20% step. The different shading positions are summarized in Figure 12.

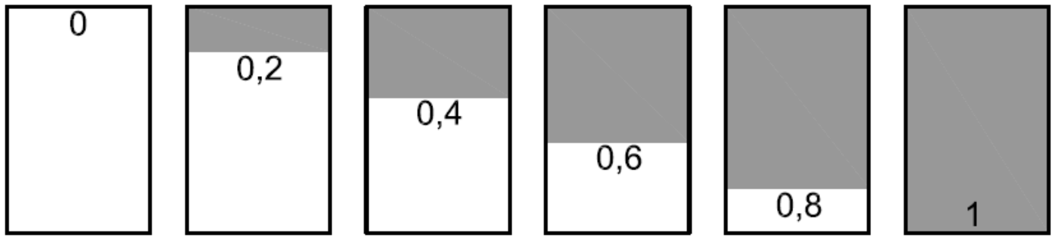


Figure 12. Shading positions

The program processes the images by comparing pixel intensities. In case of change, a visual inspection and mouse click on the shade edge is required to specify the new or confirm the previous shading position. In this context the application is semi-automated because it requires human visual assistance. The output of the program is an Excel table listing in columns the time of taking the image (DD.MM.YY hh:mm) and the shading position values of each window.

2.4.5 General data structure (SenSelect / SenSat)

Being delivered by three different sources, the indoor, outdoor and shading position data do not have unified structure. Before starting the data analysis it was necessary to unify the different row data types. The issue was to generate a standardized data matrix, based on time-line over the entire observation period, consisted of 5 min. intervals. Considering the large amount of recorded data points and the fact that they should be transformed to 5 min. intervals, software, called SenSelect (developed by a Claus Pröglhöf, member of the project team) has been used to automatically process the row data. The program is created with MATLAB (numerical computer environment and program language by Mathworks, Inc., USA). The inputs are '.TXT' and '.XLS' files, generated by the various sensors' software during the data collection. The output is in Excel format, containing categories with automatically assigned column headers, depending on the selected input parameters, always starting with Date/Time (DD.MM.YY hh:mm). Advantageous is the possibility of SenSelect to combine parameters with different origins (for example indoor illuminance and shading position) in one table. SenSelect has an option to structure the data with variable time intervals (from seconds to hours) which makes it flexible for different types of analysis.

The collected data of each monitored room (indoor parameters and shading position) has been processed with SenSelect separately. The outdoor data has also a separate output.

So synchronized and unified, the indoor and outdoor data has been imported into a specially developed database, called SenSat (developers Claus Pröglhöf and Johannes Taxacher, members of the project team). SenSat is MySQL database (multi-user Structured Query Language (SQL) database management system, MySQL 2007) with function to store collected (measured and derived) data on one side and execute various data queries for analysis purposes on the other side.

The database consists of two chapters – 'Excel Import' and 'Dataquery'. Before importing the data, processed with SenSelect, the test spaces have been numerically defined, following a hierarchy: Floor→Zone→Room→Work station. The SenSelect output and computationally derived data have been imported in the last category 'Work station'. In total data from 17 work stations have been imported into the database. The weather data parameters have been also imported into the database separately from the test space hierarchy.

The first step in 'Dataquery' has been to define the time period for data execution. The range of time considered has been limited to working days between the hours 08:00h and 19:00h. The weekends and the official holidays have been excluded. Considering this time limitation the amount of data points has been reduced to 33.383 rows, fitting in a single Excel sheet, quite convenient for analysis. Any combination of parameters (up to 60 at a time) could be selected and executed under various conditions, applicable for all available data categories. For instance the illuminance and the shading position of one work station can be listed for these time periods when the room has been occupied (condition 'occupancy=1'). Another possibility is to list indoor or/and outdoor parameters prior or after the occurrence of event. Event in this context is any numerical change in the data flow. For instance, changing the shading position from 0 (fully open) to 0,8 (80% closed) is considered as closing event, as well as changing the status of electrical lighting from 0 (switched off) to 1 (switched on) is event of switching the light on. The time, for which selected parameters should be listed, before or/and after the event, is user-defined and proportional to 5min. More about the data classification and type of data queries is included in the next chapter. Each executed data query is exported as '.CSV' file (delimited text file, using comma to separate values), compatible with Excel. The '.CSV' lists the data in tabular form with categories separated in columns, always starting with Date and Time (DD.MM.YY hh:mm). The SenSat output is convenient for further manipulation in Excel.

2.5 Data analysis

The data analysis is expected to determine relations between the control actions/preferences of people toward building systems and the indoor/outdoor environmental phenomena. Considering the collected indoor and outdoor data as basis for this complex analysis, a semantic data structure has been proposed, transforming the numerical data to 'Events' and 'States'. The complex interaction between these two semantic groups has been merged into standard data queries. The queries have been executed and the results reprocessed with the methods of descriptive statistics.

2.5.1 Semantic data structure

The collected data has been numerically structured in '.XLS' format with a Date/Time stamp assigned for each parameter. The measurements were semantically divided into two categories - event (E) and state (S) (Mahdavi et al. 2006c). The events represent numerical changes in the data sequence (for instance from 0 to 1 or reverse for occupancy or light switch on/off) and can be either system-related (E_s) or occupancy-related (E_o). The states represent status in the context of four categories: indoor environment (S_i); outdoor environment (S_e); status of system (light switched on/off, shades opened/closed etc.); status of occupancy (occupied/vacant). The content parameters of events and states are adopted on one side directly from the structured measured data, on the other side in case of states – derived based on the measured environmental parameters. Such parameters are for instance 'sol-air' temperature and the calculated amount of radiation, entering the room ($W.m^{-2}$). The calculation algorithms are explained in Chapter 3.

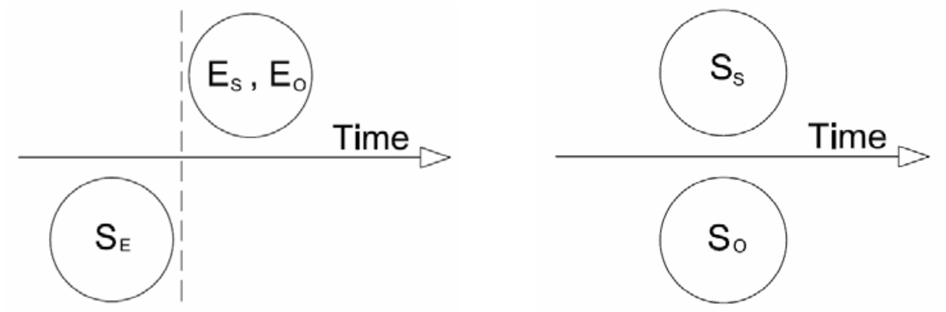
The semantic data structure, primary data types and full list of instant parameters are summarized in Table 1.

Table 1. Semantic data structure

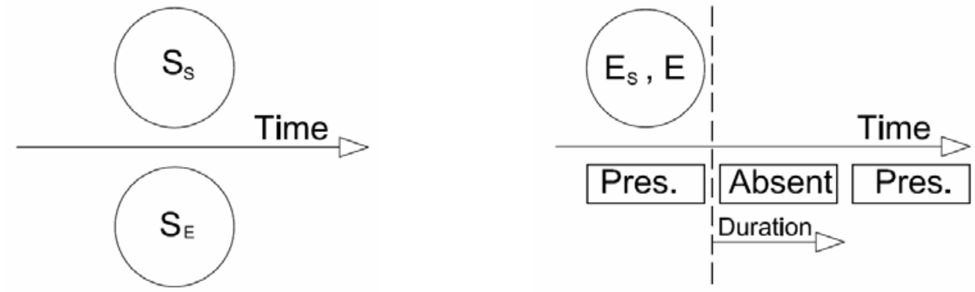
Data	Type	Instances
Events (E)	System-related (E_s)	Switch lights on/off
		Open / close shades
	Occupancy-related (E_o)	Entering / leaving the office
States (S)	System-related (S_s)	Lights on /off [0 or 1]
		Position of shades [0; 0.2; 0.4; 0.6; 0.8; 1]
	Indoor environment (S_i)	Indoor air temperature [°C]
		Illuminance level [lx]
	Outdoor environment (S_e)	Global horizontal irradiance [$W.m^{-2}$]
		Global vertical irradiance [$W.m^{-2}$]
		Outdoor air temperature [°C]
		Sol-air temperature [°C]
		Solar angle [°]
		Amount of daylight, entering the room [$W.m^{-2}$]
	Occupancy-related (S_o)	Office/workstation occupied/vacant [0 or 1]

2.5.2 Standard queries

It has been assumed that the nature and frequency of events as well as status of building systems has been related to the state of environment. In order to prove these hypothesized relationships, queries have been defined, relating events and states under certain conditions. Schematic representation of these standard queries can be seen in Figure 13.



a) Status-Environment prior Event(s) *b) Status-Systems versus Status-Occ.*



c) Status-Systems versus Status-Environ. *d) Event versus Duration of absence*

Figure 13. Standard queries for data analysis

The query in Figure 13a, listing the state of environment immediately before event(s) occur, is the basic for analysis of the frequency or probability of control actions in relation to the environmental conditions. For instance the light intensity on the work station could be related to switching on/off the light or the solar radiation incident on the façade could trigger opening/closing shades.

For instance the query in Figure 13a has been used for extracting the probability of switching the lights on upon arrival in the office in relation to the illuminance at the work station.

Figure 13b and Figure 13c represent a group of queries plotting state versus state. Figure 13b lists states of the system (S_S) versus state of occupancy (S_O), implemented in the analysis for light operation in relation to occupancy. Figure 13c plots state of system (S_S) versus state of environment (S_E). For instance the shade position has been plotted as a function of the solar radiation incident on the façade or the light intensity on the work station.

Figure 13d visualizes a query applied for deriving the probability of switching lights off when leaving the office in relation to the duration of absence before the next entering.

3 Results

3.1 Occupancy

Figure 14 shows the mean occupancy level over the course of a reference day. Considering the resolution of the graph, the values for each 5 minutes have been averaged over the entire observation period. These values mark the presence at the users' offices/workstations, not the presence in the building. Moreover, as Figure 15 demonstrates, the occupancy patterns can vary considerably from office to office.

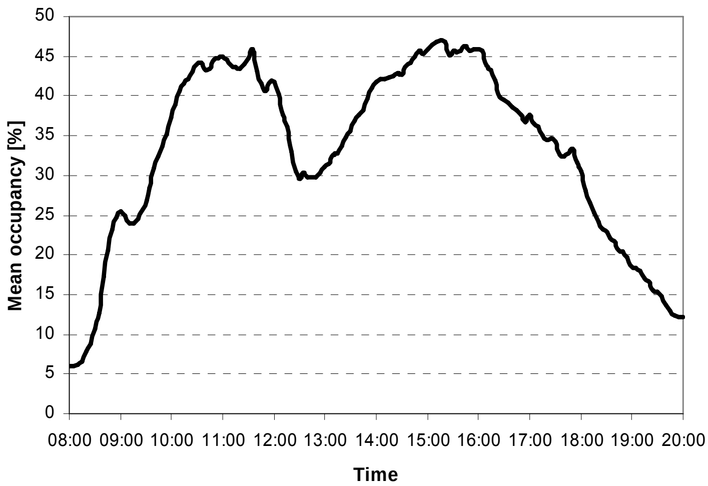


Figure 14. Mean occupancy level in FH for a reference day averaged over all offices observed

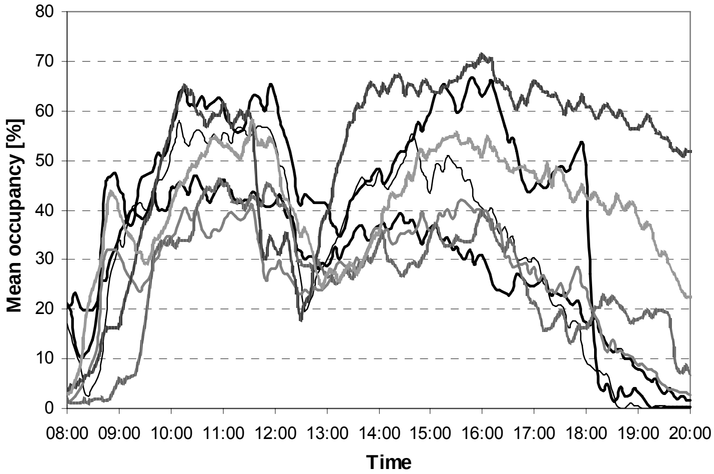


Figure 15. Observed occupancy levels in 7 different offices in FH for a reference day

Figure 16 represents the mean occupancy heating load over the course of a reference day (averaged upon the data for year 2005), which can serve as an input for building performance simulation applications. The mean occupancy heating load in $W.m^{-2}$ has been derived from the mean occupancy level and the calculated heat generation per person 0,4 $W.m^{-2}$. The heating load per person has been derived from the division of 100 W (standard heating load per person) by 240 m^2 total floor area of the monitored rooms.

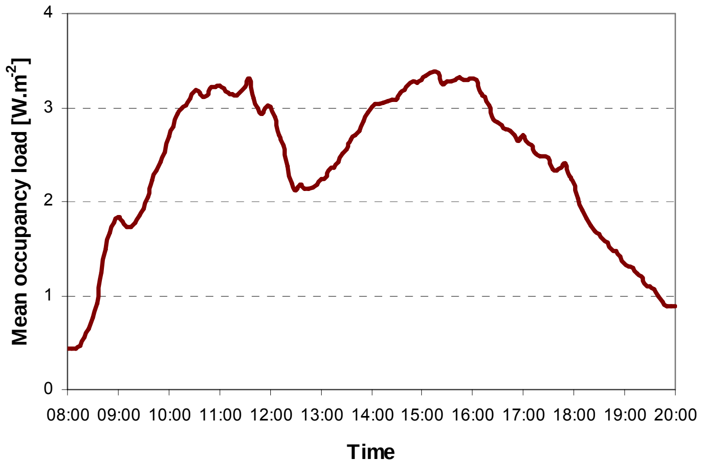


Figure 16. Mean occupancy load for a reference day

3.2 Operation of electrical lighting

The observed effective lighting operation in the course of a reference day expressed in percentage and in terms of effective electrical power can be seen in Figure 17 and Figure 18. The information in these figures concerns the general light usage in all observed offices. Analogue to the occupancy profile, the lighting operation has been derived by averaging the percentage of lights on for each 5 min. interval during the year 2005. The mean lighting load in $W.m^{-2}$ has been derived from the percentage of lighting operation and the calculated maximum lighting load 12 $W.m^{-2}$. The maximum lighting load has been derived from the maximum light power of 51 luminaires, multiplied by 58 W each, and finally divided by 240 m^2 total floor area of the monitored rooms.

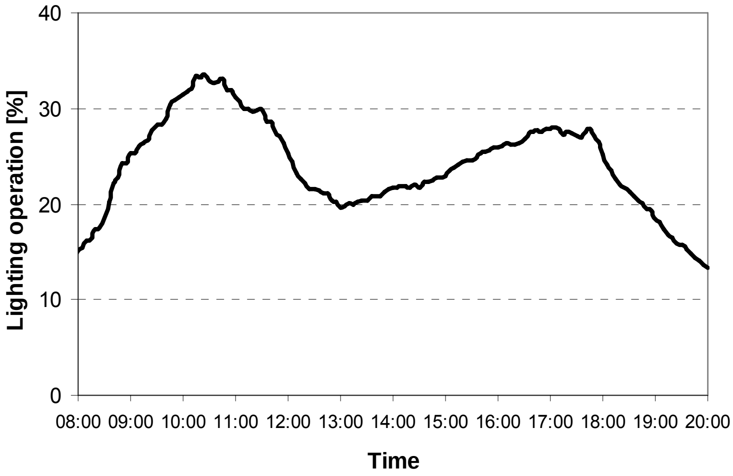


Figure 17. Lighting operation in FH offices for a reference day

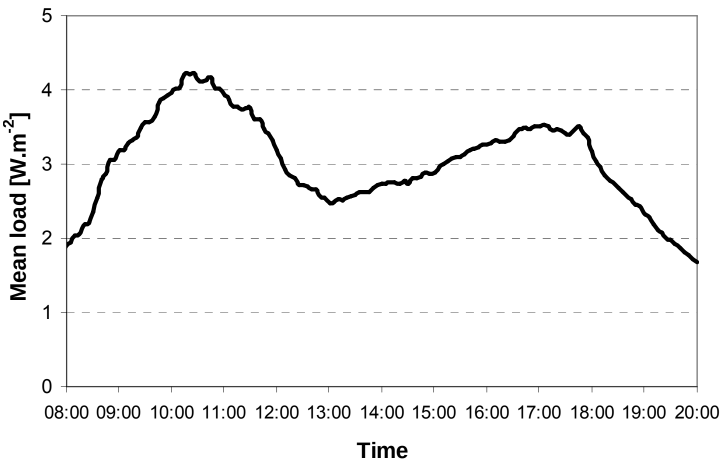


Figure 18. Mean lighting load in FH offices for a reference day

According to previous studies, one issue is to explore the existence of seasonal differences in the lighting operation. Figure 19 shows the lighting operation in %, averaged over the period of quarter of a year, covering four seasons – January to March, April to June, July to September, and October to December. The mentioned three figures about lighting operation do not consider occupancy. With consideration of occupancy Figure 20 shows the time (in percentage of the overall occupancy duration) in which at least a luminaire has been operated in an office with the intention to provide impression of the differences amongst light usage in different offices and how much light hasn't been effectively used.

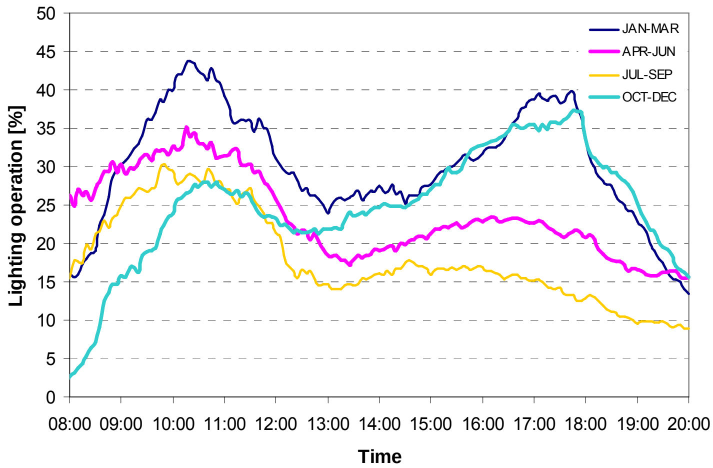


Figure 19. Lighting operation for different seasons in FH offices

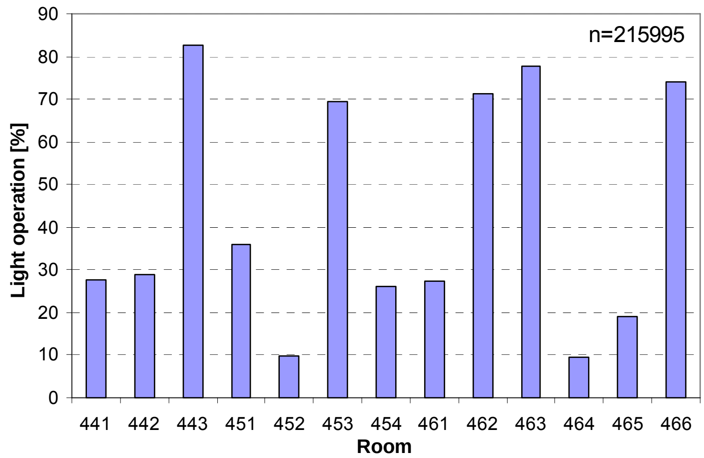


Figure 20. Duration of lighting operation (in percentage of respective overall occupied hours) in different offices of FH

The analysis of switching the lights on and off utilized already established templates. Similar to Hunt (1979) the probability of switching the lights on upon arrival in relation to the working plane illuminance has been explored. In case of FH the prevailing horizontal task illuminance immediately before arrival has been considered (see Figure 13a). The illuminance range has been divided into bins of 100 lx. For each bin category the total number of "switching on" events upon arrival has been divided by the total number of events "entering the office" ("switch on" + "remain off" events), expressed in percentage. So, for each bin independently, the "switch on" probability has been displayed in %. Figure 21 shows the “switching on” probability upon arrival in FH observed offices as a function of the prevailing task illuminance level immediately before arrival.

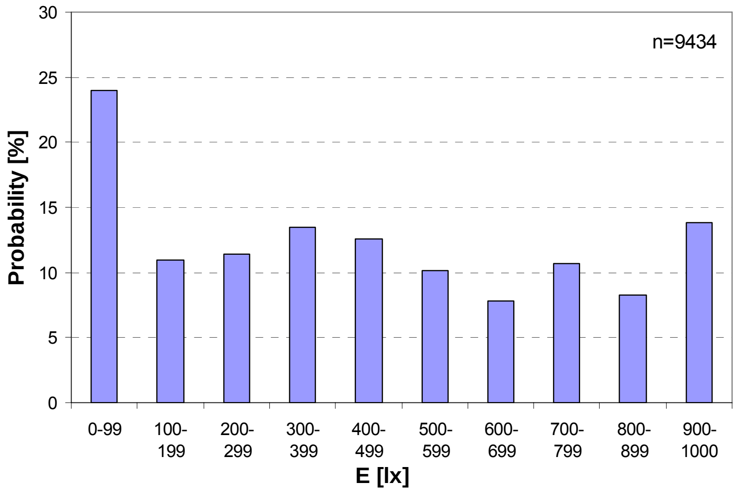


Figure 21. Probability of switching the lights on upon arrival in the office

Figure 22 shows the normalized relative frequency of “intermediate” actions “switching the lights on” as a function of the prevailing task illuminance level immediately prior to the action’s occurrence. “Intermediate” action is instantiated by occupants who have been in their offices for about 15 minutes before and after the action occurrence. The illuminance range is again divided into bins of 100 lx. Considering only the actual number of actions for each bin is not appropriate for defining a pattern because the number of actions on one side depends on the frequency of certain illuminance and on the other side – on the number of people present at the time of action. Normalization, involving these factors has been applied, by dividing the number of intermediate “switching on” actions by the number of occupied intervals, for which relevant illuminance ranges occur. Analogue normalization is applied further in the analysis of actions’ frequency.

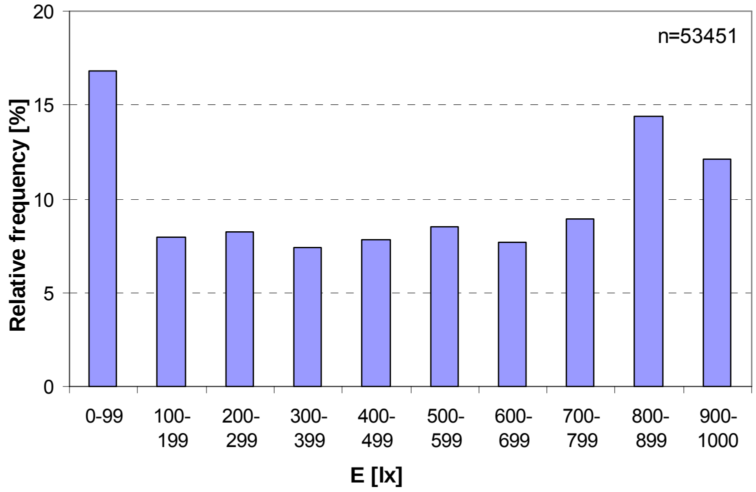


Figure 22. Normalized relative frequency of intermediate light switching on actions in FH

Figure 23 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 the actions are normalized with regard to occupancy. The number of actions for each bin is divided by the relevant mean occupancy. The mean global horizontal irradiance over the course of the day is also plotted with the intention to compare the daylight availability with the "switching on" action frequency.

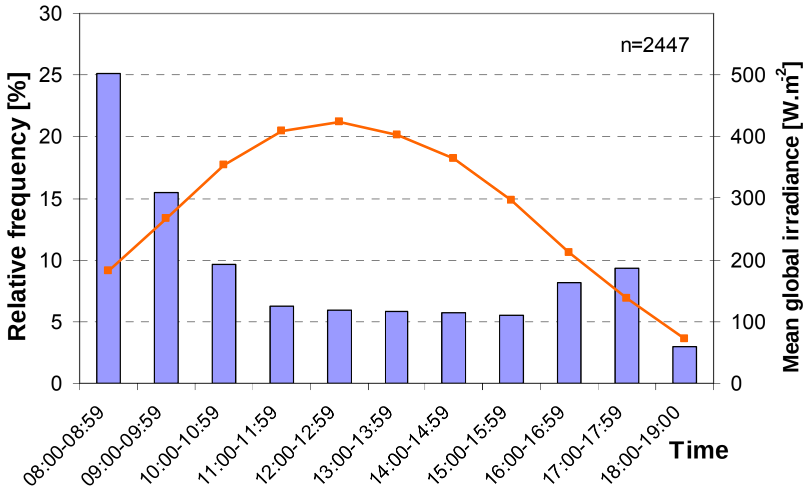


Figure 23. Normalized relative frequency of switching the lights on actions in FH over the course of a reference day

Figure 24 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 back to the office. The period of absence has been divided into 15 min. bins. All events "leaving the room" have been sorted according to their following absence periods. For each bin the number of leavings accompanied by "switching off" lights has been divided by the total number of leavings ("switching off lights" + "remain lights switched on"). Leavings of unlit spaces have not been considered.

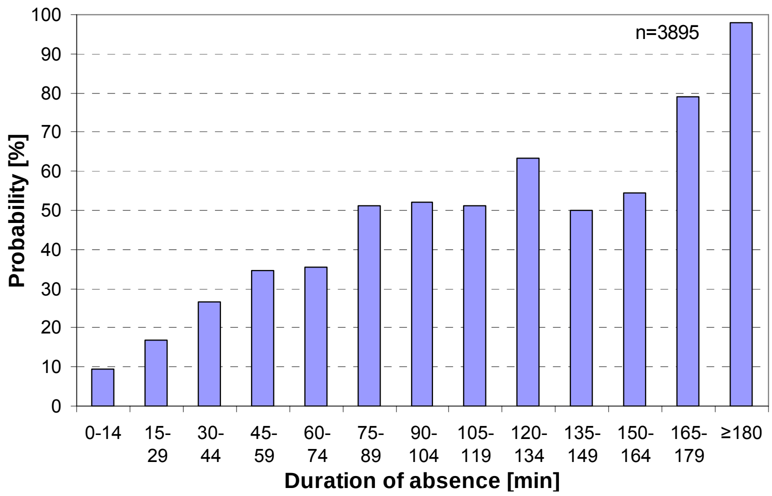


Figure 24. Probability of switching the lights off as a function of the duration of absence from the offices in FH

Figure 25 shows the normalized relative frequency of the "intermediate switching the lights off" actions as a function of the prevailing illuminance level immediately prior to the action's occurrence. "Intermediate" action is also in this case actuated by occupants who have been in their office for about 15 minutes before and after the action occurrence. As previously explained, normalization denotes the consideration of occupancy and the applicable durations of the respective illuminance bins while deriving the actions' frequency.

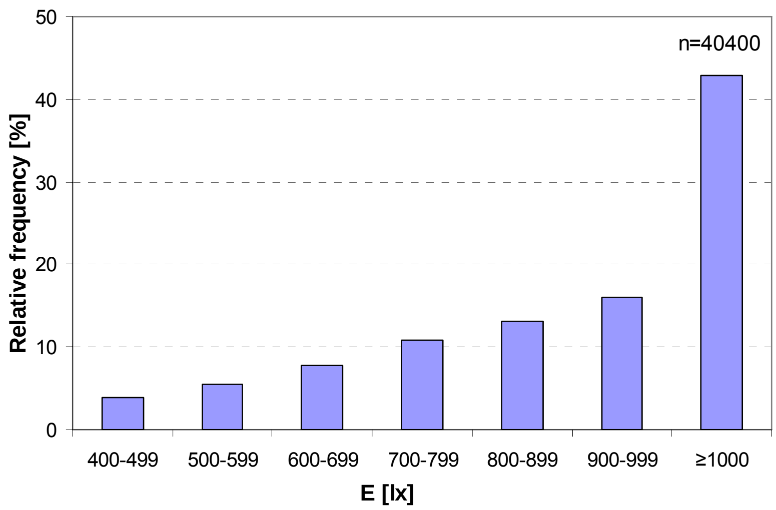


Figure 25. Normalized relative frequency of intermediate switching the lights off actions in FH offices

Figure 26 shows the normalized relative frequency of all “switching the lights off” actions (when leaving and intermediate) as a function of the time of the day. Analogue to “switching on”, the “switching off” actions are normalized with regard to occupancy.

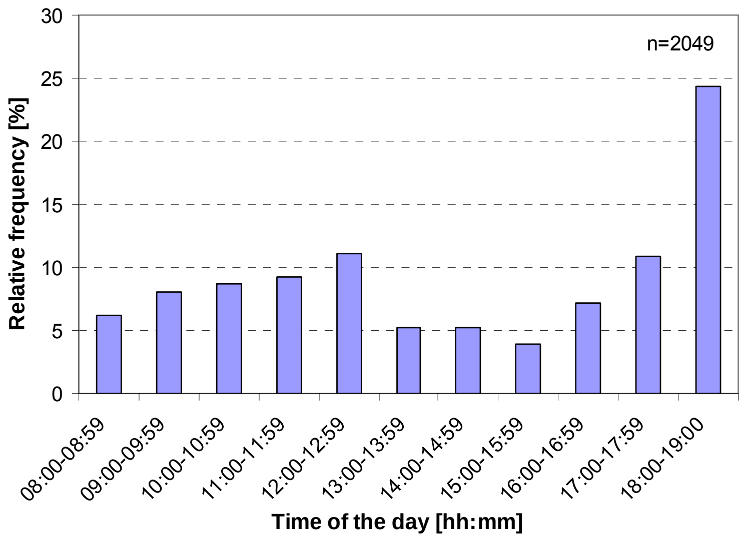


Figure 26. Normalized relative frequency of switching the lights off in FH over the course of a reference day

3.3 Operation of shades

3.3.1 Position of shades

Inoue (1988) observed regularity in the shading position over the course of the day. Likewise, the following analysis tries to determine patterns of shading operation as related to the time of the day. Another issue is to explore the existence of dependencies in the shading operation on the different seasons, which has not been explicitly analyzed in previous studies. Figure 27 shows the mean and seasonal shade deployment degrees in FH for a reference day, averaged over the entire observation period and for quarter of a year. For each 5 min. interval between 8:00h and 20:00h the shading position of the monitored windows has been averaged, thereby, 100% denotes full shades deployment, whereas 0% denotes no shades deployed.

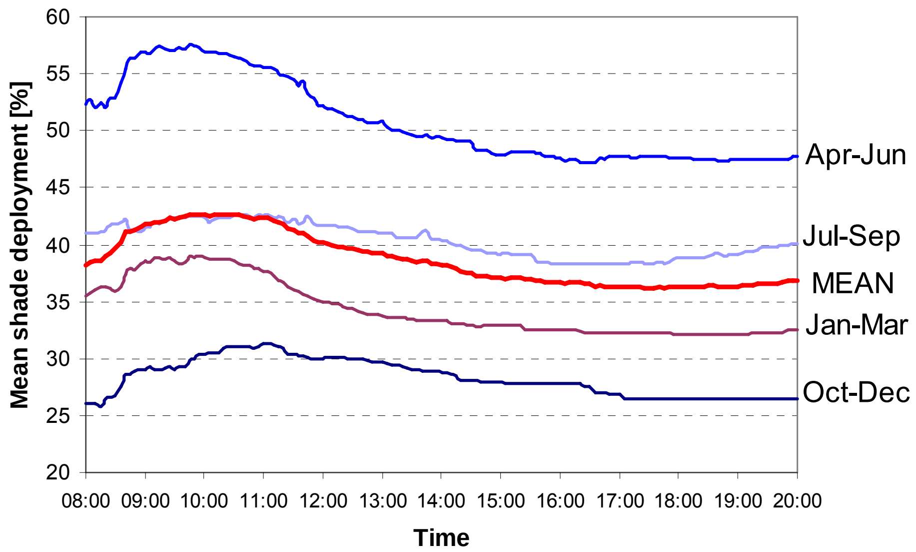


Figure 27. Mean shade deployment over the course of reference days (January to March; April to June; July to September; October to December)

The next step is to explore the mean monthly shade deployment and if it agrees with the solar radiation availability. In this context Figure 28 represents the mean monthly shade deployment degree (occupied periods) together with the mean monthly measured global horizontal irradiance. Likewise, Figure 29 represents the mean monthly shade deployment degree (occupied periods) together with the mean monthly global vertical irradiance. For this analysis the shading position data for occupied rooms only has been considered, reflecting unbiased occupants' preference.

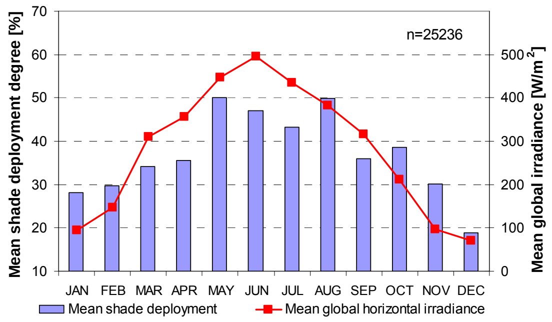


Figure 28. Mean monthly shade deployment degree together with mean global horizontal irradiance (occupied periods)

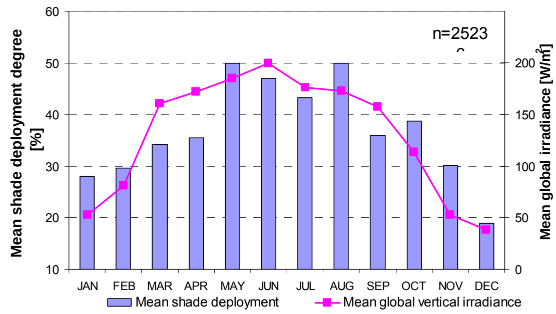


Figure 29. Mean monthly shade deployment degree together with mean global vertical irradiance (occupied periods)

The same analysis template has been applied once more, averaged over the shading position data for the working hours from 08:00 to 19:00h. The information on the actual shading position contributes to the accurate calculation of heating loads and so to the better prediction of building thermal performance. Figure 30 represents the mean monthly shade deployment degree (working hours) together with the mean monthly measured global horizontal irradiance. Figure 31 represents the mean monthly shade deployment degree (working hours) together with the mean monthly global vertical irradiance.

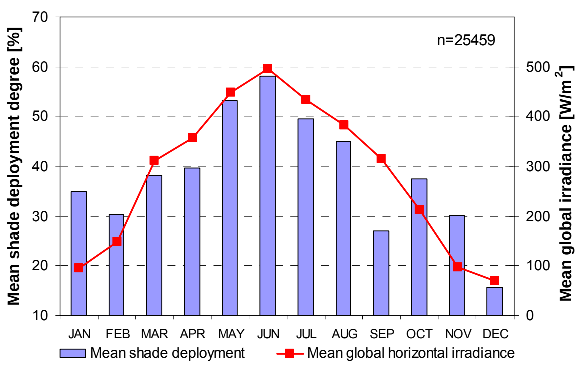


Figure 30. Mean monthly shade deployment degree together with mean global horizontal irradiance (working hours)

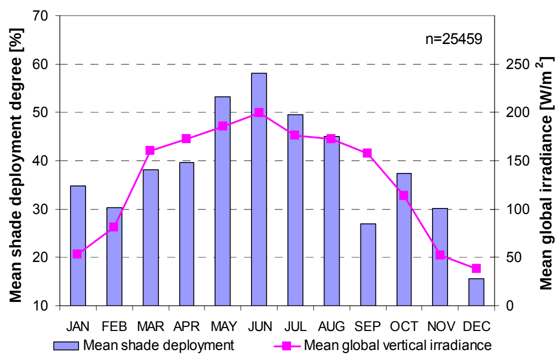


Figure 31. Mean monthly shade deployment degree together with mean global vertical irradiance (working hours)

The following analyses address the mean shade deployment in relation to environmental factors like solar radiation, sun position, outdoor, and sol-air temperature.

Figure 32 shows the mean shade deployment degree as a function of the global vertical irradiance incident on the façade. The solar radiation spectrum has been divided into bins of 50 $W.m^{-2}$. The values for each bin have been averaged over the entire observation period. Likewise, Figure 33 shows the mean shade deployment degree as a function of the measured global horizontal irradiance.

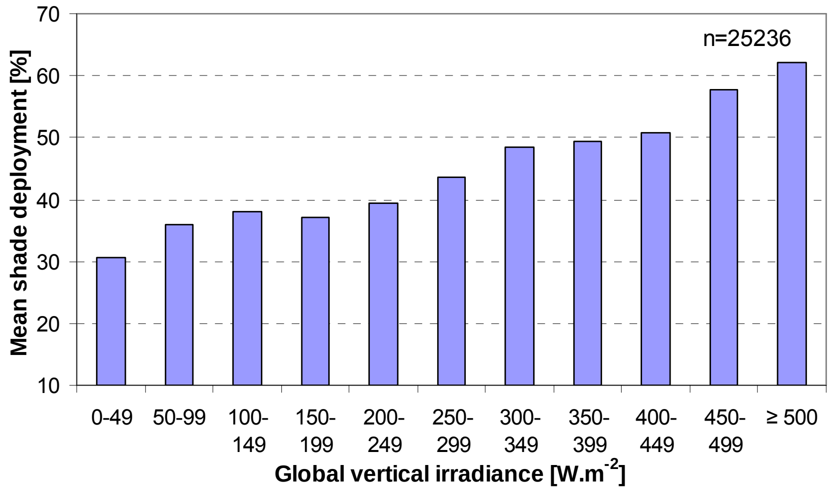


Figure 32. Mean shade deployment degree as function of global vertical irradiance

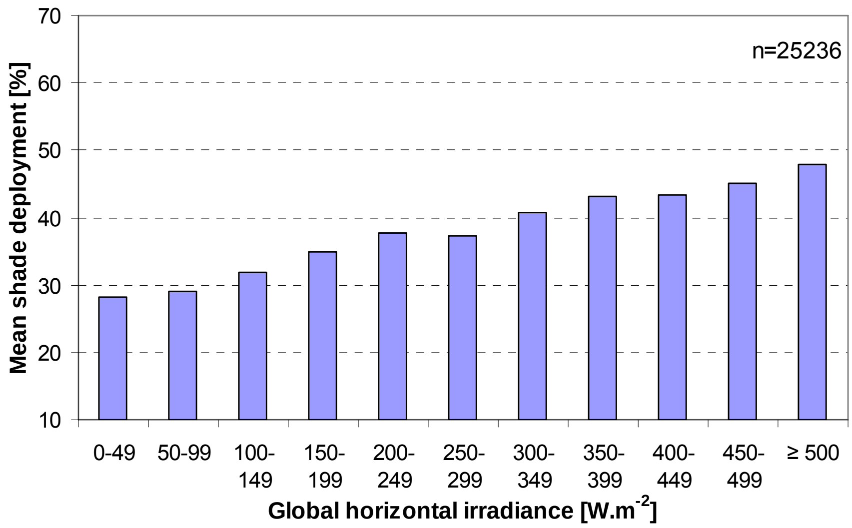


Figure 33. Mean shade deployment degree as function of global horizontal irradiance

Inoue (1988) found relationship between the shade deployment and the sun penetration distance into the room. In the present analysis the sun penetration distance has been reinterpreted and substituted by the angle between the sun and the normal to the window, the so called “solar angle”. The smaller the angle, the longer the distance of the sun patch in the room. The maximum considered angle is 90°, for which the sun is already out of visibility range of the façade. Figure 34 shows the mean shade deployment degree as a function of the “solar angle”.

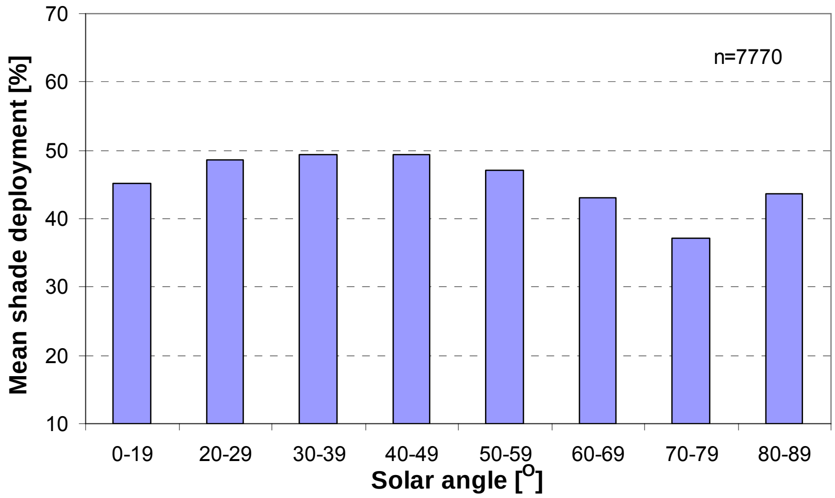


Figure 34. Mean shade deployment degree as function of the angle between the sun and the normal to the window

Except the solar radiation, another triggering factor for the manual operation of shades is the thermal factor (Bülow-Hübe 2000). Issues of overheating caused by direct sunlight and outdoor temperature have been already addressed in previous studies with inconclusive results. In this context the mean shade deployment degree in Figure 35 has been plotted as a function of the measured outdoor air temperature.

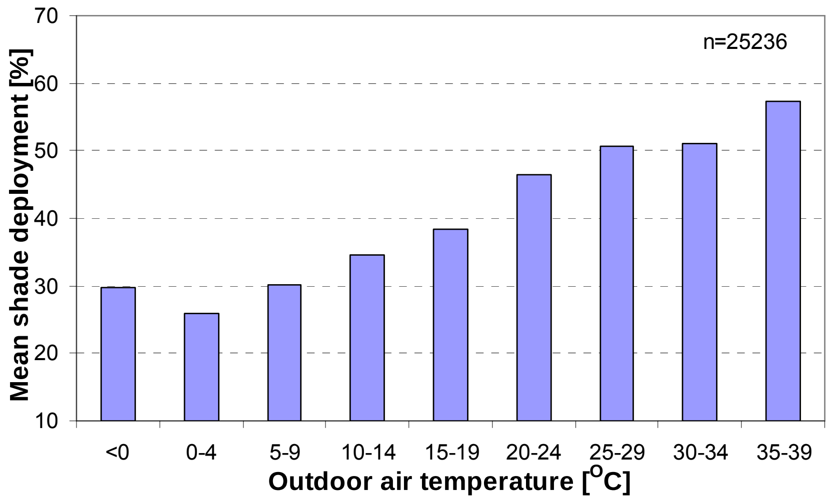


Figure 35. Mean shade deployment degree as function of outside temperature

Another try has been given to analyze the mean shade deployment degree in relation to combined solar radiation and outside temperature expressed as sol-air temperature (see Figure 36). By definition the sol-air temperate is that temperature which, in the absence of solar radiation, would give the same rate of heat transfer through the wall or roof as exists with the actual outdoor air temperature and incident solar radiation. It is effectively the outside environmental temperature. According to ASHRAE (ASHRAE Handbook 2001) the equation for calculating the sol-air temperature for vertical surfaces is as follows:

$t_{sol\text{-}air} = t_{ext} + \alpha/h_o * E_v$ *Eq. 2)*

$t_{sol\text{-}air}$ sol-air temperature

t_{ext} outdoor air temperature

α absorptance of a surface for solar radiation ($W.m^{-2}$)

h_o heat transfer coefficient for radiation by long-wave radiation and convection at outer surface (W/m^2K)

E_v global irradiance incident on the façade

ASHRAE defines a range for $\alpha/h_o \in [0,026 - 0,052]$, depending on the brightness of the façade surface. In case of FH *0,034* has been chosen considering the color intensity of the façade elements. Thus, the equation in case of FH looks like this:

$$t_{sol\text{-}air} = t_{ext} + 0{,}034 * E_v \quad \text{(Eq. 3)},$$

where t_{ext} is the outdoor temperature measured by the weather station, and E_v is the global vertical irradiance derived from the measured global horizontal irradiance.

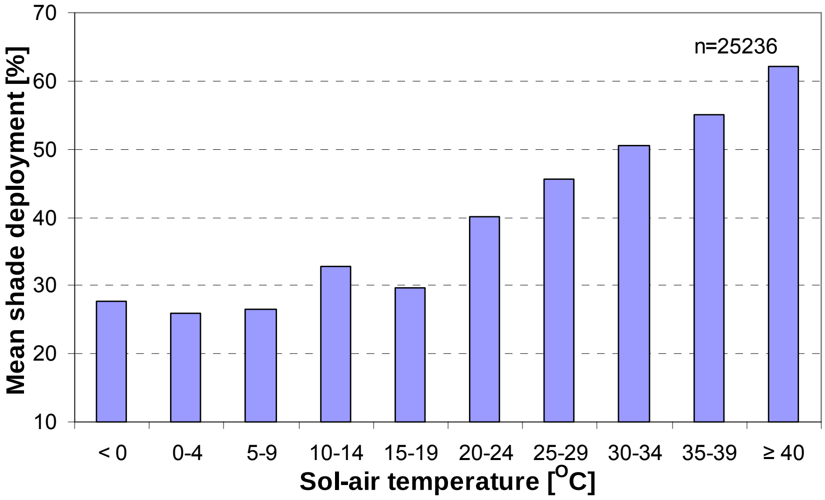


Figure 36. Mean shade deployment degree as function of sol-air temperature

3.3.2 Opening and closing of shades

As the previous chapter was dealing with the state of the shading system as related to the state of environment, the present chapter analyzes the events of opening and closing shades. The aspects are similar – to explore possible dependencies of the actions toward shading on the time of the day, the daylight availability, the sun position and the thermal conditions. The daylight dynamic is specific for each façade orientation and implies regularities in the course of the day. Inoue (1988) observed that on the east façade "closing shades" happens mostly in the morning and "opening shades" increases gradually in the afternoon. The actions "opening shades" and "closing shades" in relation to the time of the day for FH, averaged over the entire observation period, are shown on Figure 37 and Figure 38. The number of actions has been normalized with regard to occupancy: number of actions has been divided by the number of occupants present at the relevant time interval.

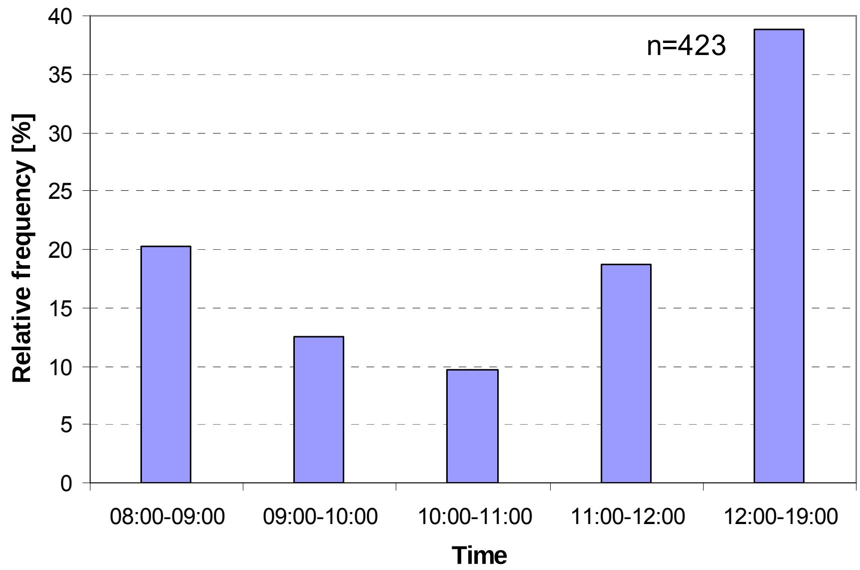


Figure 37. Normalized relative frequency of opening shades in relation to the time of the day

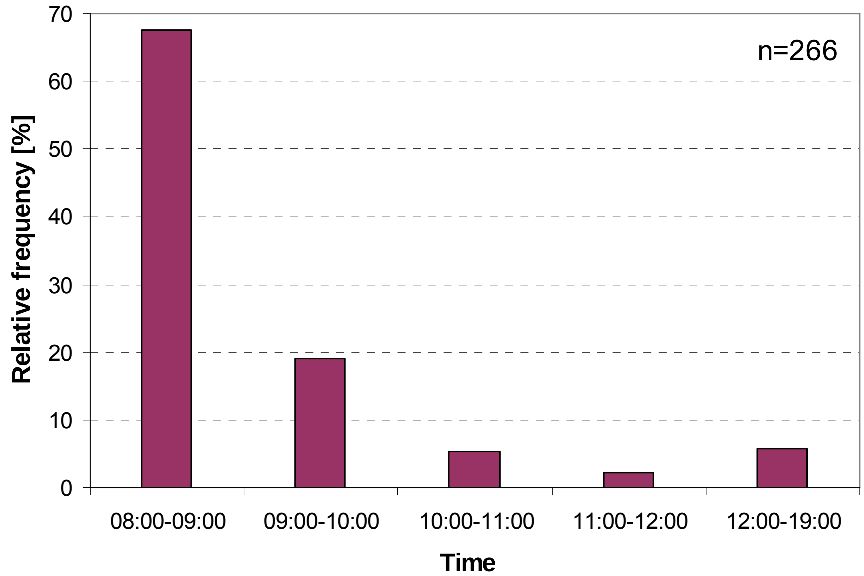


Figure 38. Normalized relative frequency of closing shades in relation to the time of the day

Figure 39 and Figure 40 show the normalized relative frequency of the actions "opening shades" and "closing shades" as a function of the global vertical irradiance incident on the façade immediately prior to the action's occurrence. Likewise, Figure 41 and Figure 42 show the normalized relative frequency of the actions "opening shades" and "closing shades" as a function of the measured global horizontal irradiance. The global irradiance in both cases has been divided into bins of 50 W.m^{-2}. Similar normalization procedure to the one for lighting has been applied taking into consideration the frequency of occurrence of certain global solar irradiances (for each room when occupied) and the number of people present at the time of action. The normalization has been performed by dividing the number of events for each bin by the number of intervals, for which relevant irradiances occur.

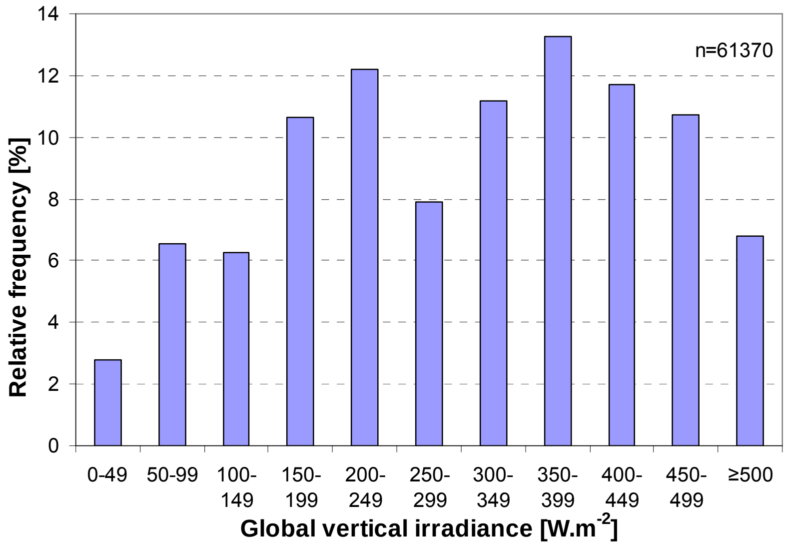


Figure 39. Normalized relative frequency of opening shades as a function of global vertical irradiance

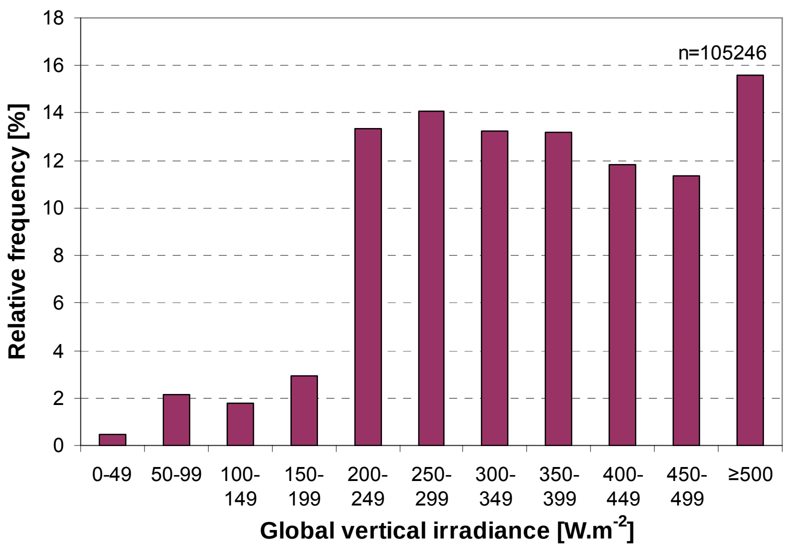


Figure 40. Normalized relative frequency of closing shades as a function of the global vertical irradiance

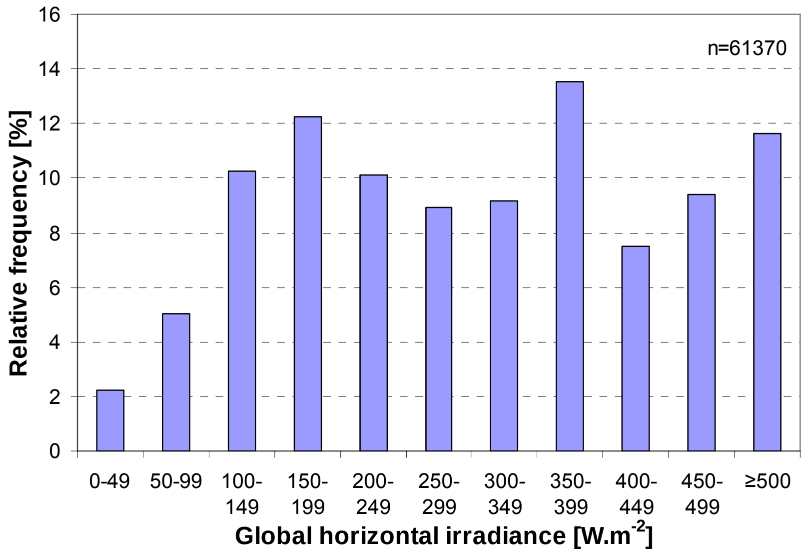


Figure 41. Normalized relative frequency of opening shades as a function of global horizontal irradiance

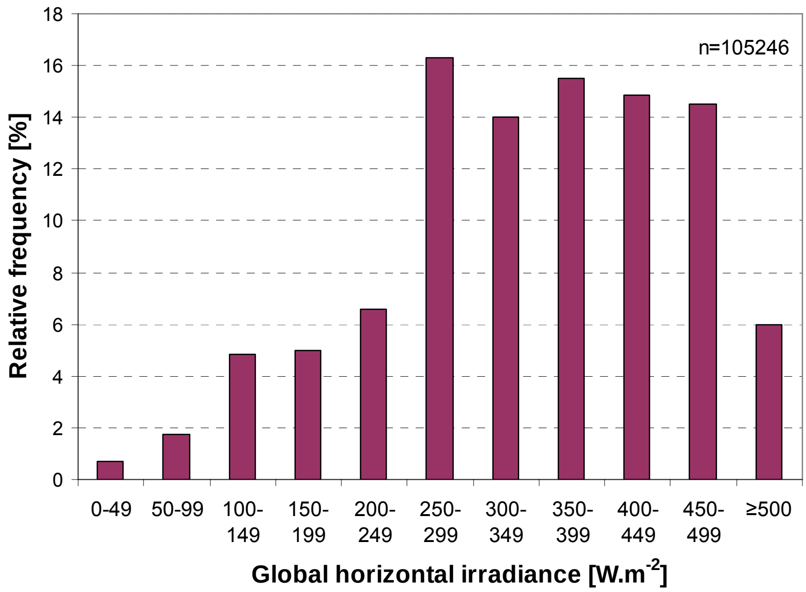


Figure 42. Normalized relative frequency of closing shades as a function of the global horizontal irradiance

Figure 43 and Figure 44 show the normalized relative frequency of the actions "opening" and "closing" shades as a function of the outdoor air temperature prior to the action's occurrence. Likewise, Figure 45 and Figure 46 show the normalized relative frequency of the actions "opening shades" and "closing shades" as a function of the sol-air temperature. Normalization also in this case denotes that the frequency of actions (opening and closing shades) is related to both occupancy and the number of intervals in which the outdoor and sol-air temperature have been within a certain range (bin).

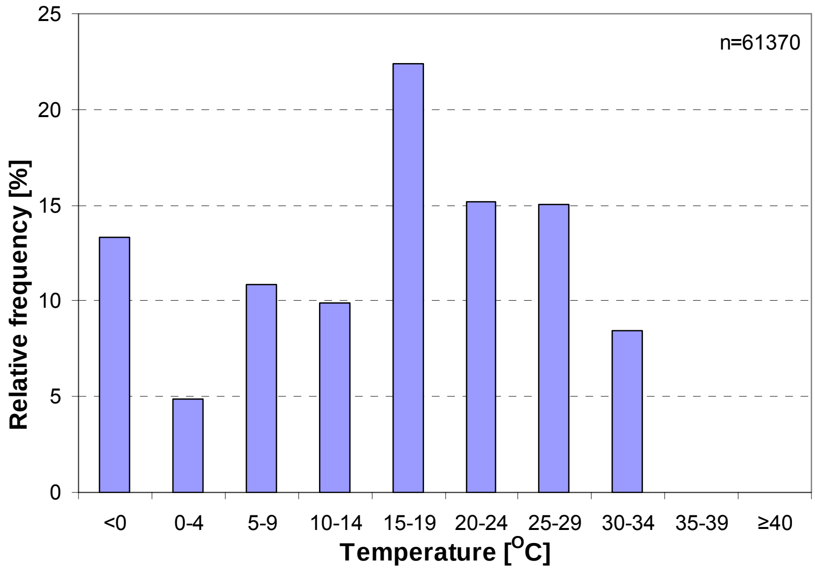


Figure 43. Normalized relative frequency of opening shades as a function of outdoor air temperature

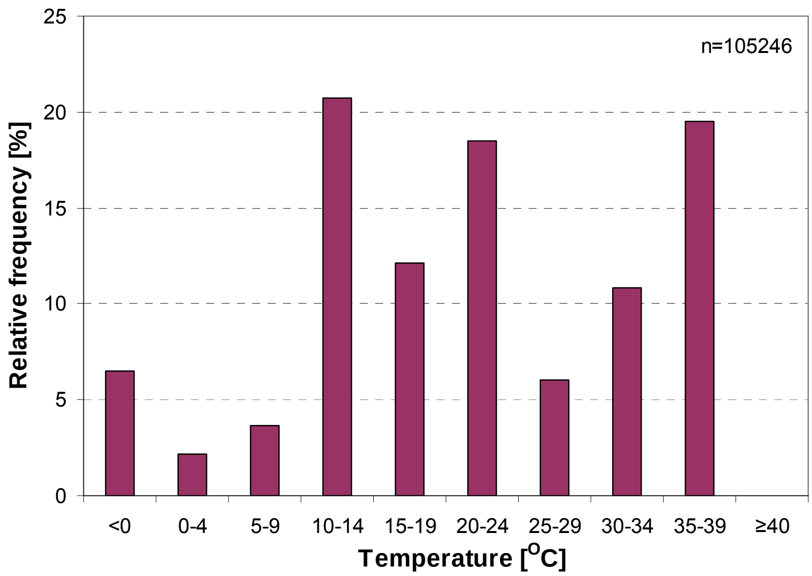


Figure 44. Normalized relative frequency of closing shades as a function of outdoor air temperature

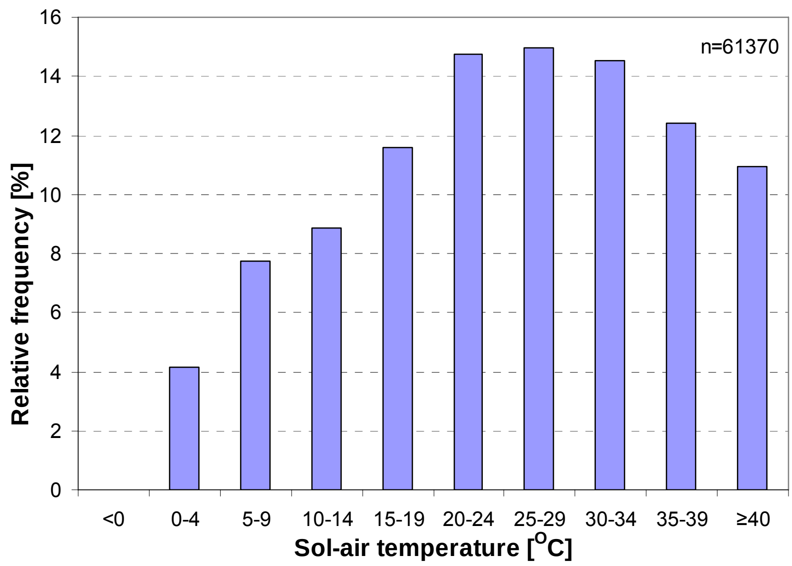


Figure 45. Normalized relative frequency of opening shades as a function of sol-air temperature

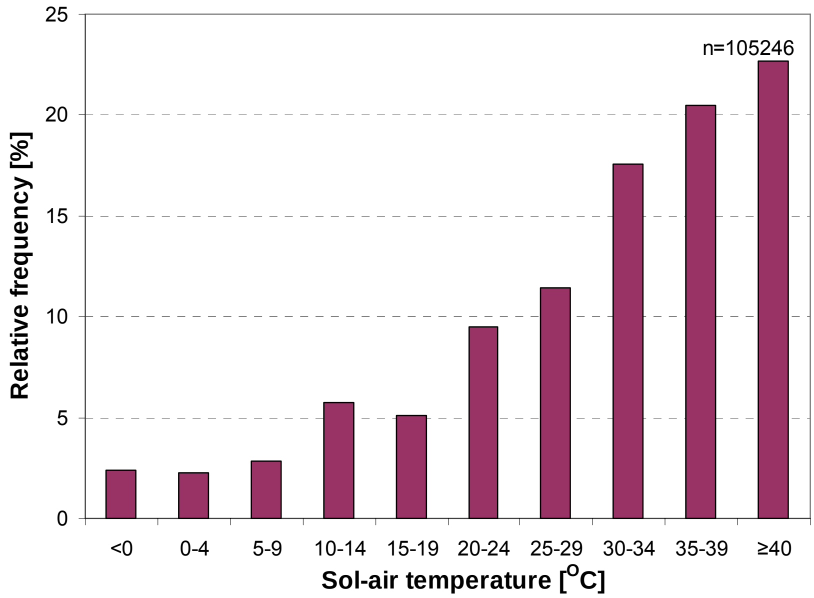


Figure 46. Normalized relative frequency of closing shades as a function of sol-air temperature

Figure 47 and Figure 48 show the normalized relative frequency of the actions "opening shades" and "closing shades" as a function of the angle between the sun and normal to the window (solar angle). The normalization procedure is analogue to the previous ones.

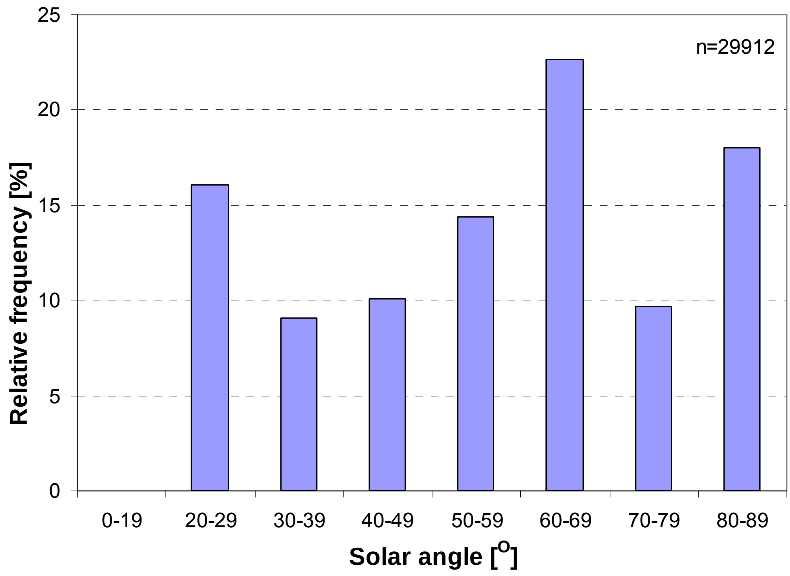


Figure 47. Normalized relative frequency of opening shades as a function of angle between the sun and the normal to the window

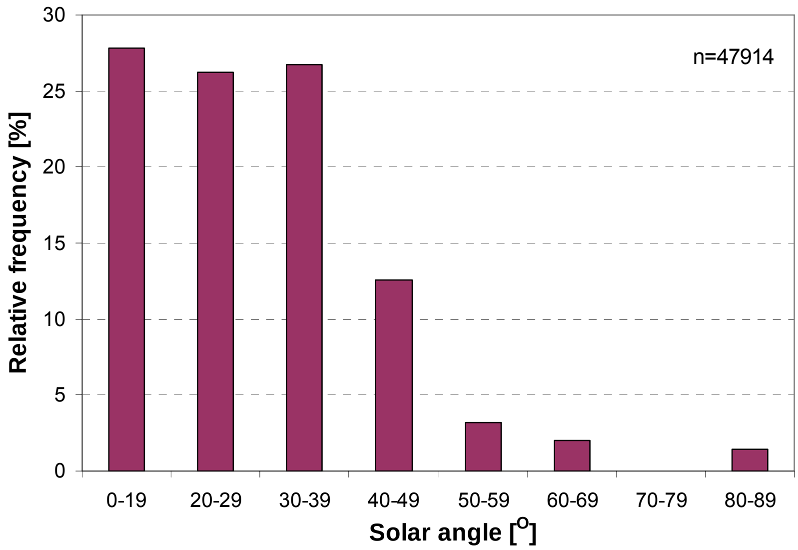


Figure 48. Normalized relative frequency of closing shades as a function of angle between the sun and the normal to the window

The operation of shades as a function of the amount of light ($W.m^{-2}$) entering the room has been also explored (see Figure 49 and Figure 50). The amount of light ($E_{i\ calc}$) has been calculated according to the following equation:

$$E_{i\ calc} = E_v.\tau.A_w \qquad (Eq.\ 4),$$

where E_v is the global vertical irradiance, $\tilde{\imath}$ is transmission of the window and A_w is the ratio between the net window surface (without window frame) and the external wall.

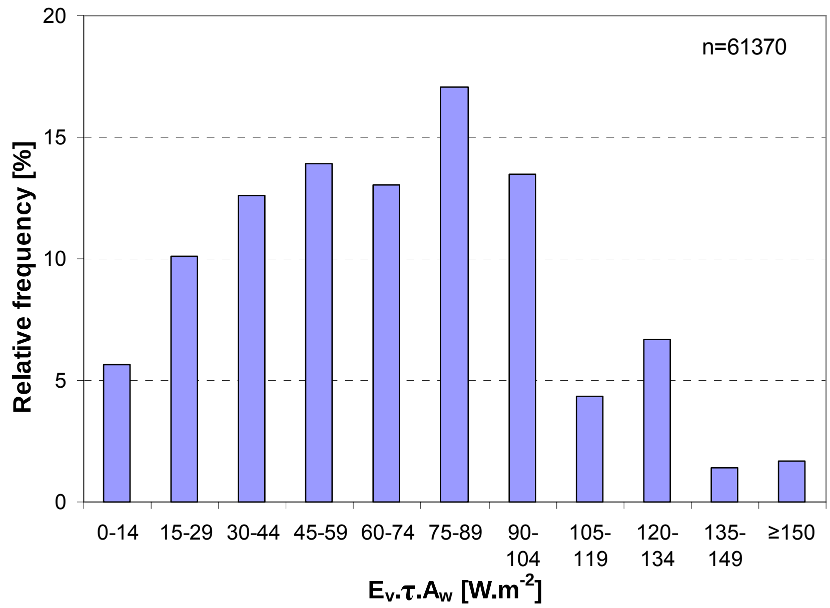


Figure 49. Normalized relative frequency of opening shades as a function of $E_v.\tau.A_w$

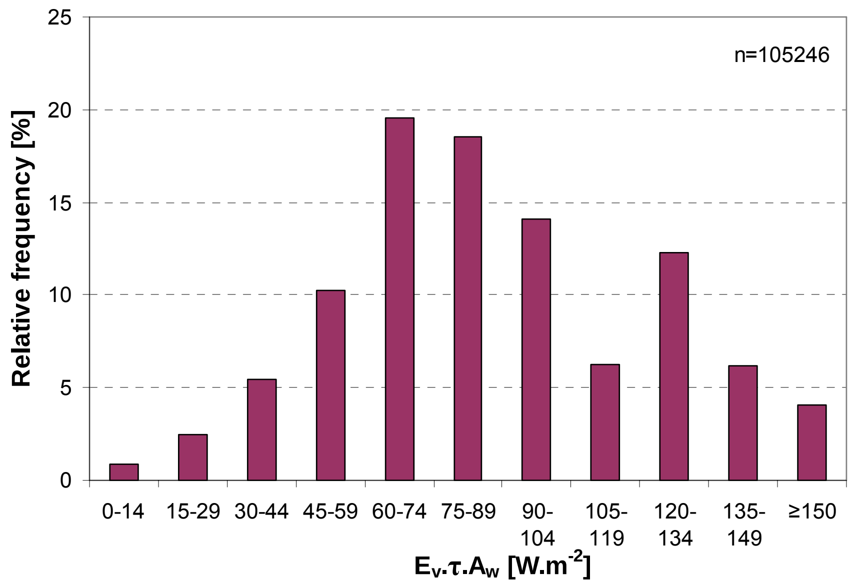


Figure 50. Normalized relative frequency of closing shades as a function of $E_v.\tau.A_w$

Note that in the figures above opening and closing actions are not limited only 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 20% to 40% or changing from 80% to 40%) is considered to be an opening/closing action" (Mahdavi 2007b). To provide a quantitative impression about these changes analysis of frequency distribution of the extents of opening/closing (proportional to 20%) was conducted (see Figure 51).

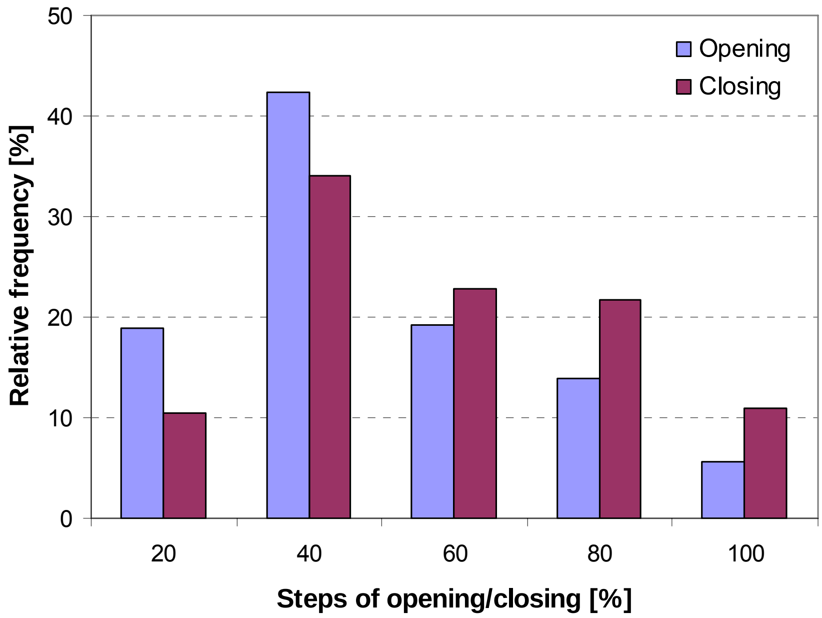


Figure 51. Relative frequency of the steps (proportional to 20%) of opening/closing shades

3.4 Electrical energy consumption and costs

The electrical energy consumption for year 2005 is summarized in the following Table 2.

Table 2. Electrical energy consumption for year 2005

Month	Light/Equipment MWh	Ventilation MWh	Chillers MWh	Lab, Elev., ZID MWh	Total MWh
January	250,00	257,00	195,36	216,00	918,36
February	250,00	251,00	153,50	208,00	862,50
March	221,00	237,00	142,03	211,00	811,03
April	246,00	279,00	182,10	240,00	947,10
May	243,00	264,00	175,55	249,00	931,55
June	244,00	264,00	215,57	242,00	965,57
July	247,00	273,00	347,84	218,00	1.085,84
August	240,00	280,00	383,66	291,00	1.194,66
September	232,00	286,00	343,34	251,00	1.112,34
October	241,00	269,00	237,64	278,00	1.025,64
November	256,00	264,00	246,39	243,00	1.009,39
December	261,00	248,00	218,99	285,00	1.012,99
∑ Total	2.931,00	3.172,00	2.841,97	2.932,00	11.876,97
% of the total electricity consumption	24,68	26,71	23,93	24,69	

24,68% of the total consumed electrical energy is used for lighting and office equipment. The net monetary equivalent of the total electricity consumption (year 2005) of the building is € 450.137,31. Figure 52 shows the monthly distribution of the energy consumption for lighting and office equipment.

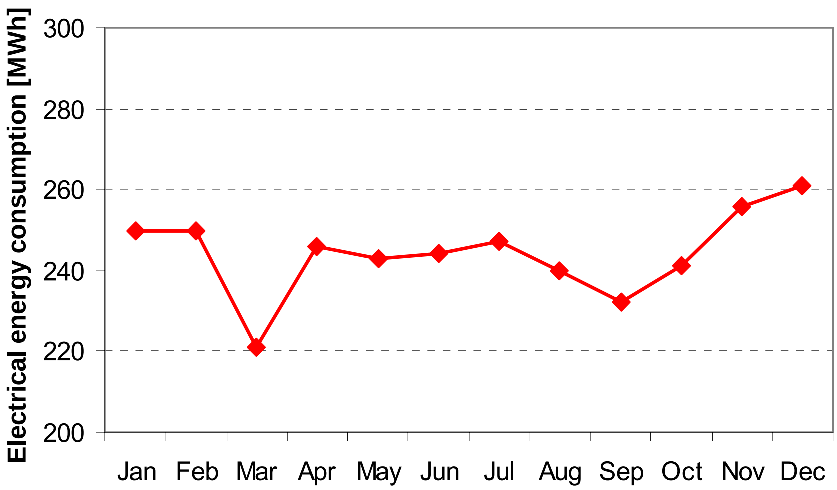


Figure 52. Monthly distribution of energy consumption for lighting and office equipment

The data for heating (year 2005) is summarized in Table 3. The heating load per m^2, considering 63.390 m^2 total area, is 60,4 $kWh.m^{-2}.a^{-1}$.

Table 3. Energy consumption for heating (year 2005)

Month	Energy consumption MWh	Net price € (50,14 €..MWh^{-1})	Heating load $kWh.m^{-2}.a^{-1}$
January	525,40	26.343,36	
February	584,38	29.300,56	
March	575,93	28.877,28	
April	454,08	22.767,52	
May	212,06	10.632,69	
June	115,57	5.794,58	
July	138,33	6.936,12	
August	116,76	5.854,55	
September	149,07	7.474,57	
October	268,74	13.474,72	
November	426,99	21.409,18	
December	474,16	23.774,43	
∑ Total	3.830,14	192.043,07	60,42075

Figure 53 shows a graphical representation of the year energy consumption data for heating.

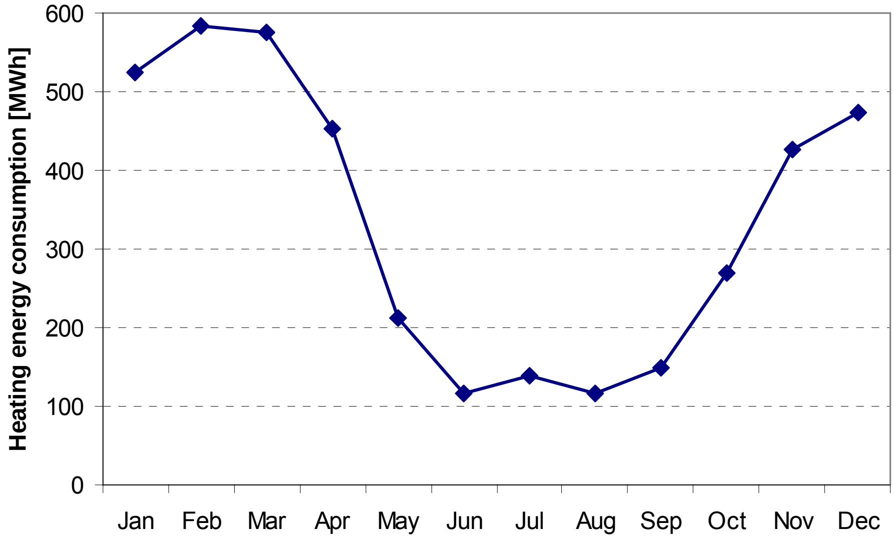


Figure 53. Monthly distribution of heating energy consumption

3.5 Interviews

This chapter summarizes the results of the interviews with the occupants of the monitored rooms, conducted at the end of the observation period. In total 20 persons have been interviewed.

As already mentioned the questions are divided into 5 groups: 1. Personal information about the occupants; 2. Evaluation of the indoor climate and control systems; 3. Operation and accessibility of the systems and system controls; 4. Awareness of the functionality of the building control systems and energy conscious behaviour; 5. Personal preferences of organizing the current / ideal working space; health complaints.

Table 4 summarizes the content of the questionnaire together with the answers of the occupants, expressed in terms of percentage of people.

Table 4. Summary of the questionnaire and the interview results

	Question	Category	%
1.	Personal information		
1.1	Gender	M	85
		F	15
1.2	Age	25-35 years	50
		36-45 years	25
		46-55 years	5
		>55 years	20
1.3	Nationality	AT	85
		DE	10
		IT	5
1.4	Occupation	Univ. Prof.	50
		Univ. Doz.	10
		Pr. Assistant	40
1.5	How many hours in average do you work per week?	40 hours	30
		50 hours	40
		60 hours	25
		>60 hours	5
1.6	Of these, how many hours do you spend at your workstation?	20 hours	5
		30 hours	20
		40 hours	40
		50 hours	30
		≥60 hours	5
1.7	What percentage of your work do you perform on computer?	20 %	10
		30 %	30
		40 %	10
		50 %	25
		60 %	20
		>60 %	5
1.8	How long have you been working in your current office	6 months	25
		12 months	0
		24 months	10
		36 months	5
		60 months	5
		120 months	15
		180 months	5
		>180 months	35
2.	Evaluation of the indoor climate and environ. control systems		
2.1	How do you find the air quality in your office?	Very bad	0
		Bad	25
		It's OK	40
		Good	35
		Very good	0
2.1a	What do you mean by 'bad' air quality?	Polluted ventilation system	56
		Poor ventilation	38
		Lack of plants	6
2.2	Are you satisfied with the possibility to ventilate your office?	Not at all	25
		Less satisfied	30
		It's OK	40
		Satisfied	5
		Very satisfied	0
2.2a	Why are you not satisfied with the possibility to ventilate your office?	Not operable windows/Lack of	68

		fresh air	
		External glass layer not operable	23
		Difficult to open the windows	9
2.3	How is the average temperature in your office in winter?	Cold	0
		Cool	10
		Neutral	90
		Warm	0
		Hot	0
2.4	How is the average temperature in your office in summer?	Cold	6
		Cool	17
		Neutral	61
		Warm	17
		Hot	0
2.5	How satisfied are you with the heating system in your office?	Not at all	0
		Less satisfied	0
		It's OK	40
		Satisfied	50
		Very satisfied	10
2.6	How satisfied are you with the air-conditioning in your office?	Not at all	0
		Less satisfied	30
		It's OK	30
		Satisfied	40
		Very satisfied	0
2.7	Do you have sufficient daylight in your office?	Not sufficient	5
		Could be more	10
		It's OK	75
		A bit too much	10
		Too much	0
2.8	Are you annoyed by direct sunlight at your workstation?	Frequently	5
		Occasionally	70
		Rarely	10
		Never	15
2.9	Are you annoyed by reflections or too bright surfaces on your computer screen?	Frequently	0
		Occasionally	40
		Rarely	20
		Never	40
2.10	Do you have sufficient artificial light in your office?	Not sufficient	0
		Could be more	0
		It's OK	100
		A bit too much	0
		Too much	0
2.11	Are you annoyed by noise in your office?	Frequently	15
		Occasionally	20
		Rarely	45
		Never	20
2.11a	In case of 'Frequently' and 'Occasionally', specify the source of noise!	From the corridor	39
		Air-conditioning	31
		Colleagues in the room	14
		Equipment	8
		Street noise	4
		From neighbour	4

		rooms	
2.12	Evaluate the distance of your workstation from the window.	Too close	5
		It's OK	75
		Too far	20
2.13	Evaluate the outdoor view from your office window.	Very good	40
		Good	35
		Satisfactory	15
		Not satisfactory	10
2.14	Do you have enough privacy in your office to work undisturbed?	Yes	60
		It's OK	25
		No	15
3.	Operation and accessibility of the systems and system controls		
3.1	Can you open the windows of your office if required?	Impossible	35
		Difficult	30
		It's OK	5
		Easy	25
		Very easy	5
3.2	How important is it for you to have the possibility to open the windows?	Unimportant	0
		Not so important	10
		Don't know	10
		Important	50
		Very important	30
3.3	Can you decide independently when to open/close the windows in your office or do you have to negotiate with other people?	No	45
		Yes	55
3.4	Do you have easy access to the external shades in your office?	Impossible	0
		Difficult	10
		It's OK	20
		Easy	35
		Very easy	35
3.5	How important is it for you to have the possibility to operate the external shades?	Unimportant	0
		Not so important	5
		Don't know	0
		Important	15
		Very important	80
3.6	Can you decide independently when to operate the external shades in your office or do you have to negotiate with other people?	No	40
		Yes	60
3.7	Is the light switch easily accessible to you?	Impossible	0
		Difficult	0
		It's OK	5
		Easy	42
		Very easy	53
3.8	Can you decide independently when to switch on/off the light in your office or do you have to negotiate with other people?	No	40
		Yes	60
3.9	Is the thermostat easily accessible to you?	Impossible	0
		Difficult	20
		It's OK	40
		Easy	25

		Very easy	15
3.10	Can you regulate the temperature on your own or do you have to negotiate with other people?	No	50
		Yes	50
4.	Awareness of the functionality of the building control systems and energy conscious behaviour		
4.1	Are you sufficiently informed about how the following systems (heating, ventilation, cooling, lighting, blind protection) work in your office?		
	Heating	Not sufficient	50
		It's OK	40
		Very good	10
	Ventilation/Air-conditioning	Not sufficient	45
		It's OK	40
		Very good	15
	Lighting/Shading	Not sufficient	5
		It's OK	20
		Very good	75
4.2	Have you ever had a training concerning the systems in your office?	No	100
	If „no", would you be interested in such training?	No	35
		Don't know	20
		Yes	45
4.3	To whom do you refer in case of a problem with the building systems (heating, lighting, etc.)?	Secretary	62
		Build. Services	20
		Colleague	13
		Tech. assistant	5
4.4	Are you satisfied with the system services and support in your office?	No	5
		Don't know	45
		Yes	50
4.5	Do you think that you can influence building energy consumption in the way you operate building systems?	No	5
		Don't know	10
		Yes	85
4.6	Do you think about energy conservation, when you operate building systems?	No	50
		Don't know	0
		Yes	50
5.	Personal preferences of organizing the current / ideal working space; health complaints		
5.1	Are you satisfied with the possibilities you have to personalize your working place (furniture, plants, photos…)?	Not at all	5
		Less satisfied	
		It's OK	35
		Satisfied	35
		Very satisfied	25
5.2	Generally, do you feel fine in your office?	Not at all	5
		Less	5
		It's OK	15
		Good	60
		Very good	15
5.3	What are the most important features of the ideal working place from your point of view?	Quietness/Privacy	22
		Furniture and sufficient place	17

		Good indoor climate	17
		Single occupancy office	16
		Adequate lighting	15
		Controllable systems	11
		Personal organization of the workplace	2
5.4	Which improvement measures in your office would you consider as most urgent?	Effective furniture	22
		Operable windows	20
		Better servicing of the air-conditioning system	17
		Bigger office	15
		Quietness/Privacy	14
		Adjustable temperature	6
		Better air quality	6
5.5	Do you have any health complaints?	Backache	18
		Headache	16
		General fatigue	16
		Back pain	13
		Nasal irritation	13
		Eyestrain or –burning	9
		Respiratory problems	9
		Sore throat	6

1. Personal information

Figure 54 to Figure 61 summarize the answers to the questions 1.1 to 1.8.

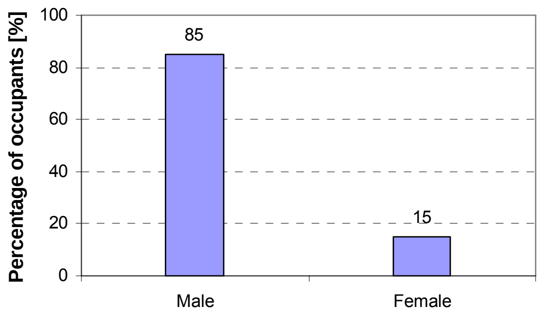


Figure 54. Gender of the interviewed persons (1.1)

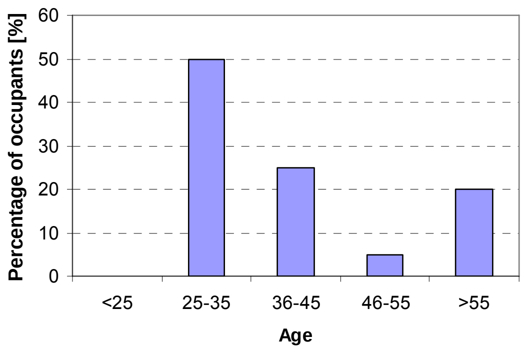


Figure 55. Age of the interviewed persons (1.2)

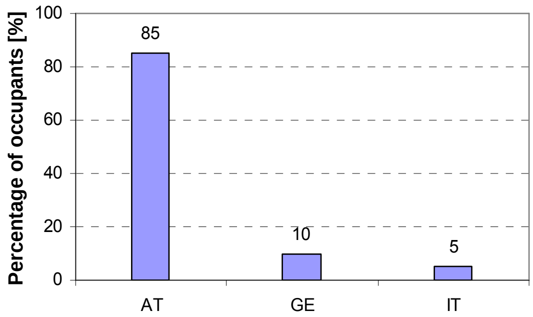


Figure 56. Nationality of the interviewed persons (1.3)

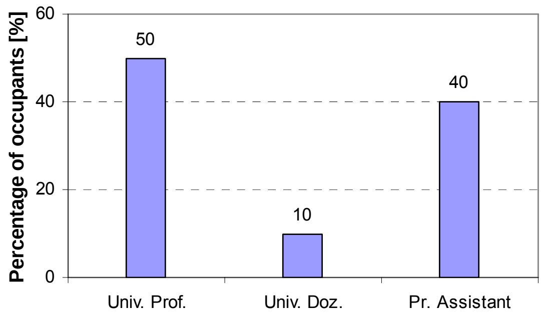


Figure 57. Occupation of the interviewed persons (1.4)

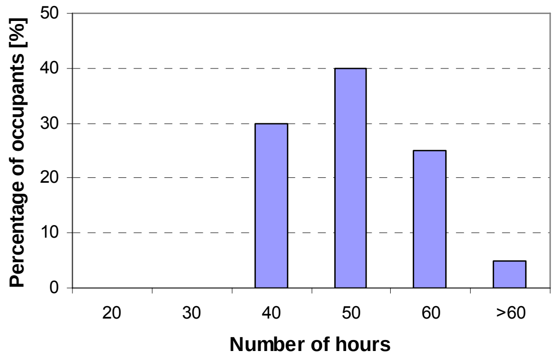


Figure 58. Average working hours per week (1.5)

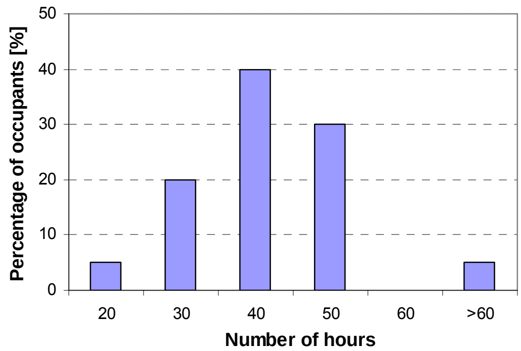


Figure 59. Working hour at the work station (1.6)

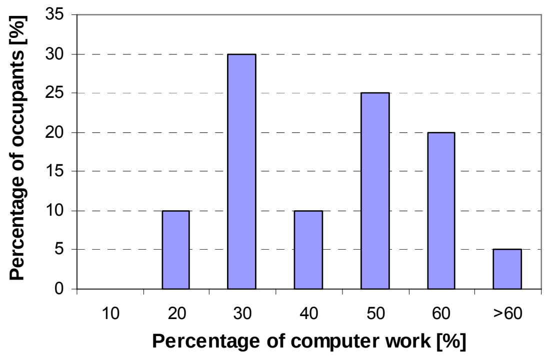


Figure 60. Percentage of computer work (1.7)

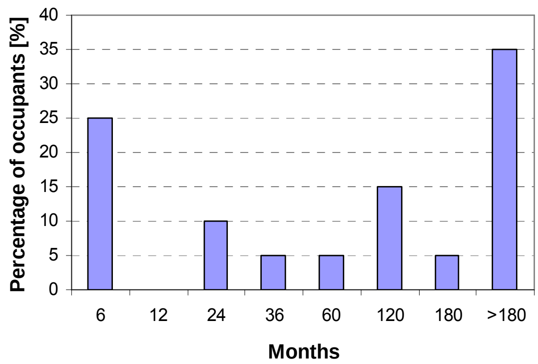


Figure 61. Working period in the current office (1.8)

2. Evaluation of the indoor climate and control systems

The answers to the questions about the evaluation of the indoor climate and control systems are summarized in Figure 62 to Figure 75.

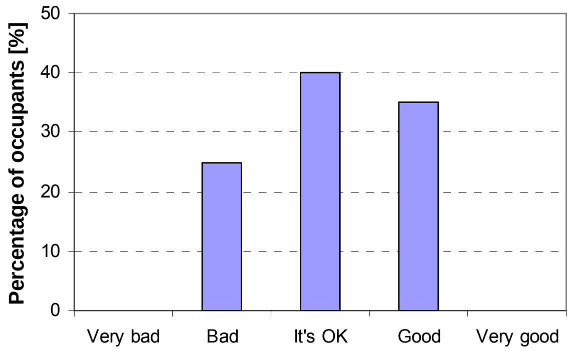


Figure 62. Assessment of air quality in the office (2.1)

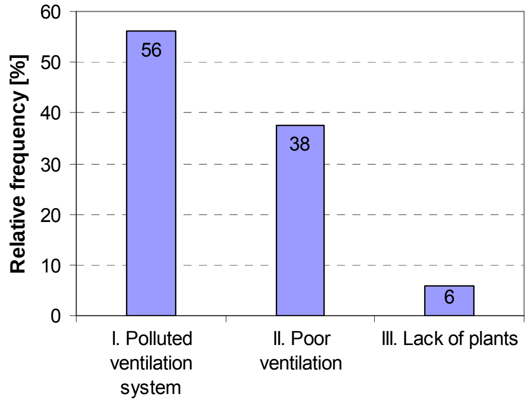


Figure 63. What do you mean by ‚bad' air quality (2.1a)

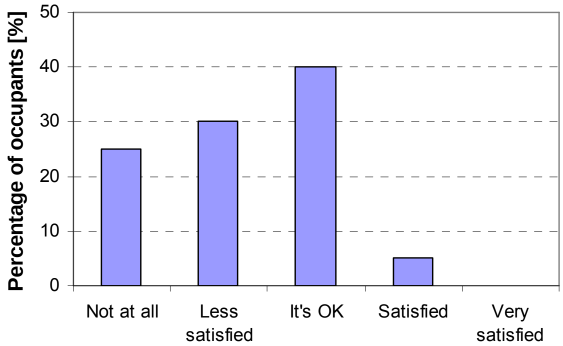


Figure 64. Satisfaction with the possibilities to ventilate the office (2.2)

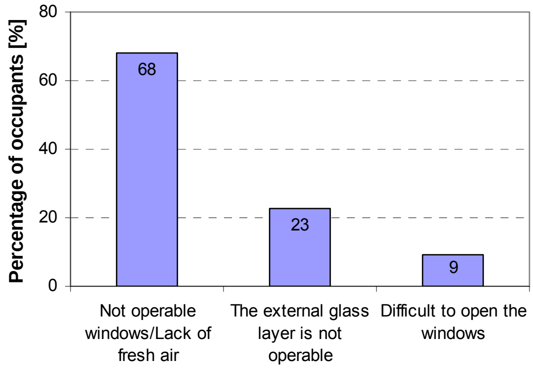


Figure 65.Criteria for dissatisfaction with the ventilation possibilities in the office (2.2a)

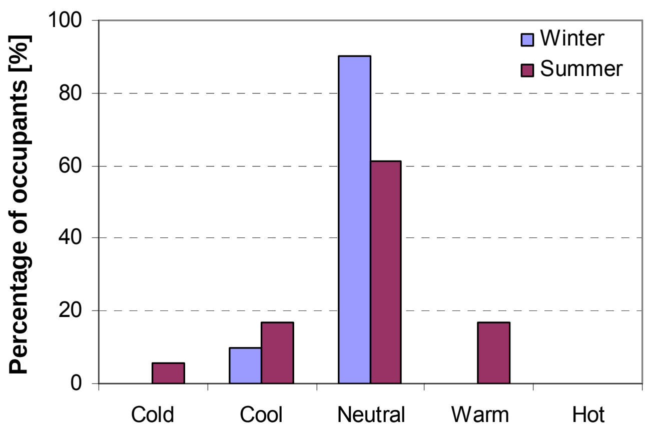


Figure 66. Assessment of the average temperature in the office in winter and summer (2.3, 2.4)

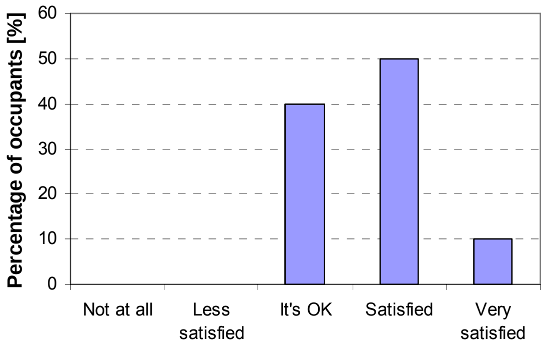


Figure 67. Satisfaction with the heating system in the office (2.5)

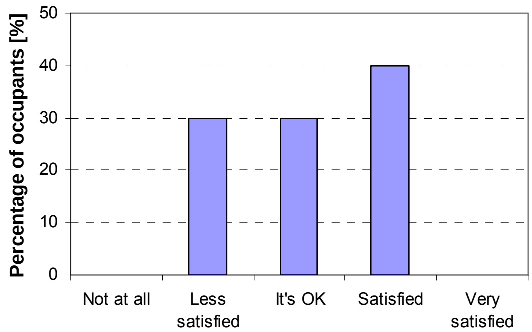


Figure 68. Satisfaction with the air-conditioning system in the office (2.6)

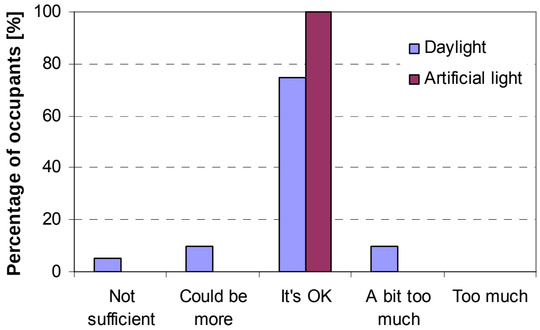


Figure 69. Sufficiency of daylight and artificial light in the office (2.7, 2.10)

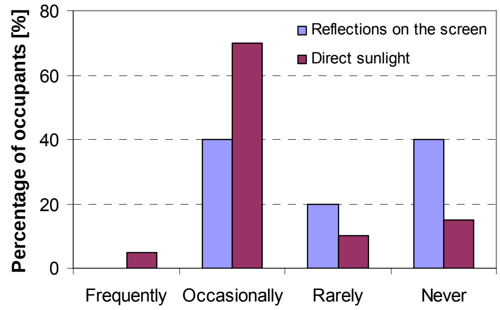


Figure 70. Occurrence of direct sunlight and reflections on the computer screen (2.8, 2.9)

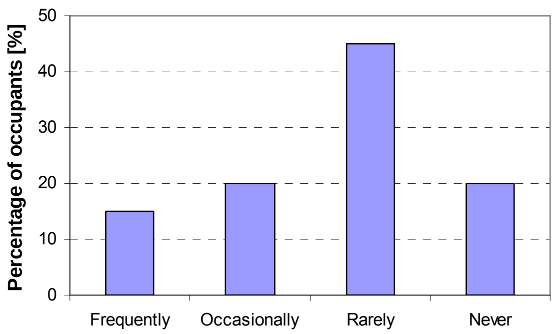
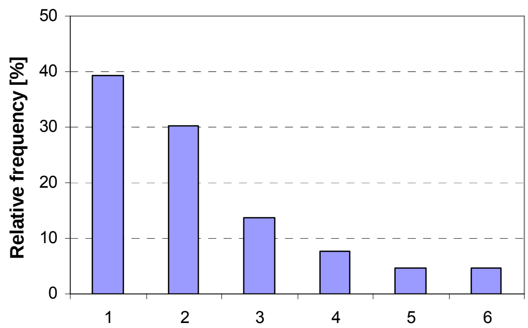


Figure 71. Noise disturbance (2.11)



1 Noise from corridor
2 Air conditioning
3 Colleagues in the room
4 Equipment
5 Street noise
6 Noise from neighbour rooms

Figure 72. Sources of noise (2.11a)

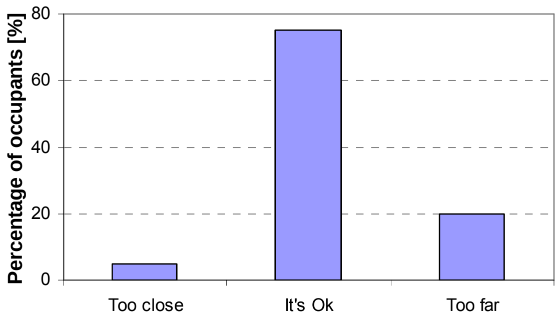


Figure 73. Evaluation of the distance of the work station from the window (2.12)

Figure 74. Evaluation of the outdoor view from the office window (2.13)

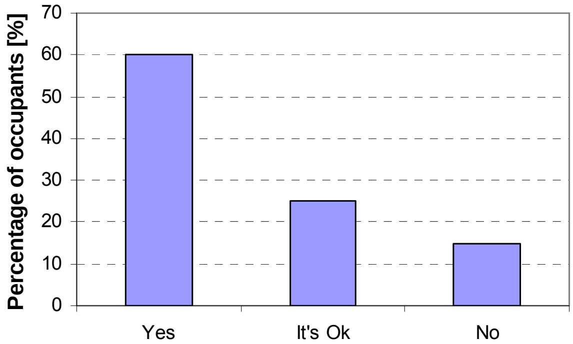


Figure 75. Availability of privacy in the office to work undisturbed (2.14)

3. Operation and accessibility of the systems and system controls

The answers of the questions about the operation and accessibility of the systems and system controls are summarized in Figure 76 to Figure 81.

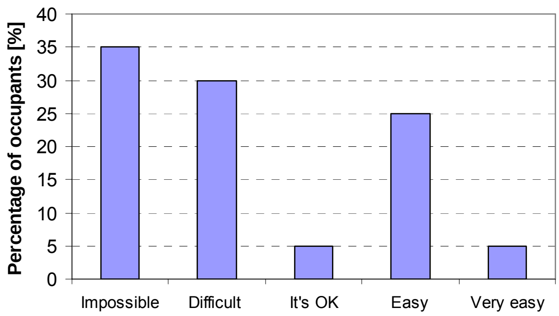


Figure 76. Possibility to operate the window if required (3.1)

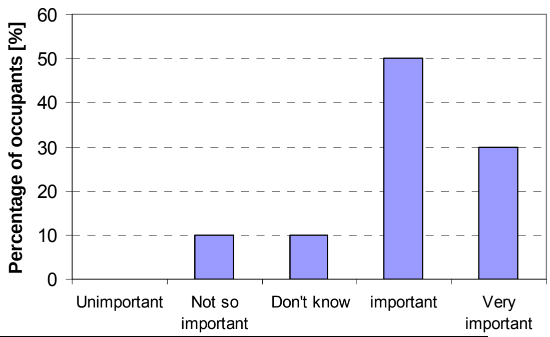


Figure 77. Importance of having the possibility to operate the windows (3.2)

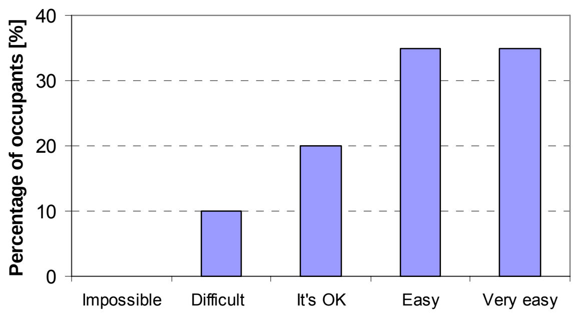


Figure 78. Accessibility of the external shades (3.4)

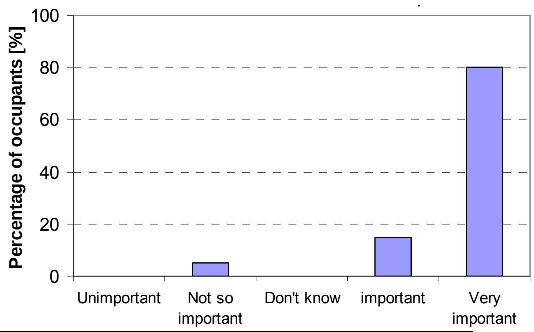


Figure 79. Importance of having the possibility to operate the external shades (3.5)

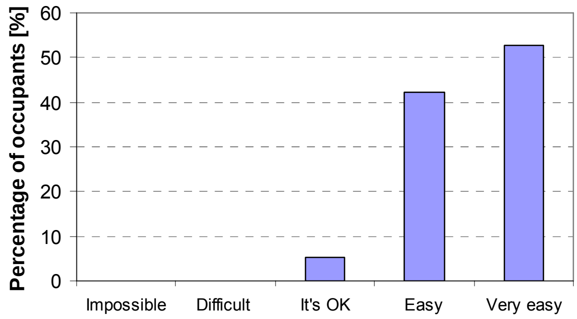


Figure 80. Accessibility of the light switch (3.7)

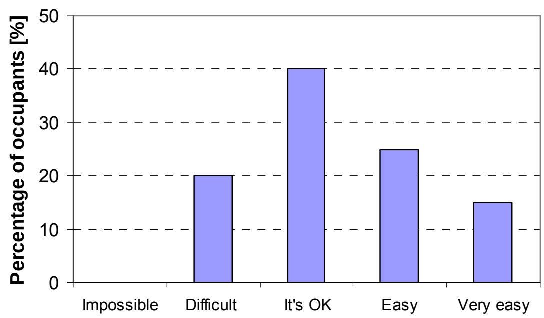


Figure 81. Accessibility of the thermostat (3.9)

For each control device a question has been asked whether the people in double and triple occupancy offices can decide independently when to control the building systems or have to negotiate with their roommates. The results are presented in Figure 82. When there is a need to change the status of a system the occupants ask each other for approval, mostly without contradiction.

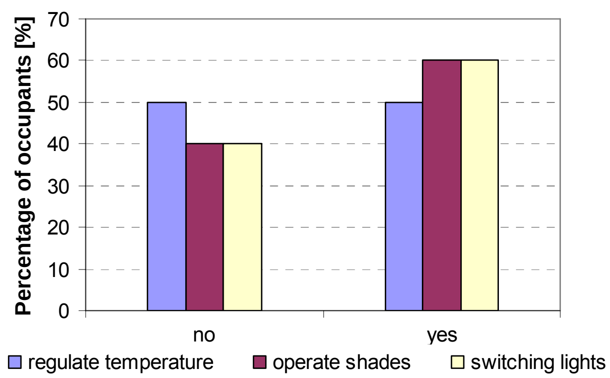


Figure 82. Possibility to decide independently when to operate the building systems

4. Awareness of the functionality of the building control systems and energy conscious behaviour

The answers to the questions about the awareness of the functionality of the building control systems and energy conscious behaviour are summarized in Figure 83 to Figure 88.

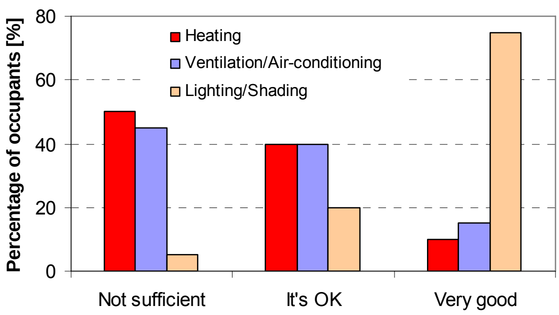


Figure 83. Level of information about the building systems (4.1)

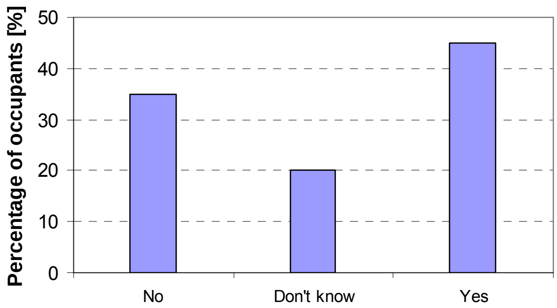


Figure 84. Availability of interest in training concerning the systems in the office (4.2)

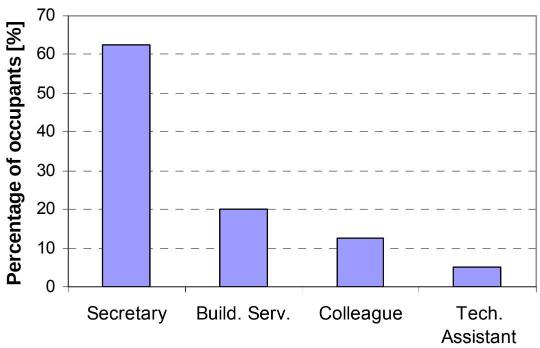


Figure 85. Reference in case of a problem with the building systems (4.3)

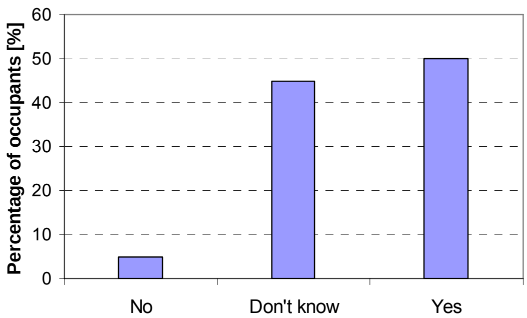


Figure 86. Satisfaction with the system services and support in the office (4.4)

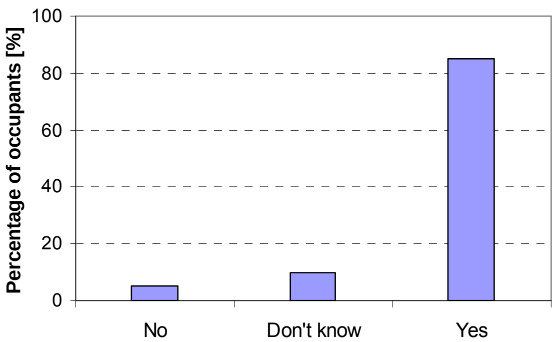


Figure 87. Consciousness about the influence on the building energy consumption from the way people operate building systems (4.5)

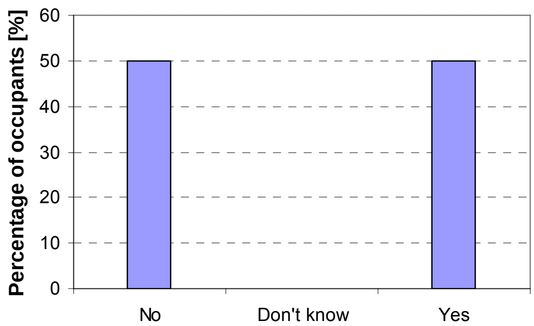


Figure 88. Consideration of energy conservation aspect when people operate building systems (4.6)

5. Personal preferences of organizing the current / ideal working space; health complaints

The answers of the questions concerning the personal preferences of organizing the current / ideal working place and health complaints are summarized in Figure 89 to Figure 93.

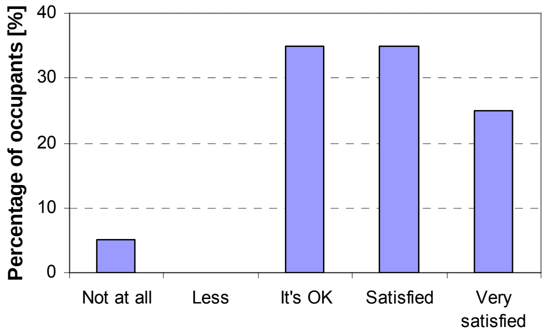


Figure 89. Satisfaction with the possibilities to personalize the working place (5.1)

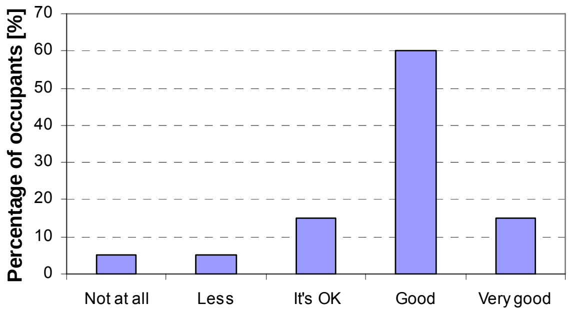


Figure 90. General well-being of the occupants in the office (5.2)

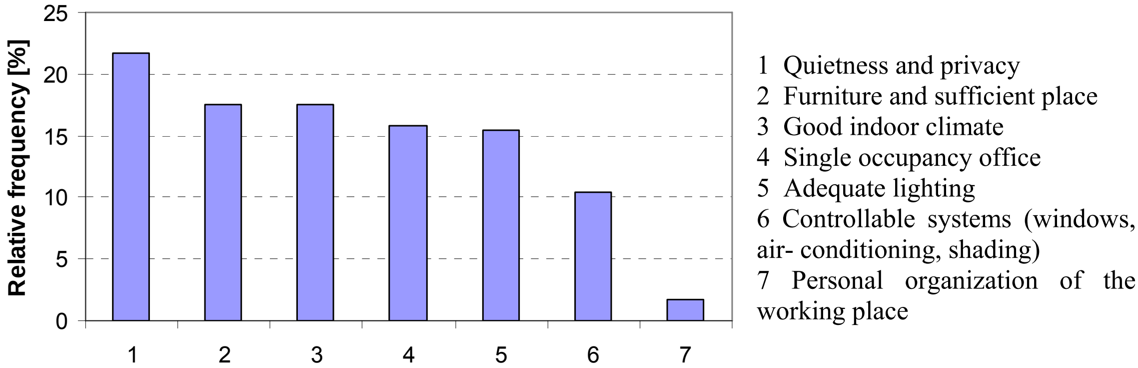


Figure 91. Features of the ideal working place from the occupants' point of view (5.3)

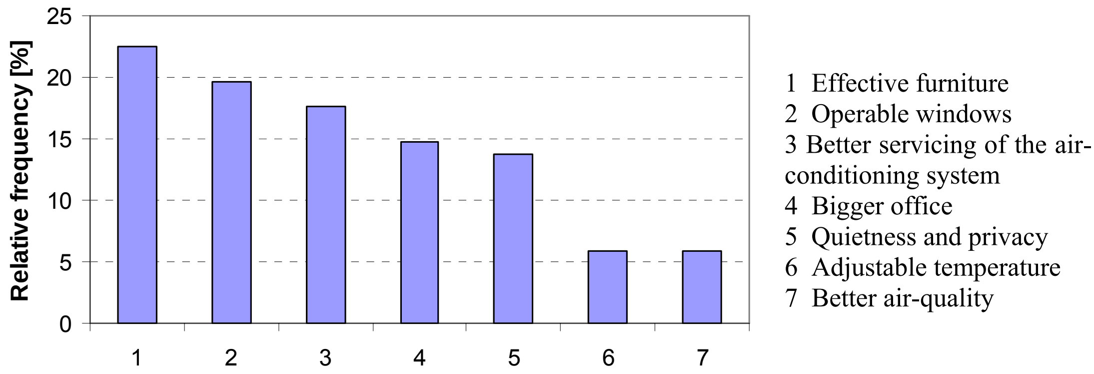


Figure 92. Urgent improvement measures in the office from the occupants' point of view (5.4)

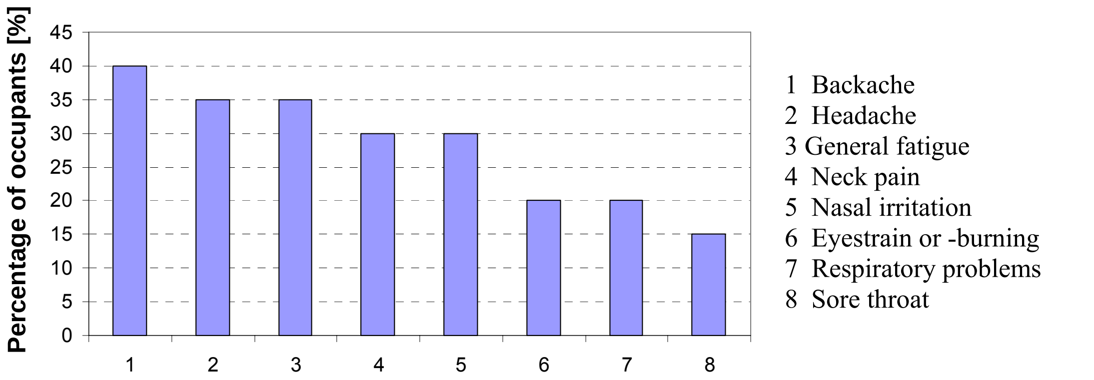


Figure 93.Frequency of health disorders (5.5)

4 Discussion

4.1 Occupancy

The monitored occupancy in FH (Figure 14) and the obviously related people load (Figure 16) 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 Figure 94 and Figure 95). 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 this case study deals with offices of teaching and research staff, who spend a considerable amount of time in classrooms and laboratories. Moreover, the differences in both occupancy levels (see Figure 15) and lighting operation (Figure 20) 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" (Mohammadi 2007). On a more general level, our observations regarding this building suggest that the environment systems in a considerable number of office buildings may be "over-designed", in a sense that they are dimensioned for occupancy levels that seldom occur (Mahdavi 2007b).

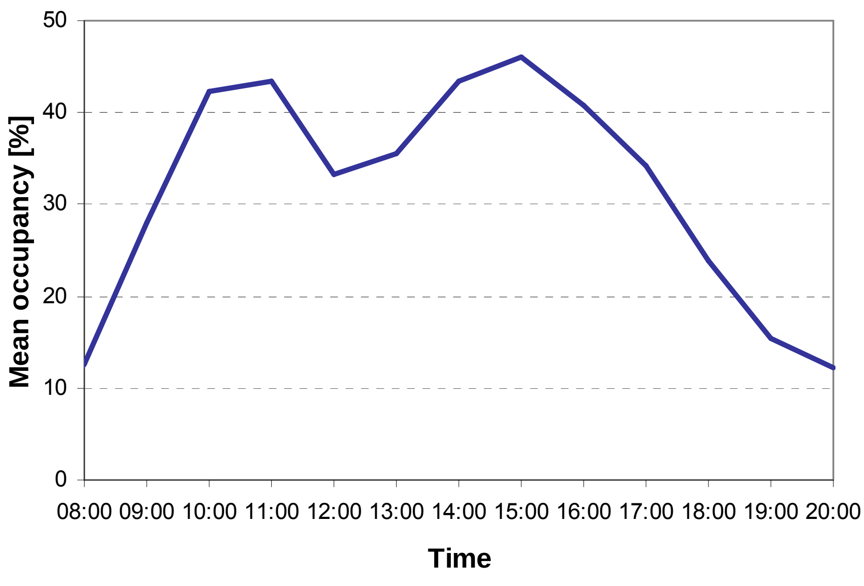


Figure 94. Illustrative simulation input data regarding mean hourly occupancy level for FH

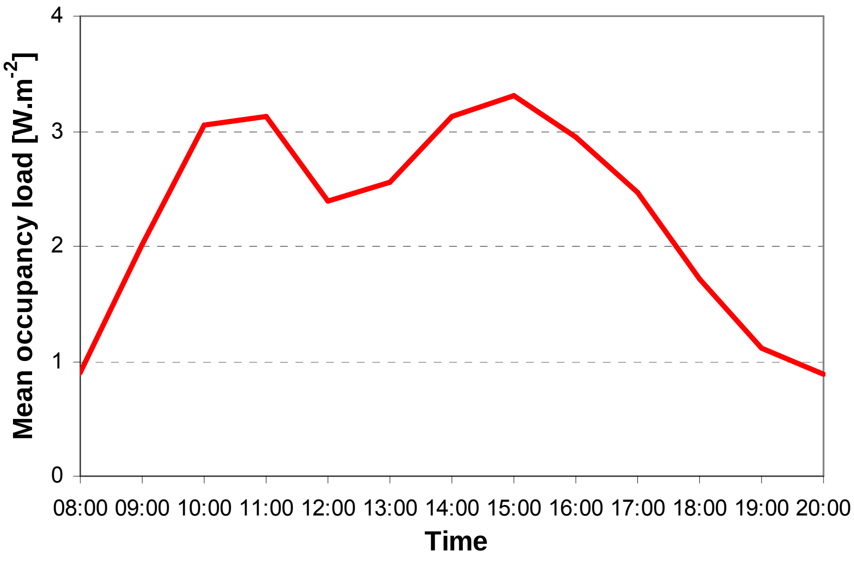


Figure 95. Illustrative simulation input data regarding mean hourly people (sensible) load for FH

4.2 Lights

4.2.1 Lighting operation

The mean lighting load over the course of a reference day (see Figure 18) follows a similar pattern to the mean occupancy distribution. The corresponding hourly averages of the mean lighting load can be used as an advanced simulation input for improved prediction of thermal performance (see Figure 96).

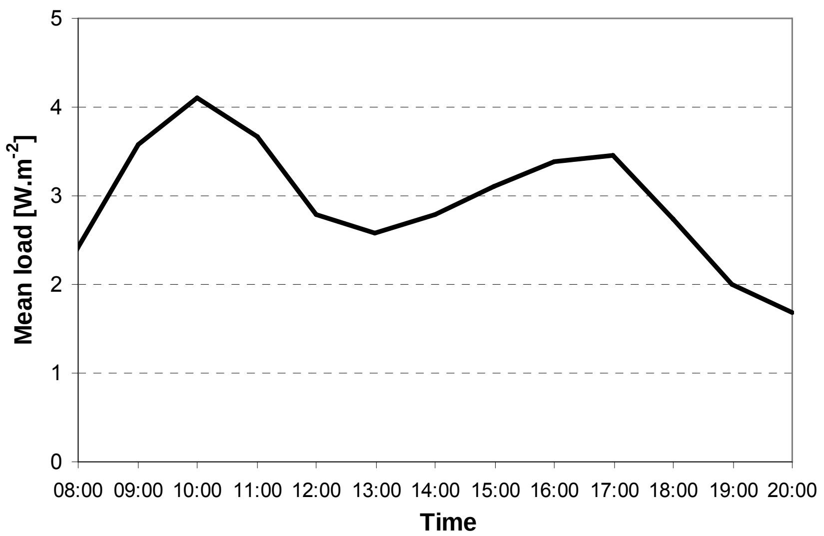


Figure 96. Illustrative simulation input data regarding mean hourly lighting load for FH

The “switching on probability at arrival” (Figure 21) and the “intermediate switching on the lights” (Figure 22) reveal similar tendencies of increasing the actions’ frequency below 100 lx and at higher illuminance levels (at average 900 lx). The first tendency is intuitive: lower illuminance levels result in more switching on actions. The second tendency may be due to the circumstance that *a)* very high outdoor illuminance levels (reflected in correspondingly high indoor values) could cause an adaptive effect and heighten the visual expectations of the occupants upon arriving in the office; *b)* higher window luminance levels (and the resulting contrast to the other interior surfaces) may lead to a dim interior appearance, thus likewise heightening the visual expectation levels of the users; *c)* people first close the shades (for example to counteract very high illuminance levels due to daylight) and then, faced with the reduced illuminance switch on the lights.

By viewing the frequency of the action “switching on the lights” in terms of the time of the day (Figure 23), a clear pattern emerges that could be harnessed while modeling the respective behavior in a simulation program.

Concerning the action "switching the lights off", a clear relationship to the subsequent duration of absence is evident (Figure 24). Based on this, a behavioral model has been derived, which can be implemented for simulation purposes and energy saving calculations (see Figure 97).

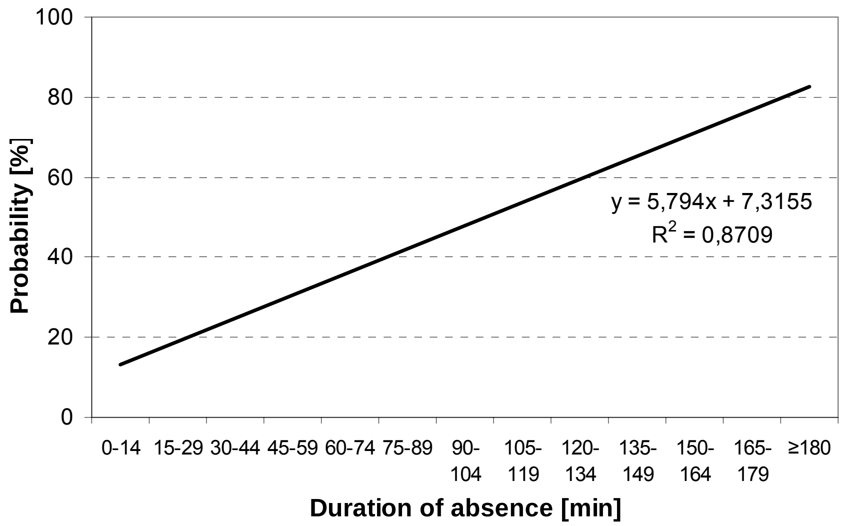


Figure 97. Model of switching the lights off probability in relation to the duration of absence

The respective “intermediate switching off” actions, shown in Figure 25, confirm the intuitively expected tendency of switching off the lights once the indoor illuminance level exceeds a threshold of 1000 lx.

As related to the time of the day, the frequency of switching off the lights (Figure 26) increases slightly at midday (when leaving the office for lunch) and more significantly in the evening hours (when leaving at the end of the working day).

4.2.2 Energy saving scenarios

High-resolution, long-term, empirical data on occupancy, status of electrical lighting and indoor illuminance is explicit for the assessment of energy effectiveness. Thus, the potential for reduction of electrical energy use for lighting in the sampled offices of FH has been calculated. Thereby, three cumulative energy saving scenarios have been developed.

The first scenario requires the automatic switching off the lights after 10 minutes absence from the office. Considering this condition, two 5 min. intervals per absence period have been subtracted from the number of 5 min. intervals with lights on and no occupancy. The subtraction result has been then divided by the total number of 5 min. intervals with lights switched on. The calculated ratio, multiplied by 100, expresses the percentage of lighting energy that can be potentially saved by consideration of occupancy profiles.

The second scenario implies, in addition, that lights are switched off, if the daylight-based task illuminance level equals or exceeds 500 lx. The daylight availability in this case is derived based on measured outside illuminance, calculated daylight factors, shading position 0% (fully opened), without consideration of direct sun light. The number of occupied 5 min. intervals with lights on and calculated daylight availability ≥ 500 lx has been subtracted from the total number of occupied 5 min. intervals with lights on. The result has been divided by the total number of occupied 5 min. intervals with lights on. So calculated ratio, multiplied by 100, expresses the percentage of lighting energy that can be potentially saved, while considering daylight availability.

The third scenario assumes furthermore an automated dimming regime, whereby luminaries are dimmed down so as to maintain an illuminance level of 500 lx while minimizing electrical energy use for lighting. In this context, the ratio 'calculated daylight illuminance (< 500 lx) divided by the maximum artificial illuminance 500 lx, multiplied by 100', represents the percentage of energy saving potential for lighting from dimming. A linear relation between voltage power and resulting light level of the dimming ballast has been considered. Furthermore, the maximum possible energy saving was limited to 60% (savings above 60% were considered as 60%). The ratios for each occupied 5 min. intervals with lights on and calculated daylight availability lower than 500 lx have been averaged over the entire observation period, resulting in a percentage of energy saving from dimming.

The energy saving potential from the 3 scenarios in percentage is 26 %, 28% and 15% accordingly, resulting in total cumulative energy saving potential of 69%. The energy saving potentials have been converted into $kWh.m^{-2}.a^{-1}$ and $€.m^{-2}$ (see Table 5). The conversion algorithm follows several steps. The lighting energy consumption (per m^2) for a reference day has been derived by summing the mean lighting loads for each working hour (see Figure 96). For deriving the energy consumption per sq. m. per year, the sum per day has been multiplied by 251 working days (excluding official holidays and weekends) and divided by 1000 to convert W into kW. The calculated total energy consumption for lighting is 9,95 $kWh.m^{-2}.a^{-1}$. The energy saving of the three scenarios can be then calculated easily as a percentage of the calculated total energy consumption. The cumulative energy saving from the three scenarios is 6,87 $kWh.m^{-2}.a^{-1}$.

The monetary equivalent in $€.m^{-2}$ is finally calculated, considering the kWh price for year 2005, which is 3,79 $Cent.kWh^{-1}$ or 0,0379 $€.kWh^{-1}$. The cumulative energy saving from the three scenarios is in this case 0,26 $€.m^{-2}$. For the entire office area of 22.000 m^2 € 5.720 per year could be theoretically saved by "a comprehensive retrofit of the office lighting system toward dynamic consideration of occupancy patterns and daylight availability" (Mahdavi 2007b).

Table 5. Energy saving scenarios for FH.

Saving potential in	Energy saving scenarios for FH			
	1	2	3	1+2+3
%	26	28	15	69
$kWh.m^{-2}.a^{-1}$	2,59	2,79	1,49	6,87
$€.m^{-2}.a^{-1}$	0,10	0,10	0,05	0,26

4.3 Shades

4.3.1 Position of shades

The position of shades is clearly related to the orientation (east) of the observed offices. This explains the higher deployment level in the morning hours (see Figure 27). Moreover, the mean monthly shade deployment levels over the course of the year show a discernible relation to the corresponding mean global horizontal and vertical irradiance incident on the façade (see Figure 28 and Figure 30). Both orientation and seasonal dependency can be considered by generating hourly schedules of mean shade deployment degree over the course of four reference days, representing each season (see Figure 98). The shade deployment information can be used to determine the effect of direct sunlight on thermal processes in buildings.

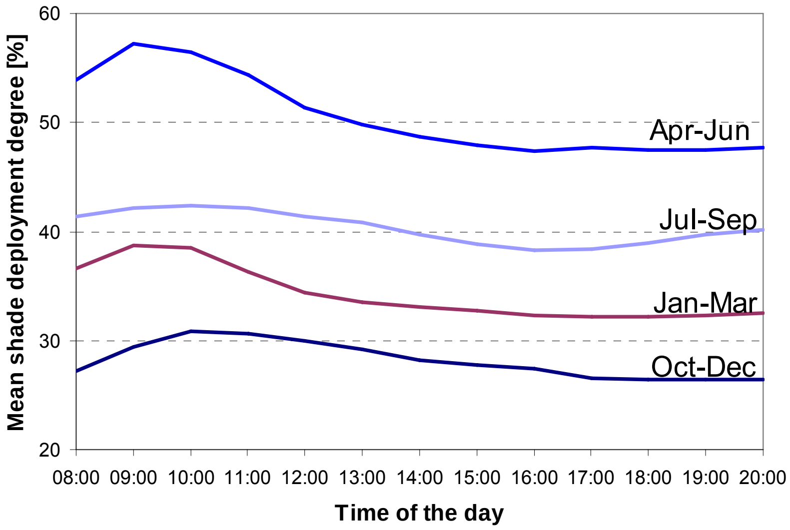


Figure 98. Illustrative simulation input data regarding mean hourly shade deployment degree in FH for different seasons

An evident relationship between shade deployment and the magnitude of solar radiation as well as outdoor temperature is demonstrated in Figure 32 to Figure 36. The latter provide a very effective basis for modeling the state of shades for FH building (see Figure 99, Figure 100, Figure 101, Figure 102).

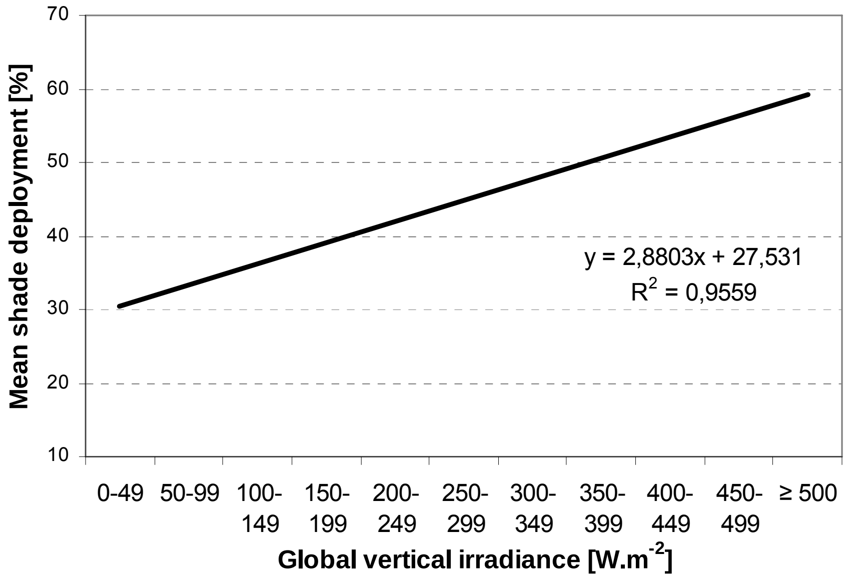


Figure 99. Illustrative model of shade deployment as a function of incident irradiance on FH's façade

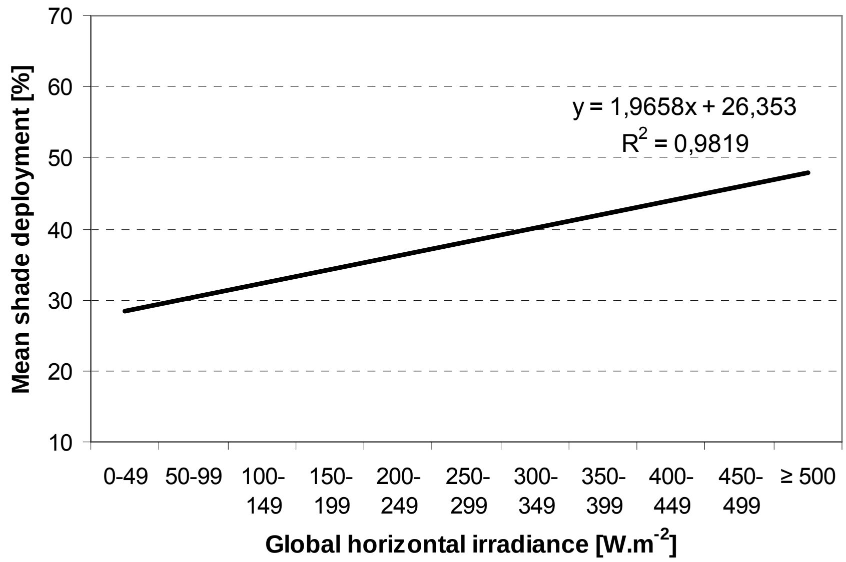


Figure 100. Illustrative model of shade deployment as a function of global horizontal irradiance

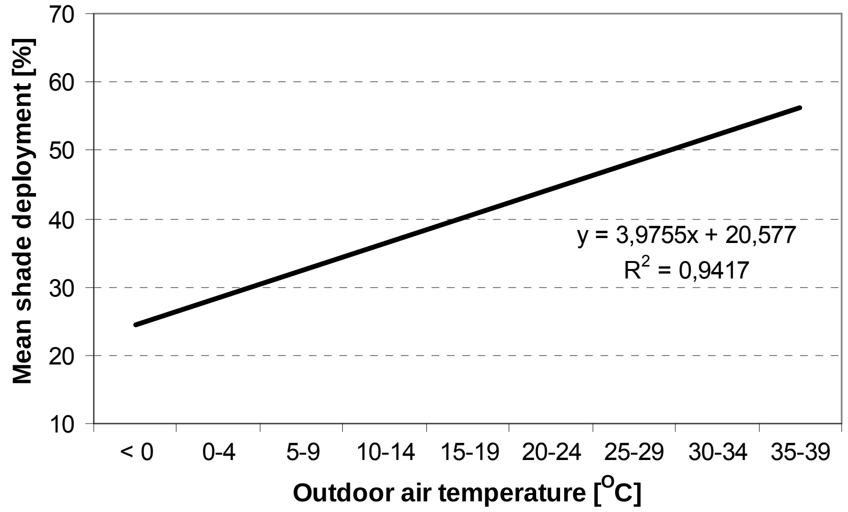


Figure 101. Illustrative model of shade deployment as a function of outdoor air temperature

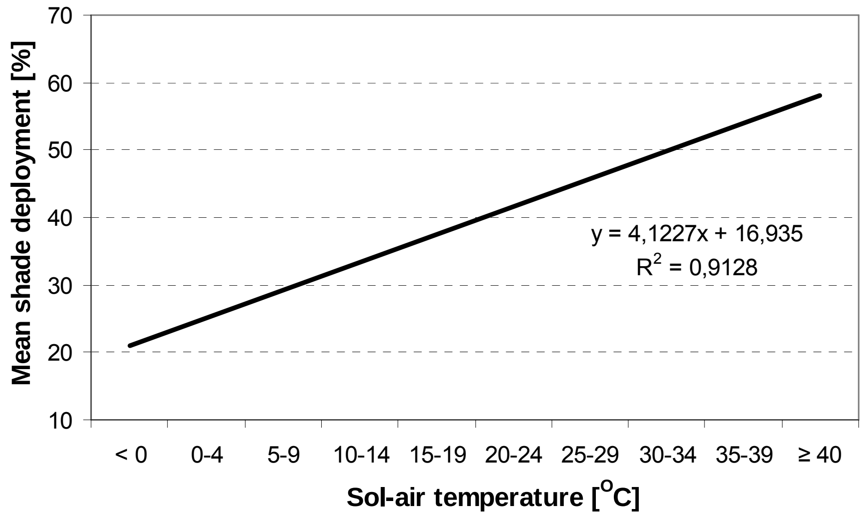


Figure 102. Illustrative model of shade deployment as a function of sol-air temperature

4.3.2 Opening and closing of shades

The analysis of the actions "opening shades" and "closing shades" in relation to the time of the day shows distinct patterns. Closing occurs mostly in the morning in the presence of direct sunlight incident on the façade (see Figure 38). Noticeable is the fact that at this early time the sun altitude is relatively low, which results in deeper penetration of the sun rays into the rooms.

On the contrary, “opening shades” happens in the afternoon when there is no direct sunlight and the daylight availability for east orientation is reduced in comparison to the morning hours (see Figure 37).

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 $W.m^{-2}$ (see Figure 39 and Figure 40). Similar conclusion about opening/closing shades can be done for the measured global horizontal irradiance. The actions “closing shades” increase in this case when the global irradiance rises above 250 $W.m^{-2}$ (see Figure 41 and Figure 42).

The occupants’ actions “opening shades” and “closing shades” do not display a clear relationship to the relevant outdoor air temperature values (see Figure 43 and Figure 44). 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 45 and Figure 46).

The action “opening shades” does not show a clear relationship to the angle between the sun and the normal to the window (see Figure 47). In contrast “closing shades” does seem to be related to the position of the sun (see Figure 48). The smaller the angle, the deeper is the solar penetration into the room. Around 80% of all closing actions occur when the solar angle is less than 40 degrees. This conclusion agrees with the statement of Inoue (1988) about relation between shading position and solar penetration into the room.

The analysis of opening and closing actions as a function of the solar radiation entering into the room ($E_v.\tau.A_w$) does not show clear patterns. Nevertheless, more than 60% of the actions “opening shades” occur when $E_v.\tau.A_w < 105$ $W.m^{-2}$. As to the action “closing shades”, around 70% of all actions take place when $E_v.\tau.A_w$ rises above 60 $W.m^{-2}$.

The frequency distribution of the steps of opening/closing shades (proportional to 20%) shows that people generally open or close the shades with 40% or more (see Figure 51). The incremental changes of the shading position (20%) are less than 20% of the total amount of actions. The changes from fully opened to fully closed and vice versa are quantitatively low because of the fact that the positions prior action are mostly not fully opened or closed. The rate of closing with 60% or more is higher than the one for opening, which leads to the conclusion that people tend to change the shading position more significantly when closing the shades than by opening.

4.4 Comparison with previous studies

Direct comparison with the results from previous studies in the area of user behavior is difficult because of the different scientific methodology used for each empirical study: different typology and geographical location of the buildings; different user sample; different type, accuracy and resolution of the collected data; different types of statistical analysis and formats of representation etc. Thus, a comparison is possible on a more general level in terms of general statements.

The switching of electrical lighting and the operation of shades in FH were put in the context of previous research studies, selected by the criteria of similarity of analysis and representation format. The switching on probability of electrical lighting in FH was compared to the probabilities derived by Hunt (1979) and Reinhart (2001). While the probabilities of Hunt and Reinhart show consistent relationship to the work plane illuminance, FH probability tends to be more independent on the desk illuminance levels (see Figure 103). The switching on probability in FH for work plane illuminance levels lower than 100 lx is significantly lower that the ones derived by Hunt and Reinhart. One reason for this discrepancy could be the type of analysis in FH representing the switching on probabilities in terms of illuminance intervals (“bins” of 100 lx). Common for all these three cases is that only illuminances lower than 100 lx cause noteworthy increase in the switching on probability upon arrival.

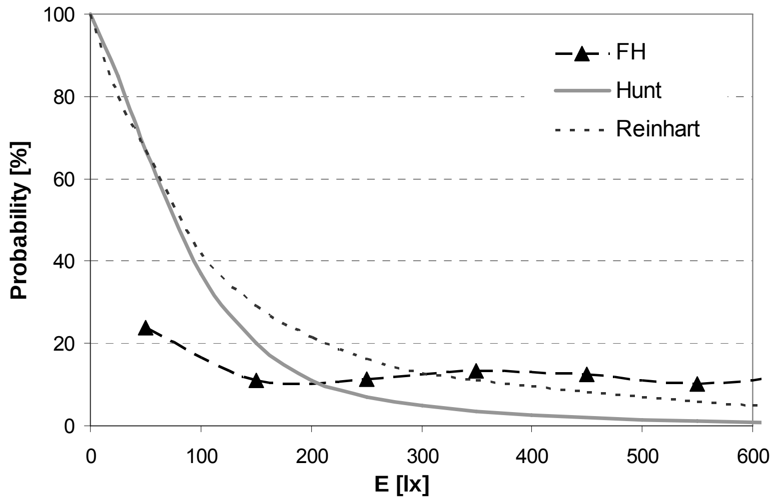


Figure 103. Comparison between the switching on probabilities upon arrival in relation to the work plane illuminance of FH, Hunt and Reinhart

The analysis of the switching off probability as related to the duration of absence in FH is analogue to the one done by Pigg (1996) while investigating people's behavior toward electrical lighting in one university office building in the USA. As Figure 104 shows, the switching off probabilities of FH and Pigg's building are very similar. Both state that people are more willing to switch off the lights if they intend to stay longer away from the office. Absences between 2 to 4 hours result in switching off probability around 60%, while longer than 4 hours result in switching off probability of almost 100%.

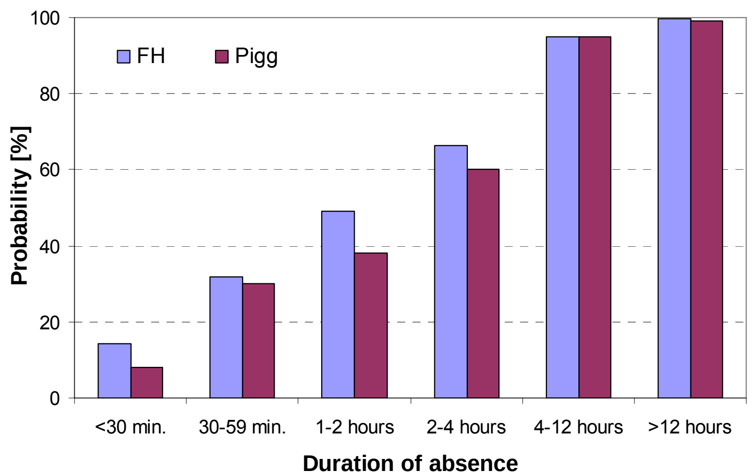


Figure 104. Comparison between the switching off probability in relation to the period of absence of FH and Pigg

Hunt's (1979) statement that switching the lights occurs mostly at arrival or when leaving the office was confirmed by FH building. In FH switching on upon arrival happens two times more frequently (1610 actions) then during the intermediate period of occupation (834 actions). The same is applicable for switching off the lights when leaving the office (1425 actions) in comparison to the number of switching off actions during the intermediate period of occupation (627).

The shading operation in FH also confirms some of the findings of previous studies. The mean shade deployment in FH over the course of a reference day was compared to the mean shade deployment of one of the office buildings, investigated by Inoue (1988). Inoue's curve represents a reference day in summer, while FH's curve includes the period April to June. For south-east oriented façade Inoue concluded that the percentage of blind occlusion was higher in the morning hours than in the afternoon, similar to the FH façade (see Figure 105). The shifted maximums are due to slight differences of the façade orientations of the two buildings, resulting in time shifted maximums of the incident solar radiation.

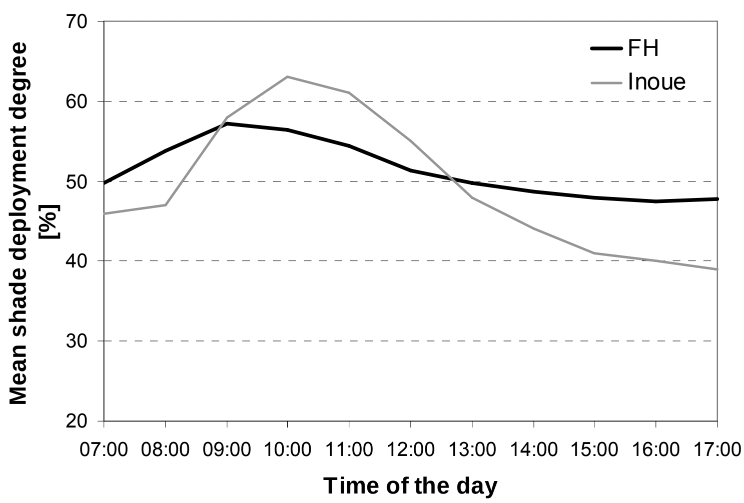


Figure 105. Comparison between the mean shade deployment over the course of a reference day in summer in FH and Inoue's building A

Inoue observed that the rate of closing shades is higher in the morning hours, while opening shades occurs mostly in the afternoon. The same pattern was observed in FH. This behavioral tendency could be a reaction to the availability of direct sunlight incident on the east façade in the morning hours. People close the shades to block the sunlight and so to avoid glare or reflections. Lindsay (1992) came to a similar conclusion stating that the avoidance of glare is the general motivation for people to use blinds.

The shading operation derived from long-term observations reveals dependency on the time of the year: higher mean shade deployment in the high-radiation summer months and lower mean shade deployment in the low-radiation winter months (Inoue 1988).

More conclusive comparisons of the findings in the area of user control behavior in buildings can be achieved by unifying the scientific methodology and particularly by developing a catalogue of standard formats for data representation.

4.5 Interviews

In total 20 people have been interviewed. The majority of them are men (85%). Half of the occupants are between 25 and 35 years old, while 20% are older than 55 years (see Figure 54 and Figure 55). All participants are central Europeans; 85% are Austrians. Concerning the occupation, 60% are teaching staff (university professors and docents) and the remaining 40% are students and project assistants (see Figure 56 and Figure 57).

All interviewed persons claim to work not less than 40 hours per week, 60% tend to work even more than 50 hours per week. 65% of the occupants spend up to 40 hours per week at their workplace, while the rest 35% - more than 50 hours per week (see Figure 58 and Figure 59). A comparison between these results and the measured occupancy (Figure 14) shows that the occupants tend to overestimate the time they spend at their work stations. Nevertheless, many of them work longer than the official working time. The occupancy curve in Figure 14 shows that at 20:00h the mean presence level is still above 10%.

50% of the interviewed occupants perform less than the half of their work on computer. 65% of the people have been working more than 3 years in their current offices, while 25% less than 6 months. The majority has a good overview on the working environment, based on long-term perception, which is advantageous for getting a reliable feed back and evaluation (see Figure 60 to Figure 61).

The majority (75%) of interviewees give a positive ranking of the air quality in the office (see Figure 62). The rest 25% find the air quality “Bad” because of several reasons: on the first place polluted ventilation system; on the second - poor ventilation; and on the third – the lack of plants (see Figure 63).

In spite of the positive evaluation of the air quality, 55% of the occupants are dissatisfied with the possibility to ventilate their offices (see Figure 64). The reasons for dissatisfaction are weighted as follows: not operable windows; not operable external glass layer; difficult to open the windows (see Figure 65). The windows of FH building have the possibility to open to the external glass layer, which cuts off the fresh air supply from outside. The lack of fresh air supply and possibility to fully open the windows could be the reason for occupants’ dissatisfaction with the ventilation possibilities in the offices.

The answers to the questions concerning thermal comfort show that the average room temperature in winter (22,7 °C) and summer (24 °C) is optimal for the majority of people – 90% in winter and 60% in summer (see Figure 66). As a consequence of these perceptions, high percentage of people evaluates positively the systems for thermal environmental control – 100% about heating and 70% about air-conditioning (see Figure 67 and Figure 68).

The answers to the questions concerning lighting in offices (see Figure 69) state that the majority of people percept daylight and artificial light as optimal and sufficient. This can be explained with the high average ‘window to wall’ ratio (0,4) and the position of the workstations mostly near the windows. The last is the reason why 70% of the occupants are occasionally disturbed by direct sunlight, while 5% experience it frequently (see Figure 70). Considering the east orientation of the rooms, direct sun light is incident on the façade mostly in the morning hours. Reflections on the computer screen occur occasionally for 40% of the people, while for the other 60% - rarely or never. The fact that direct sunlight and reflections occur “occasionally” could be the reason for the lower number of “closing shades” in comparison with “opening shades” actions.

Only 25% of the interviewees claim to be disturbed by noise (see Figure 71). The sources of noise are mostly people and activities in the corridor spaces and the room air-conditioning (see Figure 72). Surprisingly, the street noise is classified as less disturbing, probably due to the double skin façade and the windows mostly closed, requisite for noise level reduction.

The distance of the work station to the window is evaluated from 75% of the occupants as optimal, 20% claim that it is "Too far" and less than 5% perceive it as "Too close" (see Figure 73). The fact that the majority of people are satisfied with the daylight conditions could be a reason for the positive evaluation of the position of their work stations. The outdoor view from the office window is classified as "Good" and "Very good" from 75% of the occupants. Only 10% consider the view as not satisfactory (see Figure 74). Although some people express positive attitude toward the window view, they would prefer "green" or "trees" instead of urban landscape. The view from the window could also influence the peoples' preference of shading position. In case of FH, the mean shade deployment degree over the entire observation period is 30%, supposedly reflecting the positive evaluation of the window view.

The answers to the question about privacy in the office reveal that 60% of the people feel to have privacy. Although 35% of the people work in double and triple occupancy offices, only 15% claim not to have privacy to work undisturbed (see Figure 75).

For 65% of the interviewees opening the window is difficult or impossible (see Figure 76). Nevertheless, 35% evaluate positively the possibility to operate the windows. A reason for this contradiction could be the conventional mechanism for manual operation, with which the windows are equipped. The majority consider the prohibition of the building services to open the windows and probably the lack of possibility to let fresh air by eventual opening. 80% of the occupants find the possibility to open the window "Important" or "Very important" (see Figure 77). This reaction is typical for occupants in air-conditioned buildings, who generally express dissatisfaction with the ventilation possibilities in their offices when the windows are not operable.

The majority of the interviewed persons find the external shades controller easily accessible (see Figure 78). In spite of the similar position of the controller in each room on a panel under the window, 10% of the occupants find the controller difficult to access. This could be explained with the position of the tables, which makes the button difficult to reach or the people should stand up and go around the table. The easy access of the system control device could animate people to use it more often and vice versa. Anyway, in case of FH the majority of occupants should stand up to reach the shading button, which could be a reason for the relative rare use of this control device.

Considering the east orientation of FH offices and the subsequent availability of direct sunlight in the morning hours, 95% of the occupants value the importance of having possibility to operate the shades (see Figure 79). In general, manually operated shades give the occupants the freedom to adjust the daylight level optimally to their preferences and effectively protect from undesirable effects like direct sunlight, reflections and overheating.

95% of the interviewees find the light switch easily accessible. The light switch is located near the entrance door; where there are no furniture modules hindering the access (see Figure 80).

The majority of occupants evaluate positive the accessibility of the thermostat (see Figure 81). Though, the number of negative answers is 20%. Analogue to the shading controller (location for both under the window), the explanation in this case could be the position of the tables, which makes the thermostat difficultly accessible or the people should stand up and go around the table in order to reach it.

The answers to the question concerning the level of information about the buildings system show dependency on the level of building systems' complexity (see Figure 83). Thus, the percentage of people insufficiently informed about the functionality of heating, ventilation and air-conditioning, is much higher (> 40%) than the respective percentage about lighting and shading (5%). Vice versa, the majority of people (75%) feel very good informed about the systems with lower complexity for lighting and shading in comparison to the systems for heating, cooling and ventilation (10%). One of the reasons for insufficient knowledge could be the fact that 100% of the interviewed occupants have never had a training concerning the office systems for environmental control, but almost half of them (45%) would be interested in such training (see Figure 84). Better understanding of the building systems' functionality could improve the occupants' comfort and energy efficiency in buildings.

More than the half (60%) of the interviewees refer to the secretary in case of a problem with the building systems, while only 25% communicate directly to the building services or a technical assistant (see Figure 85). The half of the persons are satisfied with the office systems' support and services, while 45% are not able to evaluate it (see Figure 86).

The answers to the questions concerning energy conscious behavior show peoples' awareness of the fact that they influence (negatively or positively) the building energy consumption but do not modify their control behavior in order to save energy. More than 80% of the occupants claim that they influence the building energy consumption in the way they operate the building systems, but only the half of them considers energy conservation (see Figure 87 and Figure 88).

The majority of the participants (95%) evaluate positively the possibility to personalize their workplaces, as well as their well-being in the office (90%). Only 10%claim that they do not feel good in their rooms (seeFigure 89 and Figure 90).

Being asked to specify the most important features of a good working place, the occupants classified "Quietness/privacy" as the most important, followed by "Furniture/sufficient place" and "Good indoor climate" (see Figure 91). Features like "Single occupancy office", "Adequate lighting" and "Controllable systems" were also mentioned. As less important is considered the possibility for personal organization of the working place.

Being asked about improvements in their offices, the interviewed persons named as most urgent the improvement of office furniture (22%, see Figure 92). By "Effective furniture" people mean ergonomics, sufficient storage space and functionality. The second urgent improvement would be to have the possibility to open the windows (20%), followed by better servicing of the air-conditioning system (17%). 15% of the occupants wish to have a bigger office, while 14%

would appreciate more privacy. Only 6% would like to have the possibility to adjust the temperature in their rooms and to have better air quality. The ranking of all mentioned improvements comply with the interview results from Part 2 ‘Evaluation of the indoor climate and control systems’.

The most frequent health complaints of the interviewed occupants are backache (18%), headache (16%) and general fatigue (16%), which are typical for office workers, who spend a lot of time sitting indoors (see Figure 93). Less frequent are neck pain (13%) and nasal irritation (13%), followed by eyestrain or –burning (9%) and respiratory problems (9%). Least frequent disorder is sore throat (6%).

5 Conclusion

A study on the user interactions with the building systems for lighting and shading in 13 scientific staff offices in one educational office building in Vienna (Austria) has been presented. The nature and typology of user control actions have been explored and patterns of control behaviour extracted. Furthermore, the impact of user control-behavior on energy consumption has been investigated by developing scenarios for energy saving, considering occupancy and daylight availability.

The intention was to carry out a thorough analysis based on high-resolution empirical data. Thus, data on occupancy, status of electrical lighting, internal and external parameters like temperature, relative humidity, illuminance and global irradiance, have been recorded over the period of one year. Autarkic data loggers, distributed over the work stations, have been used for collection of indoor environmental data. Outdoor parameters have been recorded by weather station, mounted in near proximity of the monitored building.

The collected data has been analysed "to explore hypothesized relationships" between the frequency of control actions and the various indoor and outdoor environmental phenomena (Mahdavi 2006c). The results reveal distinctive patterns in the lighting and shading operation. The lighting operation profile over the course of the day agrees with the occupancy profile. Working plane illuminances under 100 lx seems to trigger switching on the lights, while switching off occurs above a threshold of 1000 lx. The period of absence from the office determines the probability that an occupant will switch off the lights when leaving. The shading operation depends on the façade orientation, the time of the day, the daylight availability as well as on the thermal factors. The mean shade deployment degree is higher during the summer months than in winter indicating existence of seasonal dynamics. 69% of the electrical energy currently used for lighting in FH building can be theoretically saved by considering occupancy, daylight availability and dimming regimes.

5.1 Contributions

The compound results of the case study are expected to enrich the existing databases toward the development of more robust occupant behavior models. Such models can: *i)* improve the reliability of computational building performance simulation applications; *ii)* provide a more dependable basis for the design and configuration of user interfaces and control algorithms for buildings' environmental control systems; *iii)* deliver a quantitative basis for the evaluation of the impact of occupancy behavior on buildings' energy consumption: *iv)* help develop strategies to inform building occupants regarding the energy and comfort implications of their control actions.

5.2 Future research

The issues of occupants' control-behavior in buildings have been treated worldwide by numerous studies in the last decades. Nevertheless, there is a need for further research on the user interactions with the building systems for heating, cooling and ventilation. Furthermore, empirical evidence on the occupants' behavior for different types of buildings, in different geographical and cultural settings will contribute to the better knowledge of the human impact. Another perspective for future development is utilization of long-term monitoring and collection of high-resolution data. Last but not least would be unifying the research design and methods (length of monitoring, logging intervals, building control systems, number of monitored offices, experimental equipment setup, methods of analysis), which would allow consistent comparison of the results from different sources (buildings and researchers).

References

Bülow-Hübe H. 2000 *Office worker preferences of exterior shading devices: A pilot study,* Submitted to EuroSun 2000, June 19-22, Copenhagen, Denmark

Bourgeois D. 2005 *Detailed occupancy prediction, occupancy-sensing control and advanced behavioral modeling within whole-building energy simulation,* Phd Thesis - Université Laval, Quebec, Canada

Boyce P. 1980 *Observations of the manual switching of lighting,* Lighting Research & Technology 12(4), pp. 195-205

Carter D., Slater A., Moore T. 1999 *A study of lighting in offices equipped with occupant controlled systems,* Proceedings of the 24th Session of CIE, Warsaw, Poland, Vienna, Austria: CIE (1999), pp. 108-110, 1 (2)

Farber Associates 1992 *Occupancy data for thermal calculations in non-domestic buildings,* Building Research Establishment, Contract F3/31158), BRE Garston Library, Watford, UK

Hunt D. 1979 *The use of artificial lighting in relation to daylight levels and occupancy*, Building Environment 14, pp. 21-33

Inoue T., Kawase T., Ibamoto T., Takakusa S., Matsuo Y. 1988 *The development of an optimal control system for window shading devices based on investigations in office buildings*, ASHRAE Transaction, Vol. 94, pp. 1034 – 1049

Konica 2007, http://konicaminolta.com

Lindelöf D., Morel N. 2006 *A field investigation of the intermediate light switching by users*, Energy and Buildings 38, pp. 790-801

Lindsay C. T. R., Littlefair P. J. 1992 *Occupant use of Venetian blinds in offices*, Building Research Establishment, Contract PD233/92, BRE Garston Library, Watford, UK

Love J. A. 1998 *Manual switching patterns observed in private offices*, Lighting Research & Technology 30(1), pp. 45-50

Mahdavi A, Dervishi S, and Spasojevic B. 2006a *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), pp. 123-125

Mahdavi A., Lambeva L., Pröglhöf C., et al. 2006b *Observing occupancy control actions in an educational building,* 17th Air -Conditioning and Ventilation Conference - May 17-19, 2006, Prague, Czech Republic, J. Schwarzer, M. Lain (Hrg.); Eigenverlag, Prague, Czech Republic (2006). pp. 201 - 204

Mahdavi A, Lambeva L, Pröglhöf C et al. 2006c *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, et al. 2007a "*People as power-plant"*, Final report of the project "People as power-plant" conducted from the Department of Building Physics and Building Ecology, Vienna University of Technology, supported by the program

"Energiesysteme der Zukunft" – an initiative of the Austrian "Bundesministerium für Verkehr, Innovation und Technologie (BMVIT)": Project number: 808563-8846.

Mahdavi A., Lambeva L., Mohammadi A., Kabir E. 2007b *User control actions in buildings: Patterns and impact*, Clima 2007 WellBeing Indoors, 10-14 June 2007, Helsinki, Finland

Mohammadi A., Kabir E., Mahdavi A., Pröglhöf C. 2007 *Modeling user control of lighting and shading devices in office buildings: An empirical case study*, BS 2007 (10th IBPSA Conference) 3-6 September 2007, Beijing, China

MySQL 2007, www.msql.com

Newsham G.R 1994 *Manual control of window blinds and electric lighting: implications for comfort and energy consumption*, Indoor Environment 3, pp. 135-144

Perez R., Seals R., Michalsky J. 1993 *All-weather model for sky luminance distribution – preliminary configuration and validation*, Solar energy Vol. 50, No. 3, pp. 235-245

Pigg S., Eilers M., Reed J. 1996 *Behavioral aspects of lighting and occupancy sensors in private office: a case study of a university office building*, Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, pp. 8.161 – 8.171

Rea M. S. 1984 *Window blind occlusion: a pilot study*, Building and Environment 19 (2), 1984, pp. 133-137

Reindl D. T., Beckman W. A., Duffie J. A. 1990 *Diffuse fraction correlations*, Solar energy, Vol. 45, No. 1, pp. 1-7

Reinhart C. 2001 *Daylight availability and manual lighting control in office buildings - simulation studies and analysis of measurements*, Phd Thesis, University of Karlsruhe, Germany)

Reinhart C., Voss K. 2003a *Monitoring manual control of electric lighting and blinds*, Lighting Research & Technology 35 (3), pp. 243-260

Reinhart C. 2003b *LIGHTSWITCH-2002: A Model for Manual Control of Electric Lighting and Blinds*, Solar Energy 77 (2004), pp. 15–28

Rubin A. I., Collins B. L., Tibbott R. L. 1978 *Window blinds as potential energy saver – a case study*, NBS Building Science Series, Vol. 112, National Institute for Standards and Technology, Gaithersburg, MA, USA

Sutter Y. et al. 2006 *The use of shading systems in VDU task offices: a pilot study*, Energy and Buildings 38, pp. 780-789

Vine E., Lee E., Clear R., DiBartolomeo D., Selkowitz S. 1998 *Office worker response to an automated venetian blind and electric lighting system: a pilot study*, Energy and Buildings 28(2), pp. 205-218

6 Appendix

A. Office layout

Figure 106, Figure 107 and Figure 108 show schematic plans of the monitored rooms in the 4th, 5th and 6th floor respectively. All rooms are accessed through an artificially lit corridor.

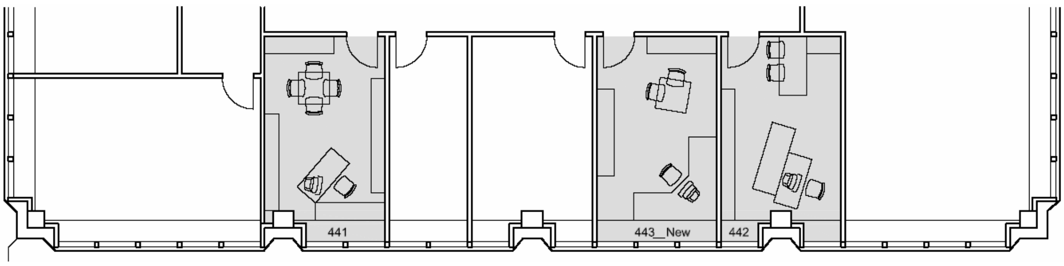


Figure 106. Schematic plan of the monitored rooms in the 4th floor

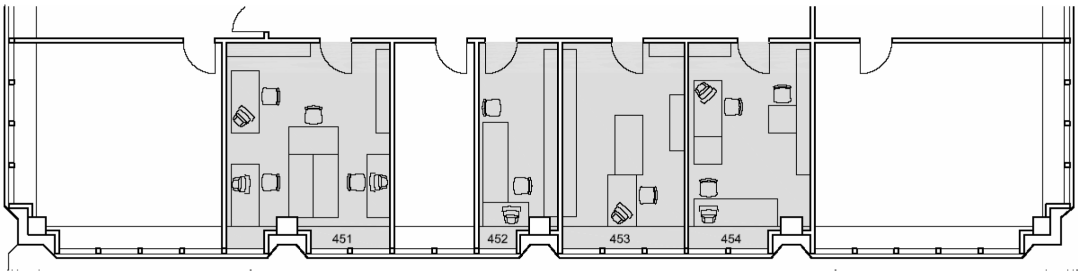


Figure 107. Schematic plan of the monitored rooms in the 5th floor

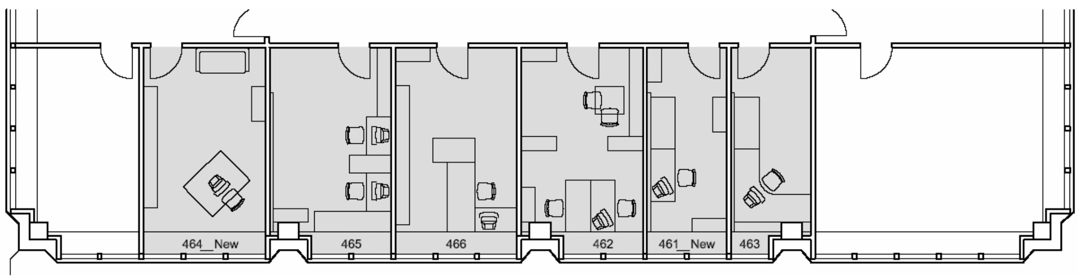


Figure 108. Schematic plan of the monitored rooms in the 6th floor

Figure 109 shows the position of the thermostat and the button for shading operation in a room in the 5th floor. In this case both are located in front of the table, easily accessible without additional physical efforts like standing up, going around table or cupboard, body stretching in order to reach the device. The accessibility of the control buttons is highly depending on the furniture configuration, which is not always the most proper one.

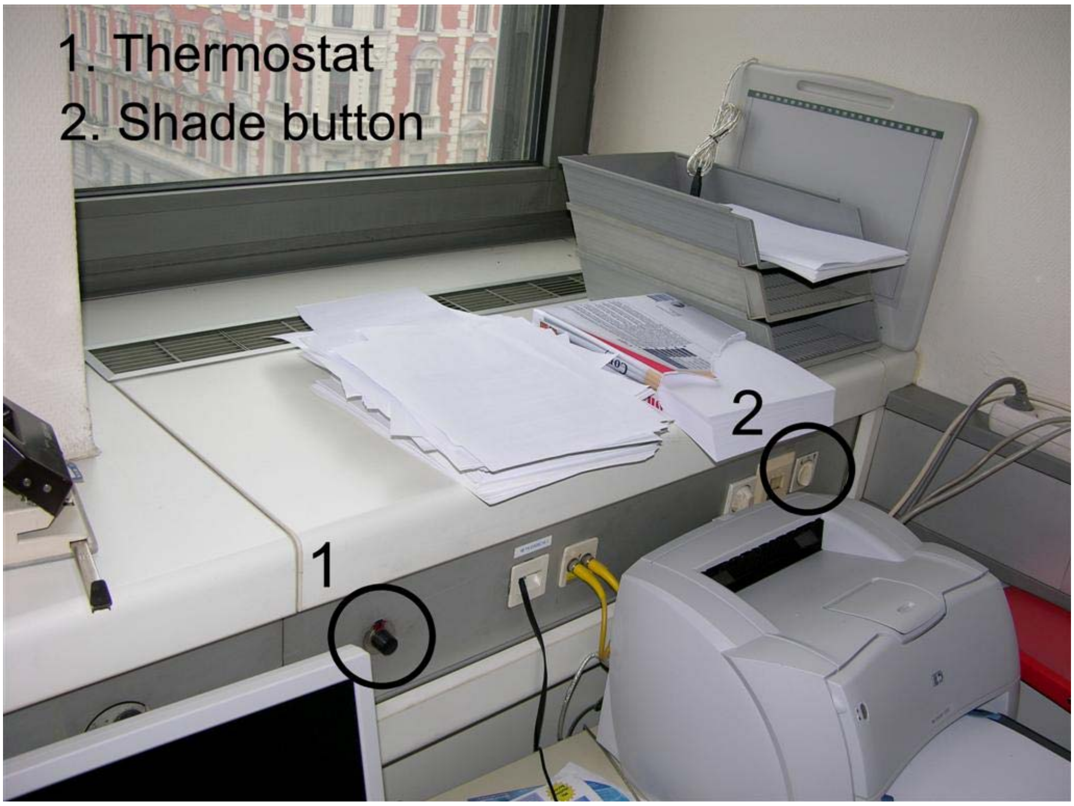


Figure 109 View of the buttons for manual control of shading and fan coils in the FH office

B. Measuring equipment

B.1 Weather station

The weather station consists of sensors and data logger, fixed on a vertical mast (see Figure 110).

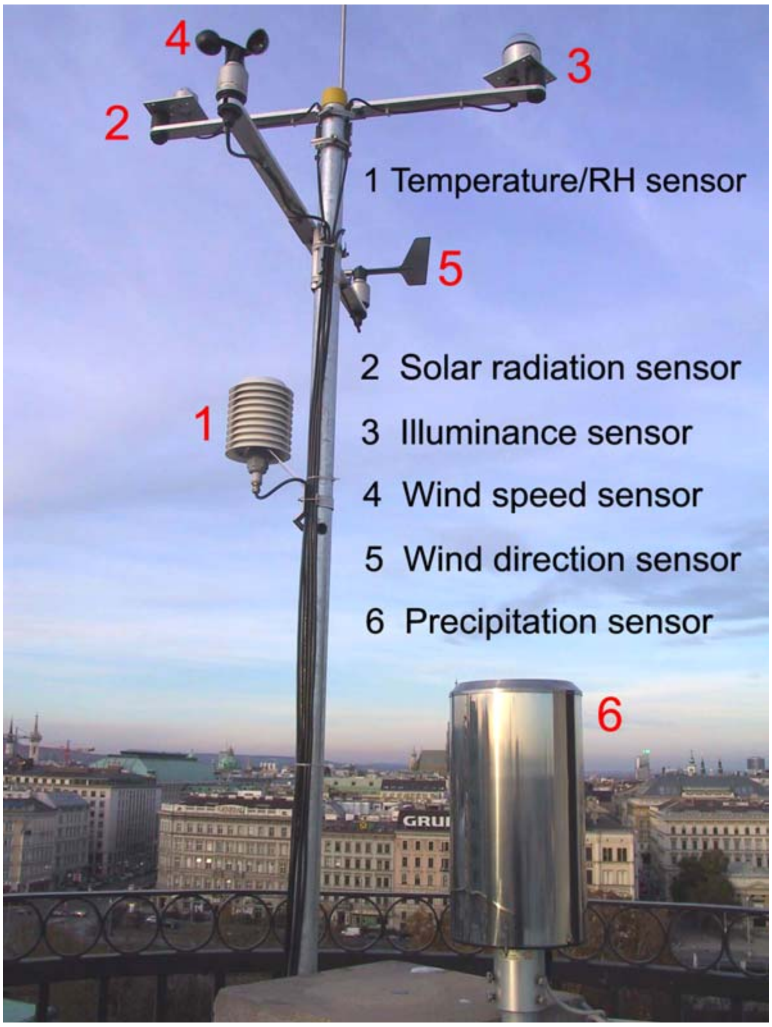


Figure 110. View of the BPI Weather Station

The entire spectrum of measured parameters includes: temperature [°C], relative humidity [%], solar radiation [$W.m^{-2}$], global illuminance [lx], wind speed [$m.s^{-1}$], wind direction [°], air pressure [Pa], outdoor illuminance [lx] and precipitation [mm]. The accuracy of the weather station components are summarized in Table 6.

Table 6. Technical description of the weather station sensors.

Sensor	Range	Accuracy
1. Temperature/RH a) Temperature b) RH	 - 40 °C to + 80 °C 0 to 100%	 ±1K at 0 °C Deviation ± 2%
2. Solar radiation (Pyranometer)	0 to 1300 $W.m^{-2}$	Sensitivity ± 0,5% Applied correction + 2%
3. Illuminance	0 to 130 klx	
4. Wind speed		± 0,5 $m.s^{-1}$
5. Wind direction	0 to 360 °	± 5 °
6. Precipitation		
7. Barometer	800 to 1600 hPa	+20°C - ± 0,3 hPa 0 °C to 40 °C - ± 1 hPa -20 °C to +45 °C - ± 1,5 hPa -40 °C to +60 °C - ± 2,5 hPa
8. Data logger	-30 °C to +50 °C	± 0,2%

The sensors deliver analog signals to the data logger, which is connected to the local network. The data logger has a built in 256 KB CMOS-RAM memory to store logged parameters. Reading out the data is either through a memory card or to a computer with cable connection over a serial port. The data logger has electrical power supply (12 V) as well as a built-in rechargeable lithium battery in case of power breakdown, which preserves the logs in the memory and keeps the internal clock running. The data logger has a built-in display and functional buttons for direct servicing.

The data logger generates ASCII output files, which can be easily processed by various programs or data bases. A LabView application, developed by the research team, transfers the log files to a Data Socket Server. The software generates '.TXT' files, which are finally stored in a dedicated data bank. The logging interval is one second, which requires additional processing for structuring the data in 5 min intervals.

B.2 Indoor data loggers

HOBO U12 - 012

Hobo U12 Temperature/Relative humidity/Light intensity/External channel is a 4-channel logger with 12-bit resolution able to record up to 43.000 measurements (see Figure 111).

Figure 111. View of Hobo U12

The logger has the following features and specifications:

- 64K memory (43,000 12-bit measurements)
- 1-year battery life (typical) – user-replaceable CR-2032 lithium battery
- Non-volatile memory retains data even if battery fails
- Operating Range: -20° to 70°C, 5% to 95% RH non-condensing, non-fogging
- Time accuracy: ± 1 minute per month at 25°C

Table 7 summarizes the technical characteristics of the sensors.

Table 7. Technical details of the measuring instrument

Sensor	Range	Accuracy	Resolution
Temperature	Range:-20 to 70 °C	±0.35 °C at 25°C	0.03 °C at 25°C
Relative humidity	5 to 95 % RH	±2.5 % RH over 10 to 90% typical	0.03 % RH
Light intensity	1 to 3000 lumens/ft^2 (foot candles)		

The HOBO logger can be maintained by computer using direct USB interface (USB port and connection cable). The software package, designed to support the device is GreenLine. Figure 112 shows the graphical interface of the program.

GreenLine has options for logger maintenance - read out, launch and status of the connected logger. The program is also able to visualize the downloaded data in different modes – diagram, list, data tree. GreenLine saves the log data as '.HOBO' file, which by using the 'Export As' function, can be exported as Excel text file for further processing in other applications.

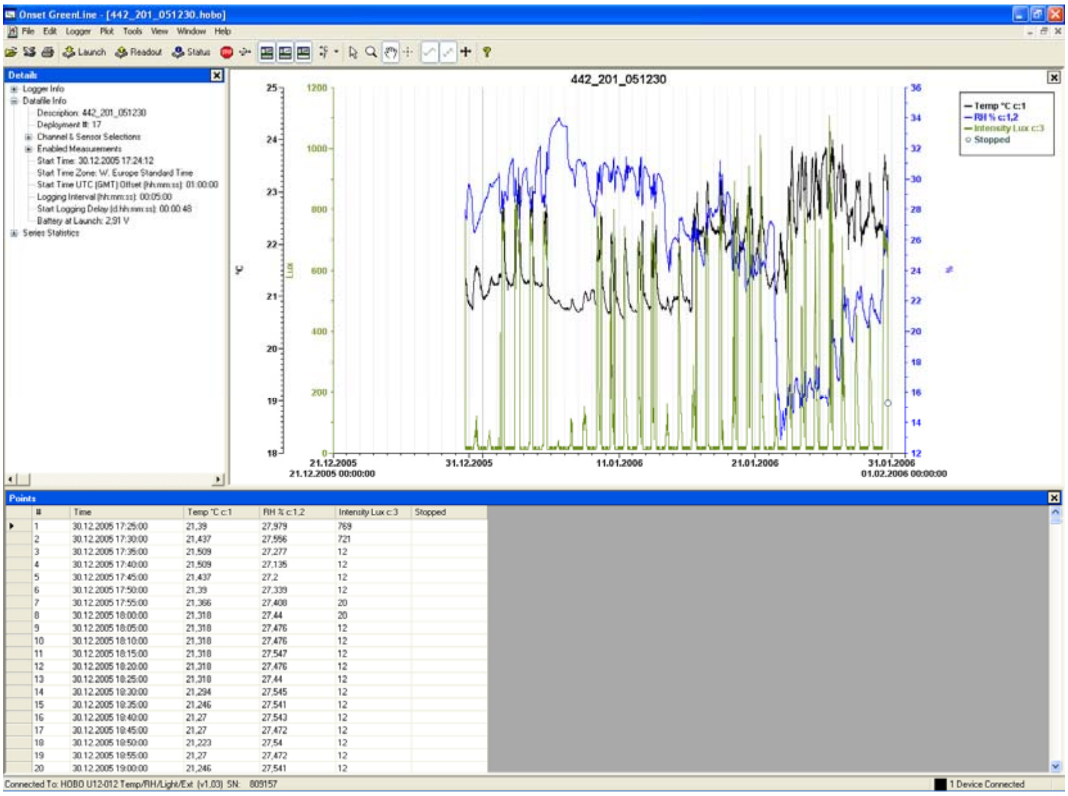


Figure 112. Graphical user interface of GreenLine

InteliTimerPro Logger

Occupancy and status of lights on/off was recorded with InteliTimerPro Logger (IT 200). The loggers were mounted on the metal double ceiling with the help of magnets, glued on the back surface of the plastic housing. The pipe of the light sensor points directly at the luminaire (see Figure 113). Considering the coverage area (max. 13,9 m^2) of the occupancy sensor (see Table 8) and the ceiling height (2,7 m), the loggers have been mounted directly above the working places.

Figure 113. View of It-200

IT-200 is an occupancy sensor, lighting sensor and data logger combined in one device. It records a log entry when a change occurs in either the occupancy or lighting status and stores a detailed history of these events. The logger is able to store up to 4096 log entries. The device is equipped with lithium battery with average life of 10 years. The occupancy sensor utilizes PIR (passive infrared) technology for detection of occupancy. The status of lights on/off is registered by adjustable light pipe. The logger should be placed so that its lens has a clear view of the workspace and the light-pipe points towards the nearest light fixture. Table 8 gives information about the coverage of the occupancy sensor in relation to the mounting height.

Table 8. Distance coverage of IT- 200

Ceiling height [m]	Behind [m]	Front [m]
2,4	0,3	4,6
3,0	0,5	5,8
3,7	0,6	7,0
4,6	0,8	8,8

IT-200 can be connected to a computer via 9-pin serial port and connector cable. The application software package designed for logger maintenance and support is ITProSoft. The program can retrieve, store, and analyze logged data, or generate data graphs and reports (see Figure 114). The log data can be kept for future use by the 'Save As' command from the File menu. This command stores the log data displayed in the main window either in a special binary data file with extension '.ITR' or as '.XLS' file for further analysis in Excel.

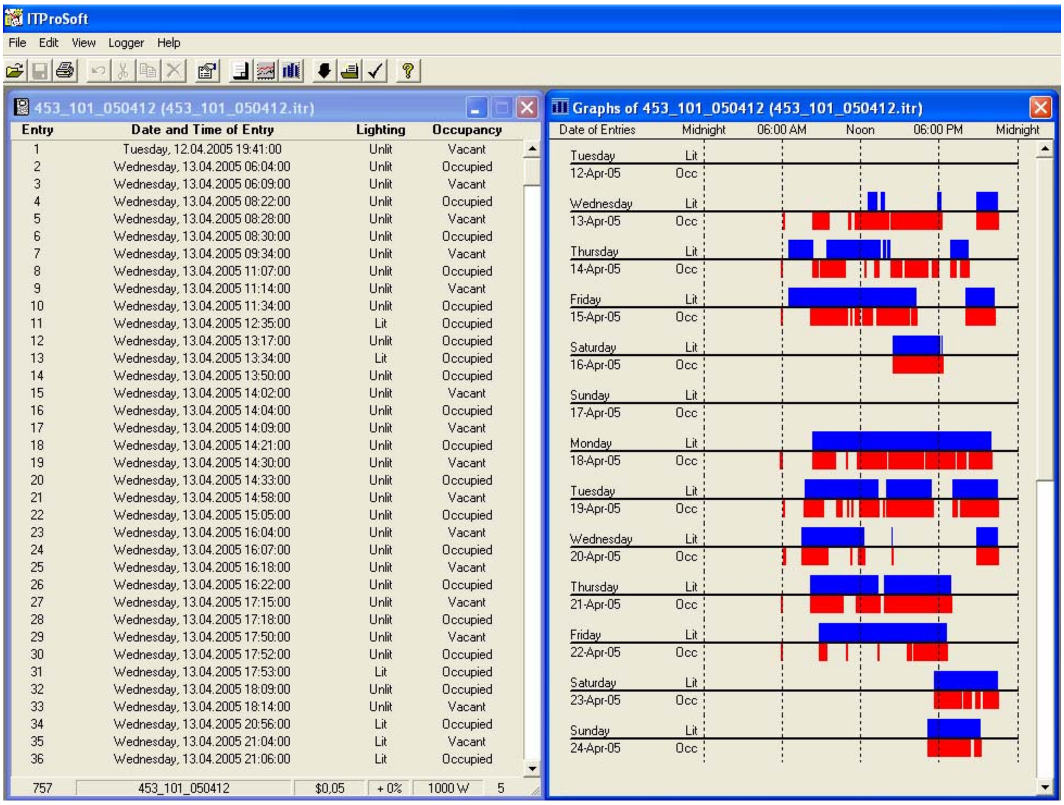


Figure 114. Graphical user interface of ITProSoft

C. Experimental setup for derivation of horizontal illuminance from measured vertical illuminance

The present paragraph describes the experimental setup used for derivation of horizontal illuminance from measured vertical illuminance. Three indoor HOBO data loggers have been placed as follows: one horizontally on the working surface in front of the person; the original sensor position, mostly vertical with exception of 3 loggers; and head position - vertical, 50 cm above the table surface (see Figure 115). The idea was to establish reliable correlation between the illuminance of these three positions, based on continuous high-resolution measurements over the wide range of daylight intensities during the period of two days. The illuminance measurements have been conducted for unoccupied periods, either on the weekend or during holidays, to avoid interference with the occupants and artificial light usage. The artificial light illuminance for all working places has been recorded late in the evening to eliminate any influence of daylight. The artificial light measurements have been carried out for approximately 5 minutes in interval of 2 seconds. The results for the three positions have been averaged separately and two correlation coefficients ("Head" and "Table") for each working place derived.

Figure 115. Equipment configuration for measuring illuminance for different positions - original (1), horizontal (2) and head (3) position

D. Questionnaire

Table 9 summarizes the questions and the typology of answers of the questionnaire.

Table 9. Content of the questionnaire

N:	Question	Category
1.	Personal information	
1.1	Gender	m, f
1.2	Age	from 1 (under 25) to 5 (above 55)
1.3	Nationality	Text
1.4	Occupation	Text
1.5	How many hours in average do you work per week?	[h]
1.6	Of these, how many hours do you spend at your workstation?	[h]
1.7	What percentage of your work do you perform on your computer?	[%]
1.8	How long have you been working in your current office?	Months
2.	Evaluation of the indoor climate and environ. control systems	
2.1	How do you find the air quality of your office?	from +2 (Very good) to -2 (Very bad)
2.1a	In case of 'Bad' and 'Very bad' what do you mean by ‚bad' air quality?	Text
2.2	Are you satisfied with the possibility to ventilate your office?	from +2 (Very satisfied) to -2 (Not at all)
2.2a	If not, please give reasons why!	Text
2.3	How is the average temperature in your office in winter?	from -2 (Cold) to +2 (Hot)
2.4	How is the average temperature in your office in summer?	from -2 (Cold) to +2 (Hot)
2.5	How satisfied are you with the heating system in your office?	from +2 (Very satisfied) to -2 (Not at all)
2.6	How satisfied are you with the air-conditioning?	from +2 (Very satisfied) to -2 (Not at all)
2.7	Do you have sufficient daylight in your office?	from +2 (Too much) to -2 (Not sufficient)
2.8	Are you annoyed by direct sunlight at your workstation?	from -2 (Frequently) to +1 (Never)
2.9	Are you annoyed by reflections or too bright surfaces on your computer screen?	from -2 (Frequently) to +1 (Never)
2.10	Do you have sufficient artificial light in your office?	from +2 (Too much) to -2 (Not sufficient)
2.11	Are you annoyed by noise in your office?	from -2 (Frequently) to +1 (Never)
2.11a	In case you marked „yes, frequently" or „occasionally", please specify the source of noise!	Text
2.12	Evaluate the distance of your workstation from the window.	from +1 (Too close) to -1 (Too far)
2.13	Evaluate the outdoor view from your office window.	from +2 (Very good) to -1 (Not satisfactory)
2.14	Do you have enough privacy in your office to work undisturbed?	from +1 (Yes) to -1 (No)

2.14a	In case you marked „no“, please explain why!	Text
3.	Operation and accessibility of the systems and system controls	
3.1	Can you open the windows of your office if required?	from -2 (Impossible) to +2 (Very easy)
3.2	How important is it for you to have the possibility to open the windows?	from -2 (Unimportant) to +2 (Very important)
3.3	Can you decide independently when to open/close the windows in your office or do you have to negotiate with other people?	Yes/No
	In case you marked „with others“, please describe the process – who, when and how	Text
3.4	Do you have easy access to the external shades in your office?	from -2 (Impossible) to +2 (Very easy)
3.5	How important is it for you to have the possibility to operate the external shades?	from -2 (Unimportant) to+2 (Very important)
3.6	Can you decide independently when to operate the external shades in your office or do you have to negotiate with other people?	Yes/No
	In case you marked „with others“, please describe the process – who, when and how	Text
3.7	Is the light switch easily accessible to you?	from -2 (Impossible) to +2 (Very easy)
3.8	Can you decide independently when to switch on/off the light in your office or do you have to negotiate with other people?	Yes/No
	In case you marked „with others“, please describe the process – who, when and how.	Text
3.9	Is the thermostat easily accessible to you?	
3.10	Can you regulate the temperature on your own or do you have to negotiate with other people?	Yes/No
	In case you marked „with others“, please describe the process – who, when and how	Text
4.	Awareness of the functionality of the building control systems and energy conscious behaviour	
4.1	Are you sufficiently informed about how the following systems (heating, ventilation, air-conditioning, lighting, blind protection) work in your office?	from -1 (Not sufficient) to +1 (Very good)
4.2	Have you ever had a training concerning the systems in your office?	Yes/No
	If „yes“, how do you evaluate this training?	Text
	If „no“, would you be interested in such training?	from -1 (No) to +1 (Yes)
4.3	To whom do you refer in case of a problem with the building systems (heating, lighting, etc.)?	Text
4.4	Are you satisfied with the system services and support in your office?	from -1 (No) to +1 (Yes)
4.5	Do you think that you can influence building energy consumption in the way you operate building systems?	from -1 (No) to +1 (Yes)
4.6	Do you think about energy conservation, when you operate building systems?	from -1 (No) to +1 (Yes)
5	Personal preferences of organizing the current / ideal working space; health complaints	
5.1	Are you satisfied with the possibilities you have to personalize your working place (furniture,	from -2 (Not at all) to +2 (Very satisfied)

	plants, photos…)?	
5.2	Generally, do you feel good in your office?	from -2 (Not at all) to +2 (Very good)
5.3	What are the most important features of one good working place from your point of view?	Text
5.4	Which improvement measures in your office would you consider as most urgent?	Text
5.5	Do you have any health complaints?	
5.5a	Backache	from -2 (Frequently) to +1 (Never)
5.5b	Eyestrain or –burning	from -2 (Frequently) to +1 (Never)
5.5c	Headache	from -2 (Frequently) to +1 (Never)
5.5d	General fatigue	from -2 (Frequently) to +1 (Never)
5.5e	Respiratory problems	from -2 (Frequently) to +1 (Never)
5.5f	Sore throat	from -2 (Frequently) to +1 (Never)
5.5g	Neck pain	from -2 (Frequently) to +1 (Never)
5.5h	Rheumatic pain	from -2 (Frequently) to +1 (Never)
5.5i	Stiffness of limbs	from -2 (Frequently) to +1 (Never)
5.5j	Nasal irritation	from -2 (Frequently) to +1 (Never)

List of figures

List of tables

List of publications in relation to this thesis

Mahdavi A., Lambeva L., Pröglhöf C., Suter G., Mohammadi A., Kabir E., Lechleitner J. *User control actions in building: From observation to predictive modelling,* Vortrag angenommen für: "Nové Poznatky v Teórii Konstrukcii Pozemnych Stavieb a Ich Uplatnenie v Stavebnej Praxi - 2005", A Puskár et al. (Hrg.); Eigenverlag (2005), pp. 64 - 73

Mahdavi A., Lambeva L., Pröglhöf C., Suter G., Mohammadi A., Kabir E., Lechleitner J. (2006) *Observing occupancy control actions in an educational building,* 17th Air -Conditioning and Ventilation Conference - May 17-19, 2006, Prague, Czech Republic, J. Schwarzer, M. Lain (Hrg.); Eigenverlag, Prague, Czech Republic (2006), pp. 201 - 204

Mahdavi, A. – Kabir, E. – Mohammadi A. – Lambeva, L. – Pröglhöf, C. (2006): *User Interactions with Environmental Control Systems in Buildings,* Proceedings of PLEA 2006 (23rd Interntational Conference on Passive and Low Energy Architecture. Geneva, Switzerland, 6-8 September 2006). Vol 1. ISBN 2-940156-30-1, pp. 399 – 404

Mahdavi, A. – Lambeva, L. – Pröglhöf, C. – Mohammadi A. – Kabir, E. (2006): *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., Lambeva L., Pröglhöf C., Mohammadi A., Kabir E. (2006) *User interactions with environmental control systems in buildings,* Tagungsband der

Ersten deutsch-österreichischen IBPSA Konferenz, 9 – 11 Oktober, Technische Universität München, Deutschland pp. 126 - 128.

Mahdavi A., Lambeva L., Mohammadi A., Kabir E., Pröglhöf C. (2007) *Two case studies on user interactions with buildings' environmental systems,* Bauphysik (Ernst & Sohn - Berlin) 29 (2007), Heft 1, ISSN 0171-5445

Mahdavi A., Suter G., Lambeva L., Pröglhöf C., Mohammadi A., Kabir E. (2007) *"People as Power Plant": Über energetische Implikationen des Nutzerverhaltens in Bürogebäuden,* Kurzfassungsband der 5. Internationalen Energiewirtschaftstagung and der TU Wien (IEWT 2007) 14 – 16 Februar 2007, Wien, Österreich, pp. 177 – 178

Mahdavi A., Lambeva L., Mohammadi A., Kabir E. 2007b *User control actions in buildings: Patterns and impact*, Clima 2007, 10-14 June 2007, Helsinki, Finland

Lambeva L., Mahdavi A. 2007 *User control of indoor-environmental conditions in buildings: An empirical case study*, BS 2007 (10th IBPSA Conference) 3-6 September 2007, Beijing, China

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