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Dissertation

MODELING OCCUPANTS' CONTROL ACTIONS AND THEIR ENERGY IMPLICATIONS IN AN OFFICE BUILDING

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

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Kurzfassung

Diese Arbeit ist das Ergebnis einer empirischen Langzeitstudie und untersucht das Nutzerverhalten in einem Bürogebäude in Wien (Österreich), bezogen auf die Steuerung von Systemen zur Heizung, Kühlung und Beleuchtung. Sie ist der Versuch kontrollorientiertes Nutzerverhalten über den Zeitraum von einem Jahr in einem großen Hochhauskomplex in über 29 Büros zu analysieren. Im Detail wurde die Anwesenheit der Nutzer, der Status der Gebäudesysteme, das Innenklima und das Außenklima beobachtet. Dazu wurde eine Wetterstation (Außentemperatur, rel. Feuchte, Windgeschwindigkeit, horizontale Globalstrahlung), Sensoren zur Messung der Innenparameter (Innentemperatur, rel. Feuchte, Beleuchtungsstärke im Innenraum, Status der künstlichen Beleuchtung) sowie zwei Digitalkameras (Öffnungsgrad der Beschattung) verwendet und die Werte in einem Intervall von fünf Minuten gespeichert. Das Hauptziel der Arbeit ist die Interaktion zwischen Nutzer und den Gebäudesystemen transparenter zu machen.

Durch die Analyse der gesammelten Daten konnte eine Vielzahl von Hypothesen über das Verhältnis zwischen der Art und Häufigkeit von Steuertätigkeiten einerseits und der Größe und Dynamik von Änderungen im Innen und Außenraum überprüft werden. Die Ergebnisse zeigen eindeutige Zusammenhänge, die in der Arbeit zusammengefasst sind. Diese Hypothesen können als Grundlage für kontrollorientierte Nutzerverhaltensmodelle herangezogen werden. Diese Modelle können in der Folge in umfassende Gebäudemodelle integriert werden um Gebäudesteuerung und Facility Management zu unterstützen. Weitergehend kann bei eingehender Kenntnis des Nutzerverhaltens der Einfluss des Faktors Mensch auf das Gebäude selbst vorhergesagt und dadurch der Energieverbrauch reduziert und der Komfort der Nutzer erhöht werden.

Abstract

The present thesis describes the results of a study to capture patterns of user control actions in an office building in Vienna, Austria with regard to buildings' technical systems for heating, cooling and lighting based on a long-term study. It describes an effort to observe control-oriented occupant behavior in 29 offices of a large high-rise office complex over a period of one year. Specifically, states and events pertaining to occupancy, building systems, indoor environment, and external environment were monitored. A weather station, a number of indoor data loggers, and two digital cameras were used to continuously monitor – and record every five minutes – such events and states: occupancy, indoor and outdoor temperature and relative humidity, internal illuminance, external air velocity and horizontal global irradiance, status of electrical light fixtures, position of shades. The main task of the project is to monitor and analyze the behavior of the monitored occupants for providing a better understanding of occupants' interactions with building energy systems.

Upon the analysis of the collected data, this work explores a number of hypothesized relationships between the nature and frequency of the control actions on one side and the magnitude and dynamism of indoor and outdoor environmental changes on the other side. The results reveal distinct patterns in the collected data. Specifically, control behavior tendencies show dependencies both on indoor environmental conditions and outdoor environmental parameters. A summary of these tendencies is presented. These kinds of relationships have the potential to provide the basis of behavioral models for control-oriented user actions in buildings. Such models can subsequently be integrated in comprehensive building information models to support facility management and indoor environmental control operations in buildings. Moreover, the modeling of occupants' behavior would make possible to predict the influence of the human factor on the building environment and increase the accuracy of the energy performance predictions and improving occupants' comfort.

Acknowledgements

I could not have done this work without the help of others. I am thankful for the opportunity to express my gratitude to them here.

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Dedicated to my parents and my wife, Elham

Table of content

1 Introduction

1.1 Overview

This work presents the results of a study conducted in 29 offices in a large high-rise office complex in Vienna, Austria in order to discover possible relationships between behavior of occupants and internal /external environment to increase knowledge about building energy performance.

Internal and external parameters were observed over the period of one year from January 2005 to December 2005. A weather station, a number of indoor data loggers, and two digital cameras were used to continuously monitor and record every five minutes such events and states; occupancy, indoor and outdoor temperature and relative humidity, internal illuminance, external wind speed and horizontal global irradiance, status of electrical light fixtures, position of shades.

Chapter 1 includes Motivation of choosing the topic and Background of previous studies in area of occupants' behavior regarding energy performance. Chapter 2 gives details about the case study, describes research methodology, measuring equipments, computer programs, data collection and processing the data. Chapter 3 is dedicated to the results of the interviews, energy consumption data and the analysis of the two groups of monitored offices divided in rooms located in North façade (VC_NO) and in south-west facade (VC_SW). Chapter 4 collects the result of the two parts, compares them together, discusses and gives comments on the results from the previous chapter and provides some input models for simulation applications and chapter 5 is conclusion and future research perspectives.

1.2 Motivation

The building sector contributes up to 40% of greenhouse gas emissions, mostly from energy use during the lifetime of buildings. Identifying opportunities to reduce these emissions like inventing more reliable construction materials, improving building systems and developing simulation applications for better understanding and prediction of building performance has become a priority in the global efforts to reduce climate change (United Nations environment program 2007).

Accurate prediction of building performance (energy consumption, indoor environment) requires, among the others, information on user control behavior, as in most buildings windows, shades, luminaires, radiators, fans, and other control devices can be operated by building occupants. Energy performance of buildings can be significantly influenced with occupants' presence, activity and control over the building systems and devices.

Thus, multiple studies have been and are being conducted internationally to collect data on building users' interactions with building control systems and devices. Such empirically based data can bring about a better understanding of the nature, type and frequency of control-oriented user behavior in buildings and support the development of corresponding behavioral models for integration in building performance simulation applications (Mohammadi 2007).

Our practices show that there are differences between the modeled and the real building energy performance. One explanation for the inaccuracy is the ignorance of an important factor affecting significantly the energy processes; the presence and activity of users. The behavior of occupants should be distinguished as a separate environmental factor with specific parameters. Proper monitoring strategy needs to be created and patterns systematically defined as a base for models.

While we know that people's attitudes and particularly occupants' behavior have significant effects on the performance of various energy systems, the exact influence of these effects is insufficiently explored. In addition, the nature of the multi-fold human-system interactions and their consequences for the performance of energy-consuming environmental systems are not well understood. Moreover, most researches on energy systems concentrate on energy generation and distribution systems and technologies and they are typically "hardware"-oriented.

The modeling of occupants' behavior would make possible to predict the influence of the human factor on the building environment and increase the accuracy of the energy performance predictions and improving occupants' comfort.

The complex was built in 1970s according to the construction technology of that time. There was also a concern on side of the facility management that the energy performance is not in the line with the current building practices and standards. Moreover, the new EU directive on energy performance of buildings (directive 2002/91/EC) requires the member states to set minimum standards in new and existing buildings and provide energy documents and certification processes for buildings. Specifically in case of renovation of areas more than 1000 m², the energy performance should be upgraded to minimum standard level (Mahdavi 2004a).

Thus the present work proposes a systematic research effort in the domain of energy systems of the built environment, which focuses on the "user-interfaces" of the environmental energy systems, how these interfaces accommodate or influence behavioral patterns of users, and how the user-system interactions affect the performance of the energy systems in an office building in Austria.

An empirically based extraction of patterns of user control behavior via systematic in-situ monitoring can augment the existing knowledge base in at least four ways:

- Improve the reliability of computational building performance simulation applications;
- Provide a more dependable basis for the design and configuration of user interfaces and control algorithms for buildings' environmental control systems;
- Deliver a quantitative basis for the evaluation of the impact of occupancy behavior on buildings' energy consumption;
- Develop strategies to inform building occupants regarding the energy and comfort implications of their control actions (Mahdavi 2007d).

1.3 Background

Comprehensive and up-to-date building information models can support operations in facility management and indoor environmental controls. Recent researches had lead to the development of advanced models of both building products and building processes. However, most researches on energy systems concentrate on energy generation and distribution systems and technologies and the representation of user behavior (occupants, visitors, technical staff) in such building information systems is still rather rudimentary.

One of the first studies about behavior of occupants regarding light on/off actions carried out by Hunt in 1979.

Hunt’s (1979) findings state that all luminaires in one room are switched on or off usually at the same time. Hunt, Love (1998) and Pigg (1998) also observed that the switching lights on/off actions either happen on arrival of the occupant to the room or while leaving.

Love divided the users upon their behavior regarding light use into two groups: those who turn on the lights and leave them on even when they are away from the room for intermediate absences and those who turn on the lights only when the illuminance is less than a threshold.

Both Hunt (1979) and Love (1998) observations agree that there is a strong relationship between illuminance in the working area on arrival and switching the lights on by the occupants (see Figure 1-1).

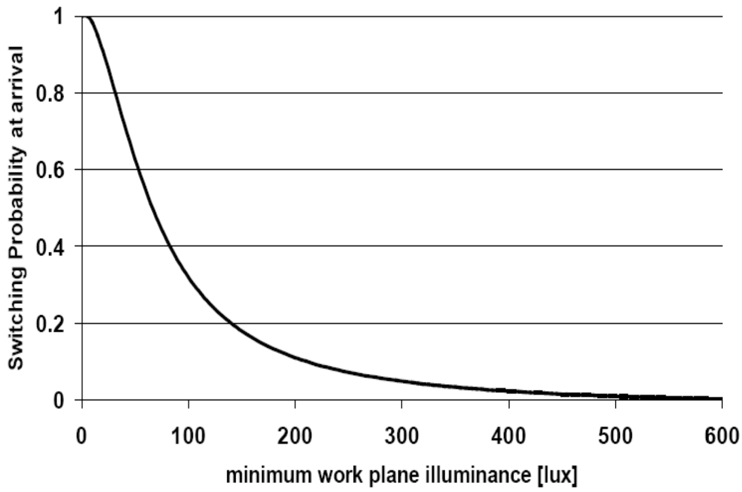


Figure 1-1 *Switch on probabilities upon arrival found by Hunt*

Pigg (1998) found a close relationship between switching lights off and the period that elapses before the occupant comes back to the room.

Reinhart (2002) monitored blinds and manual control of electric lighting. He tried to find whether manually controlled electric lighting system and automatically controlled blinds with manual override are operated in relation or independently from each other. He verified the strong relationship between period of absence from the office and also turning off the lights and increasing in probability of switching the lights on in illuminances less than 100 lx.

While a number of studies have been done on effects of user behavior on light energy use, there are not many researches about occupants' behavior in relation to heating and cooling system and energy use.

A study carried out in the Netherlands (Steg 1999) shows that the differences between socio-demographic groups are not always straightforward; highly educated people often use more heating energy, for instance, even though their home is likely to be better insulated. Young people have more wall and floor insulation in their homes, while middle-aged and elderly people take energy saving efforts more serious (United Nations environment program 2007).

The relationship between environmentally relevant behavior and income or household size is fairly straightforward; the higher the income and the larger the household, the greater the environmental burden. However, there are clear economies of scale in larger households, because people share appliances and services, making individual energy consumption relatively low (Steg 1999).

Karjalainen (2006) found that even gender can influence energy consumption in buildings. It appeared that women are less than men satisfied with room temperature and prefer higher room temperature than men. They feel uncomfortably cold and uncomfortably hot more often than men. However they are more critical of their thermal environments, men use thermostats in households more often than women.

In the controlled test experiments, while men and women were dressed similarly, and there was no gender difference in clothing insulation, women adjusted room temperature higher than men to fulfill their current temperature preferences. So the gender difference in temperature preference could not be explained by clothing.

Experience of thermal comfort at home and in the office was also studied. In offices, dress codes and trends do influence clothing and clothing insulation. In practice, this means that women wear lighter clothing than men on average. However, the gender differences in thermal comfort, which were found in this study, have been so significant that they could only partly be explained by clothing.

The respondents were asked what their principal action is when they feel uncomfortably cold and uncomfortably hot. When they feel cold, the principal action by 52% at home and 58% in the office is to put more clothes on. Clothing is not adjusted that often when feeling hot: 8% of people at home and 9% of people in the office take some clothing off to solve the problem in the first place, but the most common principal action when feeling hot is to open a window; 47% and 34% of people at home and in the office, respectively (United Nations environment program 2007).

In a European study called “Energy-efficient behavior in office buildings – EBOB” it was found that the investigated buildings (in Finland, Sweden, Italy, France and the Netherlands) were not as energy efficient as planned. The main reasons were:

- Maintenance personnel having low status and low educational level;
- Higher internal heat loads than presumed;
- Lack of information to the users;
- Difficulties using the controllers;
- Motivational problems for putting the opinions into practice;
- The windows were often left open when leaving the room in order to obtain fresh air;
- The computers were not switched off when not used;
- The office workers neglected to switch off the lights when leaving the workspace.

The “EBOB” study indicated that:

- Energy savings can be reached by designing systems that persuade people to choose the ‘best action’ from an energy saving point of view;
- Energy savings can be reached by systems that choose the ‘best action’ from an energy saving point of view;
- User interface with energy optimization or comfort optimization could obtain energy savings and result in an energy-efficient behavior of users;
- The most effective way to influence the behavior of user is likely by providing her/him information through the control system by an adequately designed interface (EBOB 2006).

Nevertheless, much more empirical data collection and pattern extraction activities are required to:

- Achieve a thorough understanding of the nature, type and frequency of control-oriented user behavior in buildings and
- Develop corresponding behavioral models for integration in building information systems (Kabir 2007).

2 Approach

2.1 Overview

The measurements were conducted in 29 offices in a large high-rise office complex in Vienna, Austria. An important feature of this complex is its use as a major seat of international organizations resulting in a diverse occupancy profile in cultural terms. 15 offices are facing north (code: "VC_NO") and 14 offices are facing south-west (code: "VC_SW"), situated on the 12th and 13th floor. All offices are with single occupancy. A schematic layout of three offices in the 12th floor could be seen on Figure 2-1. The workstations are equipped with desktop computers and (in some cases) printers. Both screen-based and paper-based tasks are performed by the occupants (Mohammadi 2007).

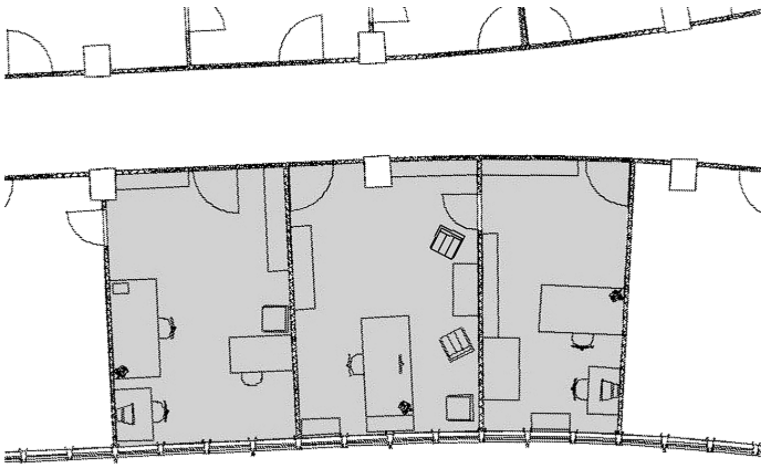


Figure 2-1 Sample office plan

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

Three rows of luminaries, 9 lamps of 36W each, divided into two circuits manually controlled by two switches near the entrance door, internal manually operable shading and three or four fan coil units under each window for fine adjustment of temperature.

The intention was to observe the actions of people toward lighting, shading and heating/cooling systems as well as under which climatic conditions they occur. The change in the status of ambient light fixtures was captured using a sensor mounted under the light fixtures. Shading was monitored via time-lapse digital photography. The degree of shade deployment for each office was derived based on regularly taken digital photographs of the façade. Shade deployment degree was expressed in percentage terms (0%: no shades deployed, 100%: full shading). The external weather conditions were monitored using a weather station, mounted on the top of the building. Internal climate conditions (temperature, relative humidity, illuminance) were measured with autarkic loggers distributed across the workstations. To obtain information regarding user presence and absence intervals, occupancy sensors were applied. All of the above parameters were logged regularly every 5 minutes. Monitored indoor parameters included room air temperature (in °C), room air relative humidity (in %), ambient illuminance level at the workstation (in lx), luminaire status (on/off), and occupancy (present/absent). Monitored outdoor environmental parameters included air temperature, relative humidity, wind speed (in $m.s^{-1}$), as well as horizontal global illuminance and horizontal global irradiance (in $W.m^{-2}$) (Mahdavi 2007c).

2.2 Object

2.2.1 Geometry / Layout

The complex is located in Vienna and was constructed in 1970's (Figure 2-2). Appendix 7.1 has detailed data about the history of the complex. It covers an area of 180,000 m² and has extraterritorial status. Maintenance and operating cost for the complex was about $19.5 million (€15.5 million) in 2003. The complex comprises about 4,500 offices, 9 conference rooms and, in 2004, accommodated about 3,600 international civil servants from about 100 countries. The Y-shaped office towers are between 48 m and 120 m high. The construction cost has been approximately € 640,000,000 (UN website).

Figure 2-2 Site (left), today's view (right)

Total net area of the floors, including kindergarten, checkpoints, technical floors and fire house is about 230,000 m^2. The towers of the complex are named from A to G and contain 92 floors; 66 floors are office floors containing 61,000 m² net office area and the rests are technical floors in which various air-conditioning plants and other technical facilities are located.

Each floor has 234 window modules and the same number of air-conditioning units and accommodates about 55-70 offices or staff. The number of air-conditioning units installed at every window module in all the office towers is 15,500. The spacing of window modules is 88 cm, centre to centre, in all these office floors (Der-Petrosian 2006).

2.2.2 Building energy systems

The complex was constructed with codes and standards of 1970's. The indoor climate of the complex is based on full air conditioning system. The windows of the buildings are not operable and as such, the entire complex requires continues supply of treated fresh air throughout working hours. Over 300 air-conditioning plants installed in the entire complex to provide comfortable indoor climate in the offices and other supporting areas.

The heating, ventilation and air-conditioning (HVAC) systems are being operated only during working hours and only 252 days per year. Operation time of the systems is between 7:00 and 18:30, except June, July and August, when it is between 7:00 and 18:00. On Monday mornings, the operation starts at 6:00 and on Friday evenings turns off half an hour earlier than the mentioned schedule. Cooling for the spaces is available from May until September (five months) and heating from September until May (nine months). In May and September both heating and cooling are available.

The ventilation inside the offices is based on fresh air supply through air ducts installed horizontally in the façade side ceiling of every floor (at the lower floor). The fresh air, after being treated (filtered, humidified and slightly heated/chilled) enters inside every air-conditioning unit and blows into the offices. This air is heated in winter or chilled in summer by passing through warm/cold radiators that are installed in every air-conditioning unit.

The radiators are heated/cooled by the supply of warm/cold water, the pipes of which are likewise running alongside the air ducts in the façade-side ceilings (at the lower floor). The ducts and the water pipes are insulated to prevent loss of thermal energy. The condensation water that is generated during chilling periods is collected at every air-conditioning unit and transmitted horizontally through a separate pipe again installed in the ceiling of the lower floor.

The fresh air for the office towers is taken from the wings of the façade, approximately 20 m above the ground floor, and treated in the technical floors, as mentioned, before entering to the main ducts in the shafts and later in the floors. Additionally there are thermostats installed in every room for occupants to lower or increase the ambient air temperature. In the corridors of the office towers the heating and cooling takes place by direct supply of preconditioned air that is blowing from the ceiling.

To achieve the desired ventilation of the offices, the air is collected through the ducts pierce in the concrete beams at every window module (corridor-side) at the ceiling and directed into horizontal air-collecting ducts installed on the corridor ceilings. Special channels on top of the lighting fixtures at every window module inside the offices cater for smooth removal of the exhausted air and delivery into the air-collecting ducts. The ventilation of the corridors takes place also through similar ducts installed on the ceilings of the corridors for this purpose (Der-Petrosian 2006).

2.2.3 Offices

The observed offices are located in tower D and floors 12th and 13th; 15 rooms are located in north façade and slightly oriented to the west. They are divided in two floors; 8 rooms in 12th floor and 7 rooms in 13th floor, however there is no major difference between the floors except elevation from the ground. These offices will be referred as VC_NO.

14 rooms are considered on the southwest façade, 8 rooms in 12th floor and 6 rooms in 13th floors. These offices mostly have south orientation but some are slightly oriented to the west (see Figure 2-3). They will be referred here as VC_SW.

Figure 2-3 illustrates 13th floor and the monitored offices.

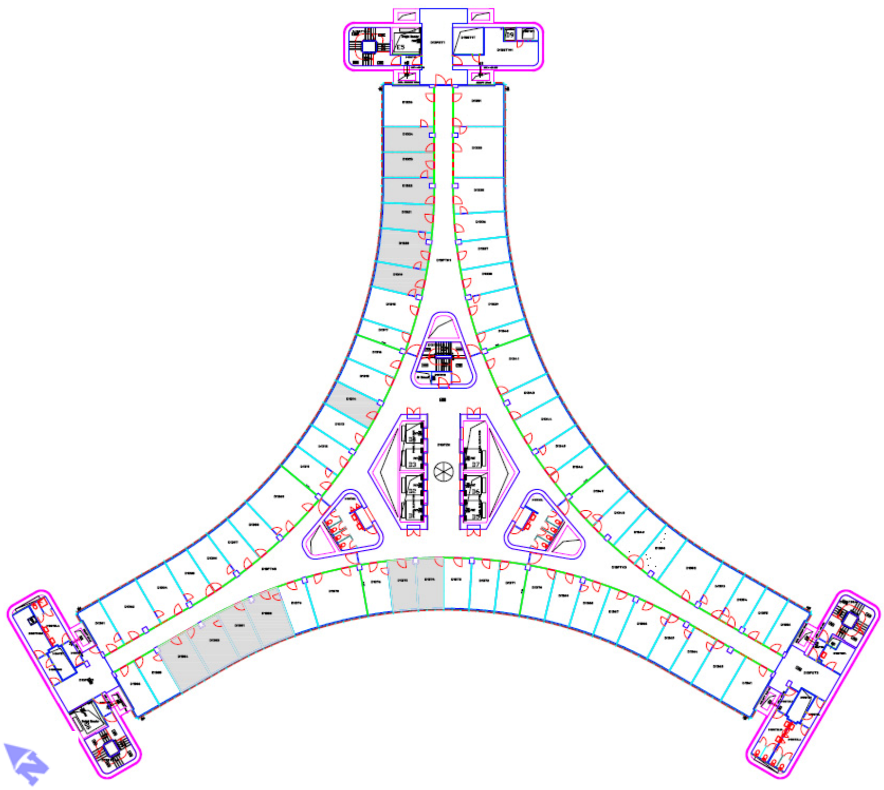


Figure 2-3 Floor plan, 13th floor

Each room is equipped with two or three tables, one computer, a telephone, one or two bookshelves and two to four chairs. The floor surface is covered by carpet, the ceiling is made out of concrete and the wall surfaces are white metal (Aluminum). Figure 2-4 shows examples of rooms' furniture, windows, blinds, lights and surfaces. About 70% of the occupants keep plants in the room.

Figure 2-4 *Two examples of rooms' furniture, windows, blinds, lights and surfaces*

2.2.4 Room devices

Windows are not operable, however a relatively large surface of the external wall is glass (about 60% of the wall, see Figure 2-4). Each room has three or four 88 cm width modules; each module has a window, one manually operable blind, one air-conditioning unit and one row of fluorescent luminaires that contains three bulbs of 36 W (see Figure 2-4).

Air-conditioning units are working non-stop according to the above-mentioned schedule, however, temperature can be controlled by thermostat. From May to September cooling is available and from September to May heating (Der-Petrosian 2006).

Luminaires are divided in two groups; the middle row can be switched on/off by the user anytime. The row close to the windows and the row close to entrance are switched on/off by a controller and can be used only if illuminance outside is less than a threshold and only between 7:00 and 21:00 on working days.

2.2.5 Occupants/Sample information

The offices are single-occupancy and the occupants are with various nationalities, 64% females and 36% males, mostly between 25 and 55 years old. 92% of them have been working in their offices more than two years (see Figure 2-5). At the time the offices were selected no information about age, gender or nationality was considered.

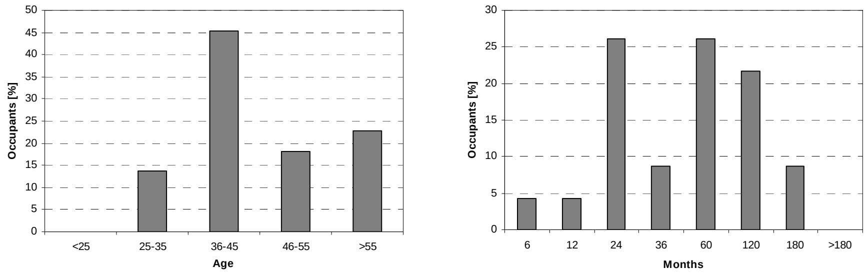


Figure 2-5 Duration of work in the office (left), age of participants (right)

2.3 Data collection

The section describes the sensors/loggers, the specifications, installation and the types of software used for downloading the data.

2.3.1 External environment

To observe external environmental parameters, a weather station was mounted on top of building D (see Figure 2-6).

Figure 2-6 Weather station

The monitored parameters by the weather station are:

- Air velocity on top of tower D [V in $m.s^{-1}$]
- External temperature [θ_e in °C]
- Relative humidity [RH_e in %]
- Solar irradiance on top of tower D (Global horizontal irradiance) [SR in $W.m^{-2}$]

The weather station' data (WS_VIC) was read out and the data stored on the project's server once per month. However, there were some losses in the collected data; from first of January to 18th of March, delay in delivering the weather station, and some days because of sensor problems. Missing values were:

01.01.2005 00:00 to 18.03.2005 16:10 all values (not installed)

15.04.2005 11:10 to 03.05.2005 15:40 Solar radiation (Sensor broken)

03.05.2005 15:40 to 06.07.2005 11:00 all values (battery empty)

Missing values obtained by adopting the present data with data from another weather station mounted on the top of university building (WS_BPI) close to the complex (see section 2.4.2 and appendix 3 for more details).

2.3.2 Internal environment

2.3.2.1 Indoor temperature/ relative humidity/ light intensity

To observe internal environment Hobo U12-012 sensors manufactured by Onset Inc. was selected. The measured parameters are:

- Room temperature [θ_i in °C]
- Relative humidity [RH_i in %]
- Light intensity [E in lx]

The four-channel 12-bit USB logger records temperature, relative humidity and light intensity measurements. The fourth external channel connects to external sensors and input cables for temperature, CO2, AC Current, AC Voltage, 4-20 mA, and DC Voltage. Figure 2-7 shows the logger and its components.

Figure 2-7 Hobo sensor/logger

Key specifications (Onset 2007):

- Temperature measurement range (internal sensor): -20° to 70°C, accuracy: ± 0.35°C from 0° to 50°C
- Relative humidity measurement range (internal sensor): 5% to 95%, RH accuracy: ± 2.5% RH from 10% to 90% typical
- Light intensity measurement range (internal sensor): 12 to 32,000 lx

- External input channel measurement range: accuracy: ± 2 mV ± 2.5% of absolute reading.

The sensors were installed on the wall near the workplace with a removable stick. The horizontal table position has not been considered as proper because it could be easily covered by objects and could bother occupants. Figure 2-8 shows typical indoor sensor positions in two offices.

Figure 2-8 Typical indoor sensor positions

The sensors were named with: 'room number_sensor ID_installation date'. For example, '118_201_041229' means the sensor is in room 118, it is the first internal sensor in the room and installed on 29.12.2004 (Pröglhöf 2005).

It is preferable that the light sensor is not exposed to direct sun light, because it produces unreliable results. Limitation of the indoor data logger is the memory capacity, which stores measurements with logging interval of 5 min. up to 50 days. Thus, the logged data was downloaded in intervals of 30 to 40 days.

2.3.2.2 Temperature of the heating unit

In VC rooms, sensors were mounted inside radiator boxes to register occupants' control actions/thermostat changes toward heating. By comparing heating unit and ambient indoor temperature, it would be possible to estimate energy consumption, energy saving potential and information on user behavior.

Hobo U12-001 from Onset Inc. was selected for measuring the temperature inside the radiator boxes. The selected type is able to record temperature in regular intervals. The device is a single channel USB temperature logger with 12-bit resolution.

Key specifications (Onset 2007):

- Measurement range: -20° to 70°C
- Accuracy: ±0.35°C from 0° to 50°C

Each room (VC) has three or four modules (see Figure 2-12 for an example of a three-module room); this means also three or four windows and the same number of air-conditioning units. All air-conditioning units in one room have one regulator to set temperature in a predefined range. The range of temperature varies depending on different months of the year and outdoor temperature and is determined by the facility management. In two months (May and September), both heating and cooling are available.

For three-module rooms, one sensor was installed in the middle radiator, for four-module rooms, it was installed in one of the middle ones (see Figure 2-9).

Figure 2-9 Installation place for temperature logger inside the radiator boxes

As described before, each sensor type or sensor was named with: "room number_sensor ID_installation date" (Pröglhöf 2005). The sensor ID for temperature loggers was starting with '3' (e.g. 215_301_041223).

2.3.3 Façade

To monitor the shading operation, a number of options were evaluated; one option was to use a web camera monitoring the façade continuously while the software takes photos in predefined intervals. For this purpose, a PC beside the camera was necessary and it had to be checked every few days, or a wireless connection had to transfer the view to a PC in the project's laboratory.

In these cases (VC_NO, VC_SW), the distances from the façade were too large for a web-cam or any low-resolution camera (see Figure 2-10).

Figure 2-10 Example of contrasts in the images in VC_SW

Thus, it was decided to use a high-resolution camera to take pictures in predefined intervals. Nikon Coolpix 8700 cameras with resolution of eight mega pixels and ability to take pictures in intervals with 2 GB compact flash cards were used.

Each camera was mounted in a box facing the building (see Figure 2-11). Power and cable for each were provided. The camera was able to take maximum of 1,800 pictures in one session; the interval for taking pictures was chosen to be 10 min (capacity for 10 days).

Figure 2-11 Camera box with power supply pointing to the VC_NO façade

2.3.4 Occupancy/ state of light (on/off)

IT-200 loggers manufactured by Wattstopper Inc. were used to log occupancy and switching on/off lights (see Figure 2-12).

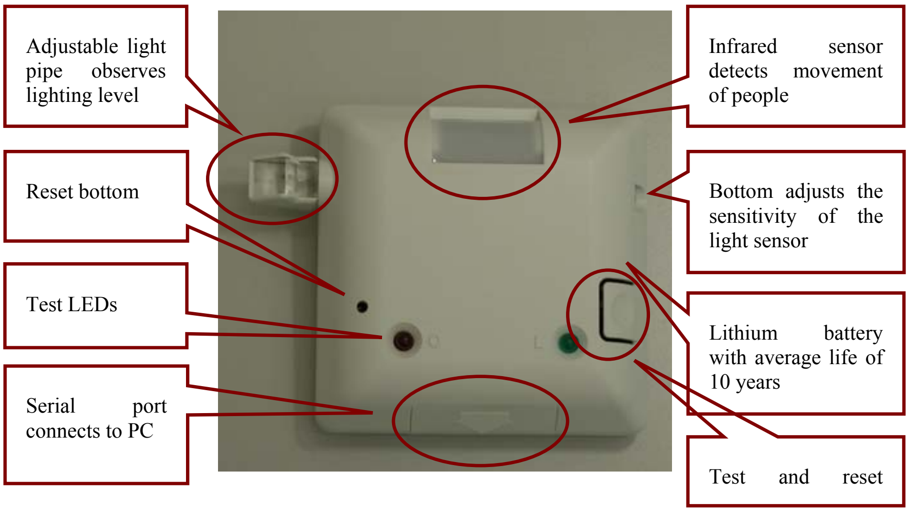


Figure 2-12 IT-200, occupancy and state of light (on/off) sensor

The IT-200 records a log entry whenever there is a change in either the occupancy or the lighting status and stores a detailed history of these events for retrieval by PC. It utilizes passive infrared technology to detect occupancy.

It observes the luminance through a plastic pipe to determine if lights are on or off. The loggers were installed so that the lens had a clear view of the workspace and the light-pipe aimed towards the nearest light fixture (see Figure 2-13).

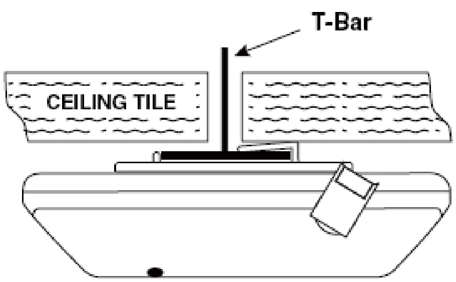


Figure 2-13 Installation of occupancy and state of light (on/off) sensor

The occupancy sensor monitors an area of up to 45 m² using passive infrared technology (PIR), (see Figure 2-14).

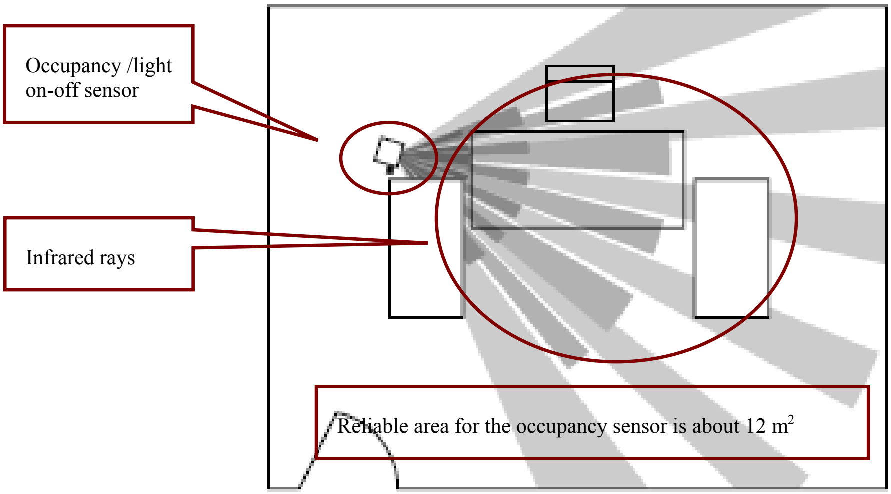


Figure 2-14 Coverage of the sensor

Key specifications:

- Lithium battery operated, average battery life ~10 years, battery life indicator
- Test button activates LEDs for 60 seconds during which sensitivity is set and proper location for occupancy detection is verified

– Red LED blinks during occupancy detection

– Green LED blinks when lighting is detected

- Recessed reset switch
- Coverage up to 45 m^2 (12 m^2 reliable)
- Stores a maximum of 4,096 entries
- Stores site name to identify the area being monitored
- Connects to computer (PC) for data retrieval via serial connector cable
- Includes a serial to USB adapter for computers without serial ports

To set an interval for the sensors, we considered two types of limitations; storage and accuracy. Finally, it was decided to accept five-minute intervals.

For all rooms of VC, it was enough to install one sensor to monitor each workplace. The 'sensor naming scheme' was used to name the sensors. The sensor ID for IT-200 loggers was starting with '1' (e.g. '115_101_041219' refers to the first IT-200 in room number 115 and the date of installation which was 19.12.2004).

2.3.5 Interviews

A set of questions was designed and sent to the observed occupants. The questionnaires had five sections; first section, general data about the occupants such as age, gender and occupation type, the second, general feeling about internal environment of the room, third part about details of the building systems and office devices, forth part, their opinions about energy saving and the last, if they have any complaints or suggestions for the systems.

2.3.6 Energy consumption data

To compare results from simulation programs and real situation in the complex, facility management provided energy consumption data for year 2005 and before.

2.4 Data processing

Excel was chosen for statistical analysis, because of its compatibility with other applications as well as various options for statistical analysis. All files of a sensor were processed by Senselect with output of two Excel sheets, containing the data for one-half of the year accordingly.

This section describes the processing of the collected data, the methods of analysis and the computer programs used for the project.

2.4.1 Data interval arrangement

"Senselect" is a program, which was developed by a colleague, Claus Pröglhöf, to arrange all sets of data in the same order. Order in this context means putting all types of data from sensors/software on the same points of a timeline with five-minute interval. The data was divided in two parts of "January 1st to June 30th" and "July 1st to December 30th", because Excel has a limitation of maximum 62,000 rows and one year in five-minute steps (105,000 rows) exceeds the threshold.

The program reads all kinds of excel sheets and text files from other programs of the sensors and arranges them. As each program has a different file arrangement, in every session the process was done for each set of data separately. Figure 2-15 shows a screen shot of the program.

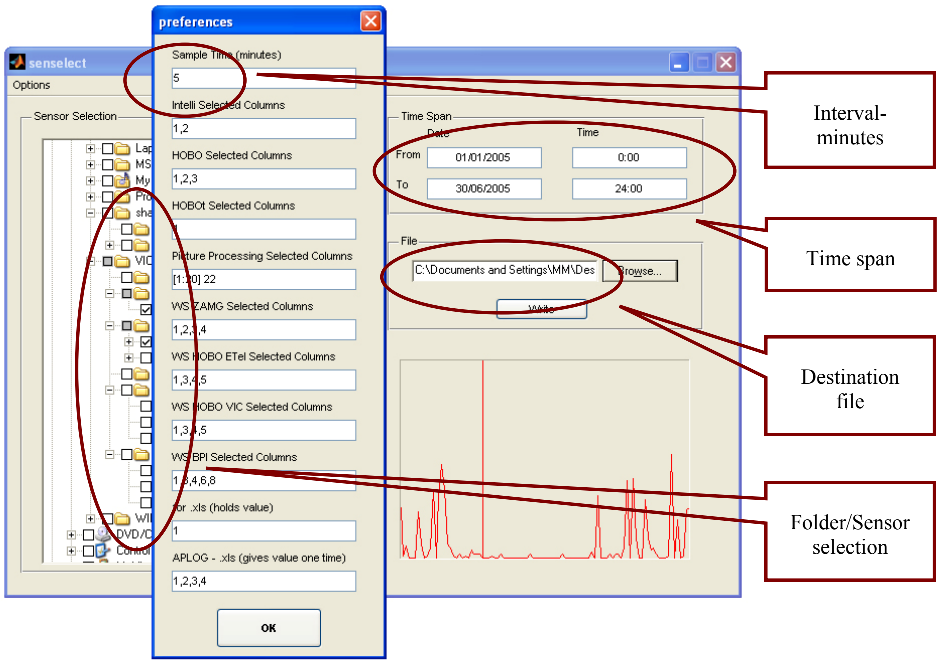


Figure 2-15 Interface of Senselect

The folder, which carries files of one sensor, should be named as:

"Building number (1 or 2)" + "floor number (1 or 2)" + "room number (1 to 9)" + "_" + "sensor ID" + "sensor number"

Files names have to be as following:

"Building code (1 or 2)" + "floor code (1 or 2)" + "room code (1 to 9)" + "_" + "sensor ID" + "sensor number (01)" + "_" + "installation date"

In case of VC, buildings codes are "1" for north façade and "2" for southwest façade. Floor code for floor "12" is "1" and for "13" is "2".

2.4.2 External environment

There were some problems with the data of the weather station (external environment) but they were solved. The process is explained in appendix 7.2: "Deriving missed external environmental data of Weather station".

The missing data was adopted from the weather station (WS_BPI), mounted on the top of BPI department, about five kilometers away in direction of southwest from the monitored building. The correlations between the recorded parameters in two weather stations were checked and based on reliable correlations, the missing values derived out of the recorded parameters in WS_BPI. Table 2-1 and Figure 2-16 shows the correlation between recorded data from the two weather stations in first quarter of year 2005.

- V: Air velocity on top of tower D [$m.s^{-1}$]
- RH_e: Relative humidity [%]
- θ_e: External temperature [°C]
- SR: Global horizontal irradiance [$W.m^{-2}$]

Table 2-1 First quarter of year 2005, comparing collected data of WS_BPI and WS_VIC

Correlation	Equation
$R^2(V) = 0.2447$	Y=0.4405X+0.4419
$R^2 (RH_e) = 0.9637$	Y=1.0606X-2.2745
$R^2 (\theta_e) = 0.9861$	Y=0.9713X-0.1796
$R^2 (SR) = 0.9439$	Y=0.9179X+4.9831

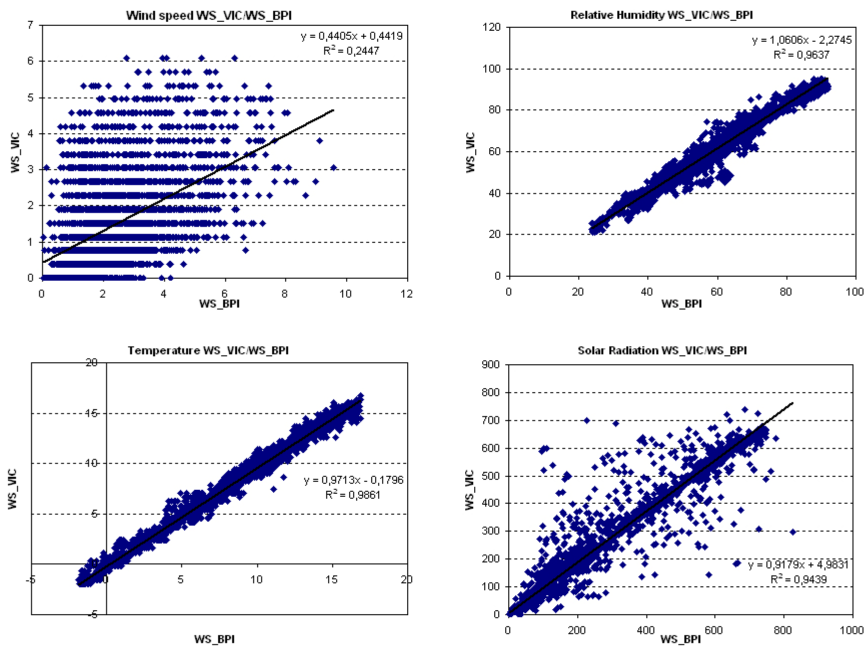


Figure 2-16 *Comparing parameters of weather stations for first quarter in VC and BPI; Wind speed, relative humidity, temperature and solar radiation*

2.4.3 Indoor environment sensor

The “Hobo” data logger measures and records three parameters; Light intensity, temperature and relative humidity (section 2.3.2.1). The sensor checks state of each parameter at certain points of the timeline and records them. The Sensor type is “2” and sensor name in all cases of this case study is “01” because each office has only one “Hobo” sensor.

The software servicing the Hobo data logger is called “Onset GreenLine”. It downloads the data from the sensors, exports the file as “txt” file for use in Excel and resets them for future operation. The software gives a simple graph that is used to check the data (see Figure 2-17).

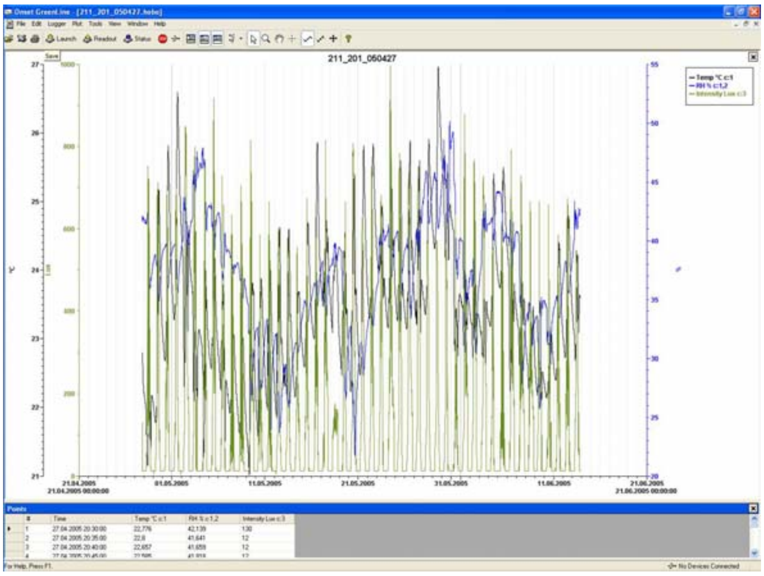


Figure 2-17 Recorded data by hobo logger

The downloaded file is a hobo file that has to be converted in an Excel-spreadsheet. The time-step in this file is five-minute but it had to be shifted to the next point of the interval (for example from 10:27:34 to 10:30:00, based on ratio-average of the period), so that it is possible to compare set of data from one workstation. "Senselect" is the program which does the step, it checks the files, distinguishes hobo files from the fifth character of the name, which is "2", merges all the files of a workstation from the downloads and shifts the data point to the correct point on timeline by calculating the ratio.

2.4.3.1 Calibration

Comparing recorded values to a high accuracy device showed that the light sensors need to be calibrated using a correction factor. The process has been done in various conditions (daylight and artificial light). Figure 2-18 shows the process to find the accuracy factor.

Figure 2-18 process to find the accuracy factor of the light sensors

2.4.4 Derivation of horizontal illuminance from measured vertical illuminance

Instead of horizontal illuminance levels on the workstation, vertical light levels on walls have been measured. Thus, the vertical illuminance levels had to be converted to horizontal ones.

For this purpose, a calibration measurement was performed in each room using two sensors. A sensor mounted on the workstation recorded the illuminance level in the same intervals as the main sensor. Figure 2-19 shows, as an example, the correlation between the two sets of data in room 114.

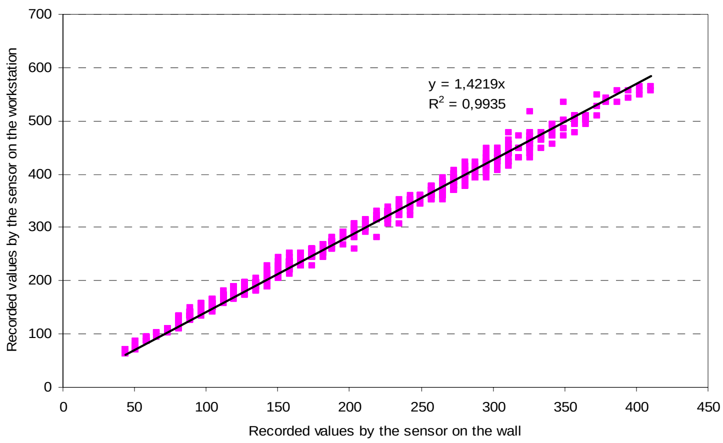


Figure 2-19 Converting vertical illuminance into horizontal illuminance on the workstation for room 114

2.4.5 Temperature of the heating unit

The files generated from temperature loggers in radiator boxes have the same concept as internal environment sensors (Hobo), unless they have only one parameter.

GreenLine is used to download data and reset the sensors, the same software that is used for other type of internal environment (Hobo) sensors (see Figure 2-20).

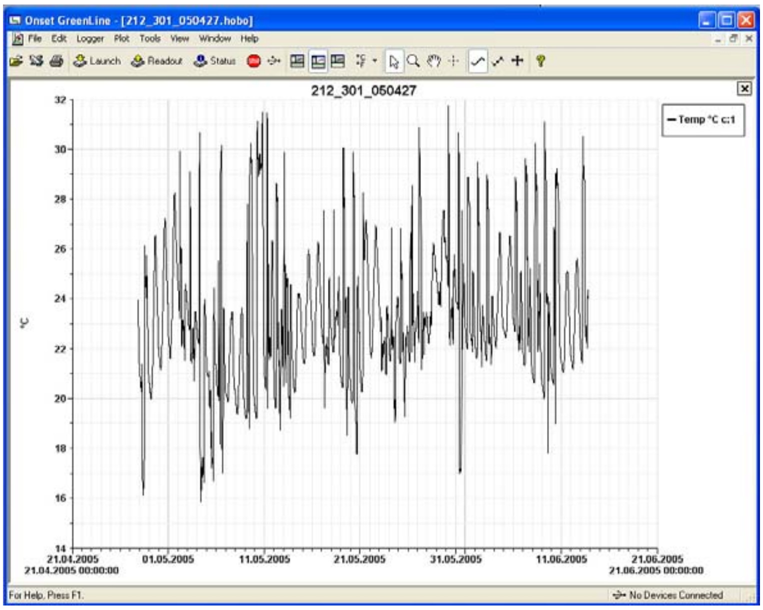


Figure 2-20 Recorded data by "hobo" temperature logger

It exports a "txt" file to be imported in Excel, and it should follow the same procedure of internal environment sensors (Hobo), namely processing by Senselect.

2.4.6 Image processing

A large number of digital images were taken by high resolution (8 mega pixels) cameras (about 50,000 pictures in each case) to register positions of windows in each photo (see Figure 2-21).

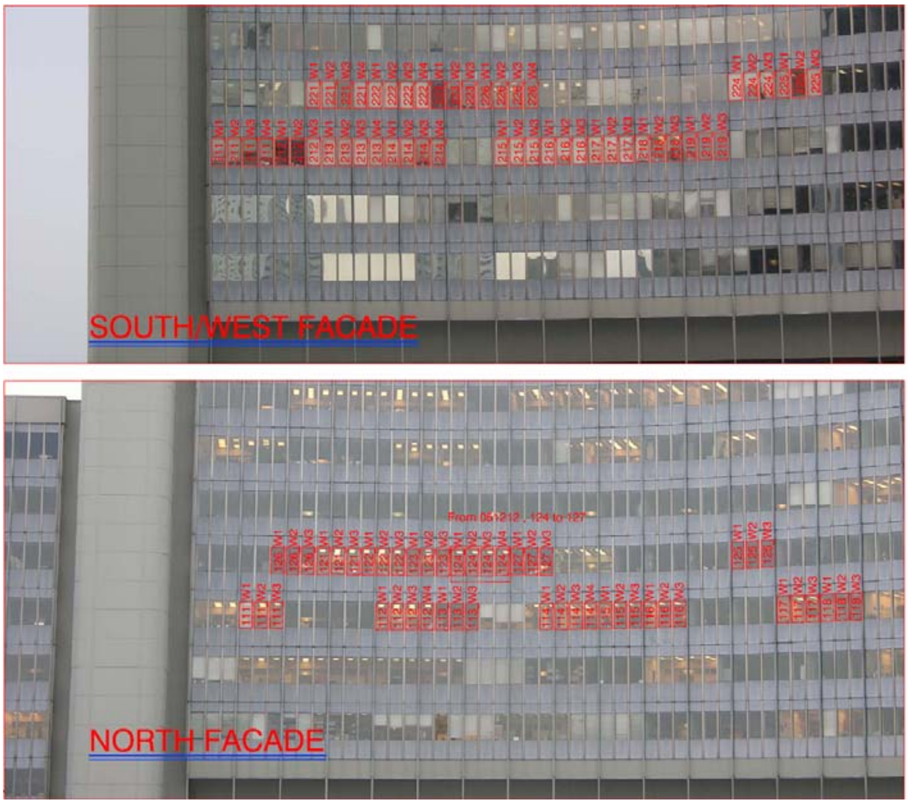


Figure 2-21 Selected windows for the program

An application (ENVO) was designed and developed by a colleague to process image analysis. The program is based on Labview and semi-automatic (see Figure 2-22).

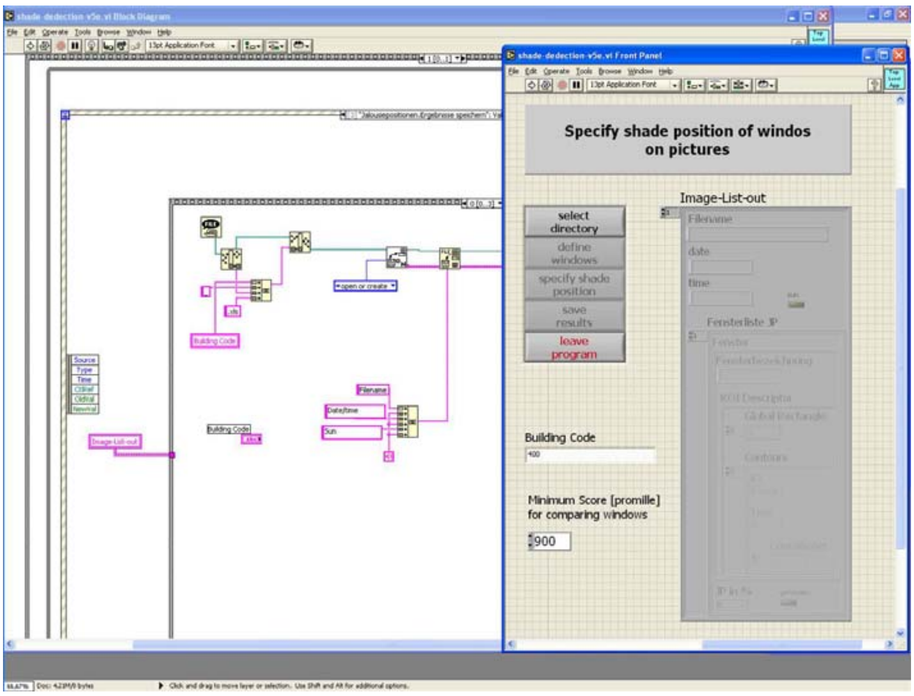


Figure 2-22 Shade detection program (ENVO)

The program compares pixels in frequent images and if there is a change, it shows the image so that the user can specify the position of the shades. Level of the shades for a completely closed shade was defined to be 100% and for an opened shade 0%. Intermediate steps of 20% between fully closed and fully opened shades were used (see Figure 2-23).

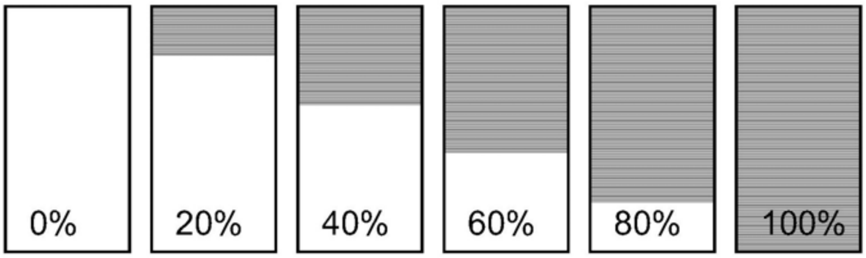


Figure 2-23 Defined positions for the shades

The accuracy of comparing two pictures in the program could be defined; for example 900 means if the similarity between the two frequent pictures is less than 90%, the subsequent picture will be shown to the user. Figure 2-24 shows snapshot of the graphical user interface of the LabVIEW application.

The program stores position of shades for future processing and all windows have to be selected before the program starts. Figure 2-24 shows selecting the windows by the program.

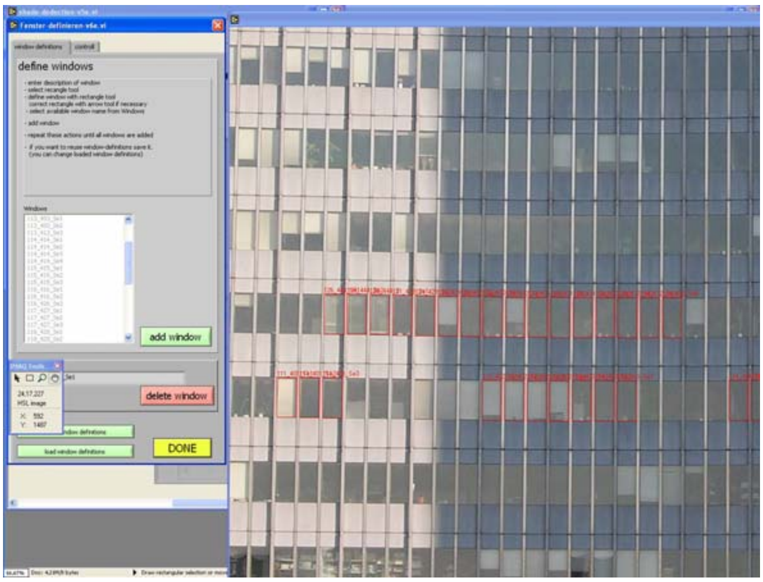


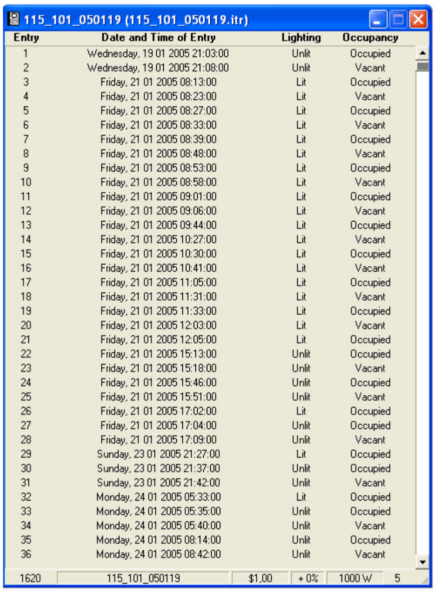
Figure 2-24 Interface of the program (ENVO)

The outputs of the program are Excel-sheets with header, picture name, the date of image capture and the names of windows. The files have ten-minute steps and are separated for each downloaded period; 'SenSelect' is necessary to combine them and adjust them to five-minute steps.

2.4.7 Occupancy and light on/off sensor-logger

For "IT-200", the sensor type is "1", and because all rooms in the case of VC are single occupant, the sensor number is always "01".

The software, "ITProsoft", is used to download data and to prepare the sensor for future work. It lists all log entries: entry number, date/time, lighting status, occupancy status. While connected, it can reset the logger in preparation for a new logging session. Figure 2-25 shows an example of a logged period. The right picture is a graph illustrating the data shown at left. The blue trace illustrates lit duration and the red one is occupied duration.


115_101_050119 (115_101_050119.itr)

Entry	Date and Time of Entry	Lighting	Occupancy
1	Wednesday, 19 01 2005 21:03:00	Unlit	Occupied
2	Wednesday, 19 01 2005 21:08:00	Unlit	Vacant
3	Friday, 21 01 2005 08:13:00	Lit	Occupied
4	Friday, 21 01 2005 08:23:00	Lit	Vacant
5	Friday, 21 01 2005 08:27:00	Lit	Occupied
6	Friday, 21 01 2005 08:33:00	Lit	Vacant
7	Friday, 21 01 2005 08:39:00	Lit	Occupied
8	Friday, 21 01 2005 08:48:00	Lit	Vacant
9	Friday, 21 01 2005 08:53:00	Lit	Occupied
10	Friday, 21 01 2005 08:58:00	Lit	Vacant
11	Friday, 21 01 2005 09:01:00	Lit	Occupied
12	Friday, 21 01 2005 09:06:00	Lit	Vacant
13	Friday, 21 01 2005 09:44:00	Lit	Occupied
14	Friday, 21 01 2005 10:27:00	Lit	Vacant
15	Friday, 21 01 2005 10:30:00	Lit	Occupied
16	Friday, 21 01 2005 10:41:00	Lit	Vacant
17	Friday, 21 01 2005 11:05:00	Lit	Occupied
18	Friday, 21 01 2005 11:31:00	Lit	Vacant
19	Friday, 21 01 2005 11:33:00	Lit	Occupied
20	Friday, 21 01 2005 12:03:00	Lit	Vacant
21	Friday, 21 01 2005 12:05:00	Lit	Occupied
22	Friday, 21 01 2005 15:13:00	Unlit	Occupied
23	Friday, 21 01 2005 15:18:00	Unlit	Vacant
24	Friday, 21 01 2005 15:46:00	Unlit	Occupied
25	Friday, 21 01 2005 15:51:00	Unlit	Vacant
26	Friday, 21 01 2005 17:02:00	Lit	Occupied
27	Friday, 21 01 2005 17:04:00	Unlit	Occupied
28	Friday, 21 01 2005 17:09:00	Unlit	Vacant
29	Sunday, 23 01 2005 21:27:00	Lit	Occupied
30	Sunday, 23 01 2005 21:37:00	Unlit	Occupied
31	Sunday, 23 01 2005 21:42:00	Unlit	Vacant
32	Monday, 24 01 2005 05:33:00	Lit	Occupied
33	Monday, 24 01 2005 05:35:00	Unlit	Occupied
34	Monday, 24 01 2005 05:40:00	Unlit	Vacant
35	Monday, 24 01 2005 08:14:00	Unlit	Occupied
36	Monday, 24 01 2005 08:42:00	Unlit	Vacant

1620 | 115_101_050119 | $1,00 | + 0% | 1000 W | 5

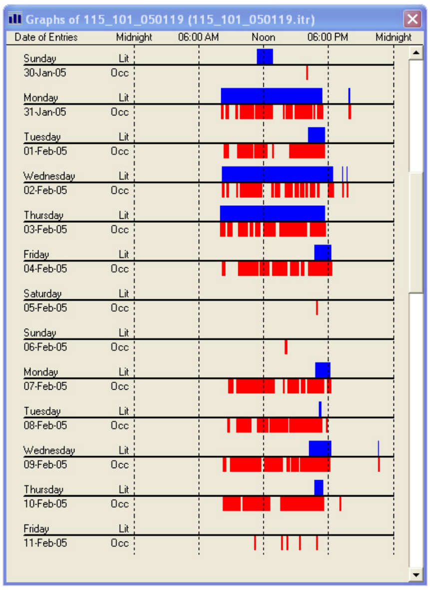


Figure 2-25 *Recorded data by the occupancy and state of light logger, logged entries (left), the graph illustrating the recorded events (right)*

The software gives a primary analysis to check the sensor every time after a download (see Figure 2-26).

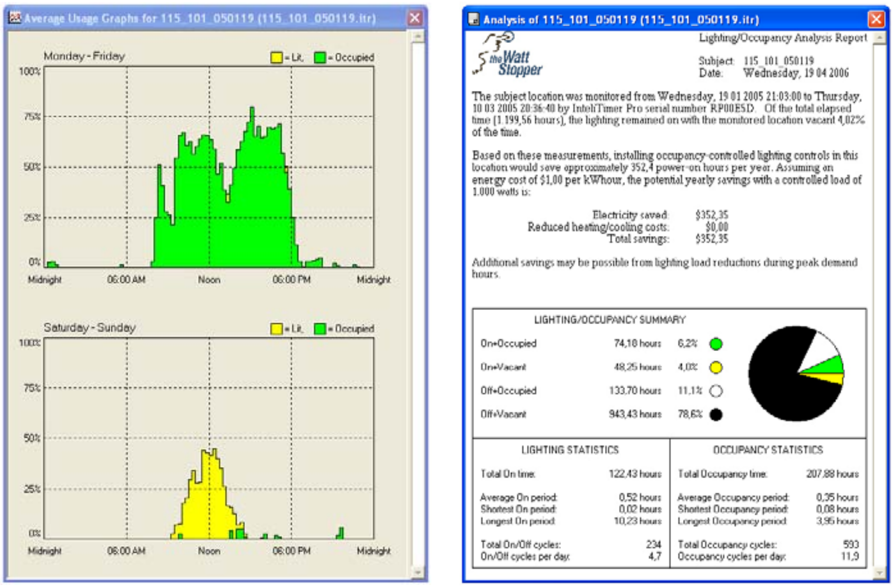


Figure 2-26 Primary analysis provided by the software

2.4.7.1 Calibration

An experiment was performed to check accuracy of the occupancy sensors. For this purpose, four IT-200s were installed to point towards a test workplace, and the presence at the test workstation was recorded for the whole period of the experiment. Figure 2-27 shows the equipment setup.

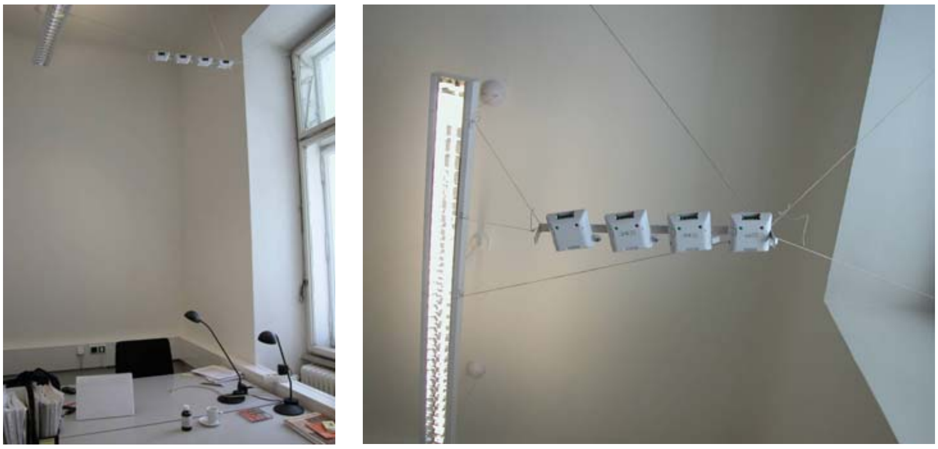


Figure 2-27 Experiments of accuracy of occupancy loggers

The recorded data was downloaded and processed by SenSelect; it was found that by filling five-minute gaps in the occupancy sensor data stream, the highest level of reliability (95%) can be achieved.

2.4.8 Database

"Sensat" is a database program developed by a colleague to handle data files. The program is a database with ability of exporting particular data of sensors, rooms, hours or dates. It has two interfaces, one to import excel spreadsheets to the database and combine them and the second to export specified range of data from selected rooms and dates. Figure 2-28 shows first interface of Sensat.

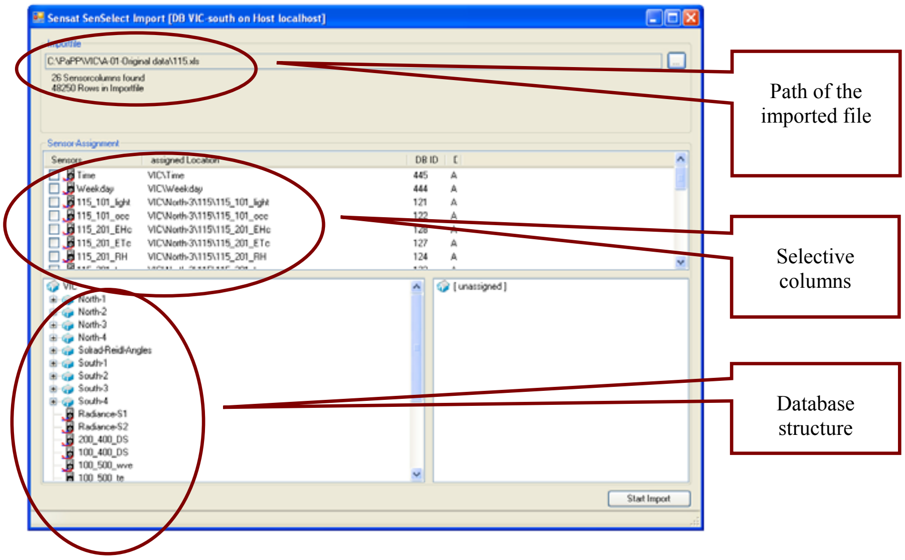


Figure 2-28 Sensat database interface: "Excel import"

Figure 2-29 illustrates the second interface of the program used to specify dates, hours, sensors, conditions and the arrangement in which data can be exported.

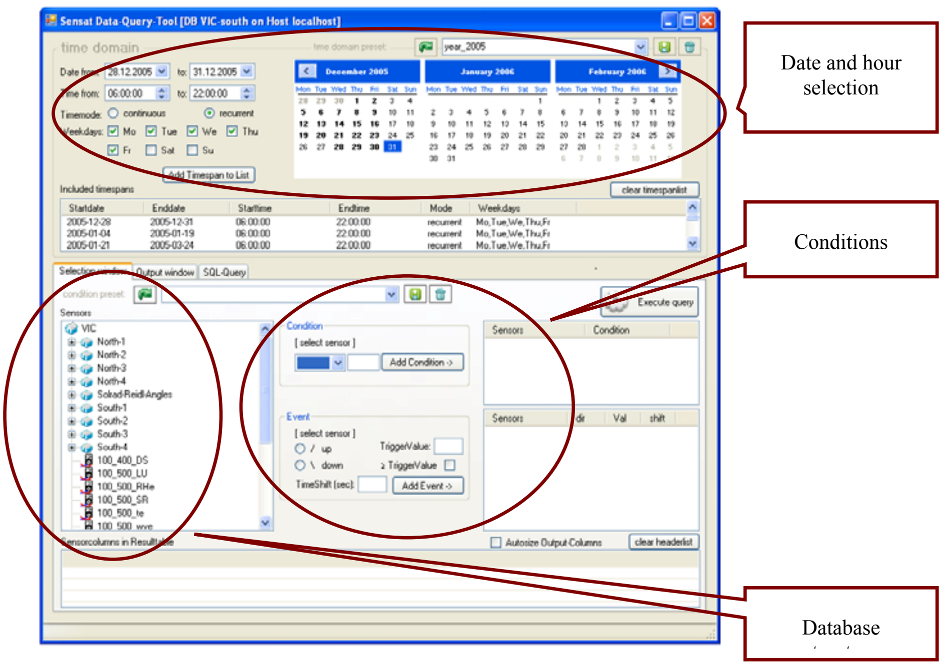


Figure 2-29 Sensat database interface: "Data query"

2.4.9 Interviews

80% of the questionnaires from the observed occupants were returned and digitized; the data out of them collected and analyzed.

2.4.10 Energy consumption data

The data digitized to be used in simulation programs.

2.5 Data analysis

2.5.1 Data structure

The primary data structure follows a distinction between various types of "events" and "states" that occur at a certain point in time or persist over a certain time period. This data structure and primary data types are summarized in Table 2-2 (Mahdavi 2006c).

Table 2-2 The structure of the collected data

Data	Type	Instances
Events	System-related	Switch lights on/off
		Pull shades up/down
	Occupancy-Related	Entering into/leaving an office
States	System-related	Lights on /off
		Position of shades/windows
	Indoor environment	Air temperature
		Illuminance level
	Outdoor environment	Outdoor temperature
		Global irradiance
	Occupancy-Related	Office/workstation occupied/vacant

The hypothesized relationships are relationships between environmental conditions (e.g. temperature, light intensity) and internal states (e.g. state of light, state of shades) or events (e.g. switching on/off the lights, opening/closing shades).

2.5.2 Analysis terms

In order to analyze the data, following terms were considered:

“Frequency” is used for number of instances, for example, frequency of “switching light on” actions as a function of illuminance on workstations gives the number of the actions that occur between ranges of illuminance on workstations.

“Relative frequency” denotes the ratio (in percentage) of particular instances to all instances. For example relative frequency of “switching light on” actions as a function of illuminance on workstations gives the percentage of the actions that occur in various illuminance ranges.

“Normalized relative frequency” is used to consider all relevant conditions. For example, the numbers of actions are divided by the respective periods of observations. Thus, frequency of actions observed over different time-periods can be made comparable.

“Probability” is used to specify the likelihood of an action occurrence given a certain set of conditions. For example, probability of “switching light off” action as a function of the duration of absence from the office means in what percentage of the instances where a person left his/her office for x minutes, he/she switched the light.

3 Results

3.1 Overview

For purpose of the analysis, the range of the data considered was limited to working days between the hours 06:00 to 22:00. The collected data was analyzed to explore hypothesized relationships between the nature and frequency of the control actions on one side and the magnitude and dynamism of indoor and outdoor environmental changes on the other side.

First part of the results is dedicated to the interviews. Second part gives the result of energy consumption data. Third part will be results of observations divided in the two groups of VC_NO and VC_SW.

3.2 Interviews

Figure 3-1 shows two graphs with results of satisfaction with air quality and ventilation.

Figure 3-1 *Occupants' evaluation of air quality (left), satisfaction with ventilation (right)*

Figure 3-2 represents occupants feeling of temperature in winter and summer. Figure 3-3 shows the satisfaction with air-conditioning and effect of direct sunlight.

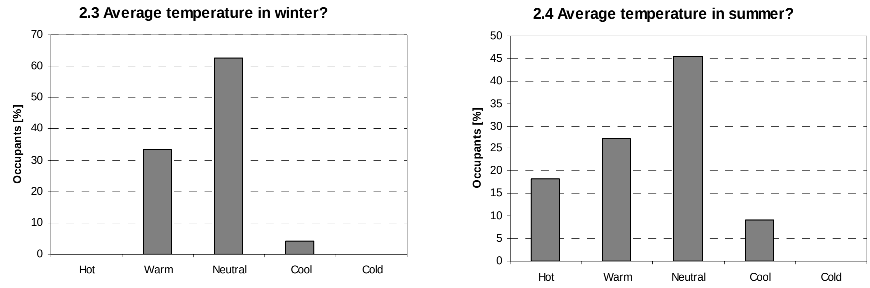


Figure 3-2 *Occupants' evaluation of temperature in winter (left) and summer (right)*

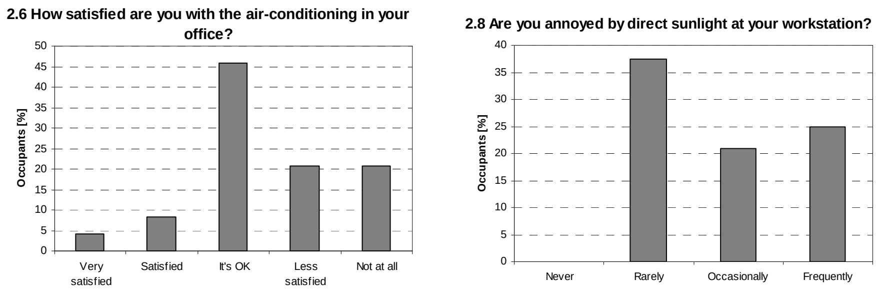


Figure 3-3 *Satisfaction with air-conditioning (left), annoying by direct sun light (right)*

3.3 Energy consumption data

Average annual cost of heating in the last ten years (1995-2004) for towers A+B+D+E (office towers) has been about 620,000 Euro and for the whole complex 1,310,000 Euro. For cooling, the averages annual cost for towers A+B+D+E has been about 915,000 Euro and for the whole complex 1,930,000 Euro.

Table 3-1 and Figure 3-4 show comparison between energy costs and total costs for maintenance and operation of the complex (Vienna international center website and Der-Petrosian 2006)

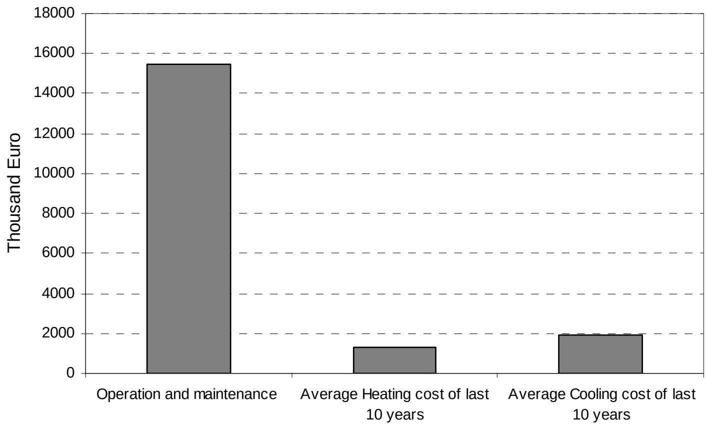


Figure 3-4 *Operation and maintenance costs, Heating and cooling energy*

Table 3-1 *Maintenance and operation cost and energy cost*

VC-ENERGY	Euro
Maintenance and operation cost of the VC in year 2003	15,500,000
Average Heating cost of last 10 years	1,308,368
Average Cooling cost of last 10 years	1,928,874

Table 3-2 represents annual energy consumption for the complex in year 2005. Figure 3-5 shows heating, cooling and lighting energy consumption for the offices and the entire complex (Der-Petrosian 2006).

Table 3-2 *Annual energy consumption in year 2005*

	MWh	€/KWh	€	Area (m^2)	€/m^{-2}
Lighting in offices	1,855	0.054	10,0170	108,800	0.92
office devices (+fans)	1,700	0.054	91,800	108,800	0.84
Electricity (all types)	24,610	0.054	1,328,940	229,482	5.79
Heating	32,730	0.059	1,931,070	229,482	8.41
Cooling	8,000	0.208	1,664,000	229,482	7.25

Table 3-3 shows average annual energy consumption for office areas only.

Table 3-3 *Average annual energy consumption for offices only (averaged over last 10 years)*

	€	Area (m^2)	€/m^{-2}
Average annual cost of heating for towers A+B+D+E	620,312	108,800	5.70
Average annual cost of cooling for towers A+B+D+E	914,501	108,800	8.41

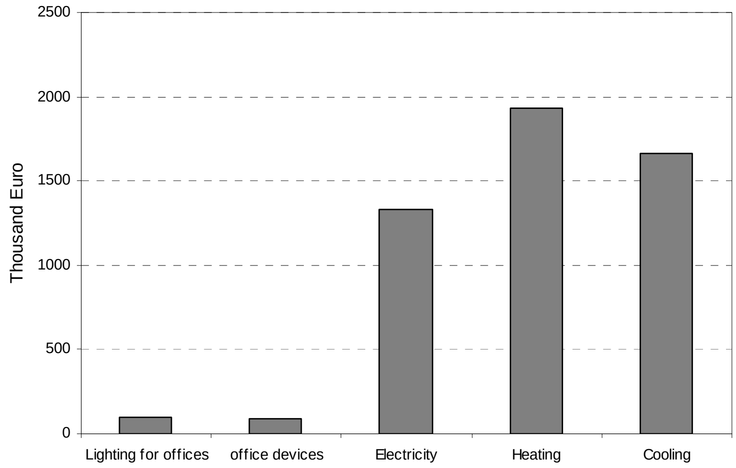


Figure 3-5 *Heating, cooling and lighting and electricity energy (all types) consumption for the complex in 2005*

Table 3-4 and Figure 3-6 show detailed energy consumption of electricity, heating and cooling energy for two towers of "D+E" in year 2005.

Table 3-4 *Energy consumed in Buildings D+E*

	MWh	€/KWh	€	Area	€. m^{-2}
Total electricity consumed (all means)	2,769	0.078	215,982	53,371	4.05
Total Heating consumed	9,016	0.059	531,944	53,372	9.97
Total Cooling consumed	2,800	0.18	504,000	53,373	9.44

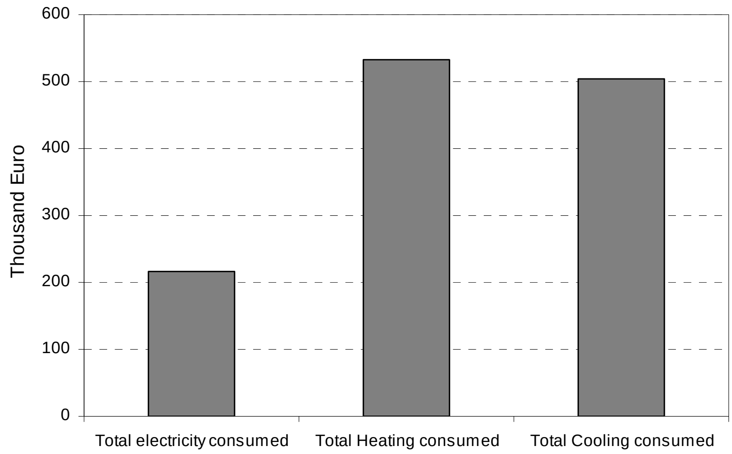


Figure 3-6 Energy consumed in Buildings D+E

In appendix 7.3, “Energy consumption data”, more details are presented.

3.4 VC_NO

3.4.1 Occupancy

Figure 3-7 illustrates the mean monthly occupancy level in VC_NO, averaged over all observed offices, over the observed period (2005) in percentage. The data in this and the following occupancy figures is for working days (from 8:00 to 20:00)

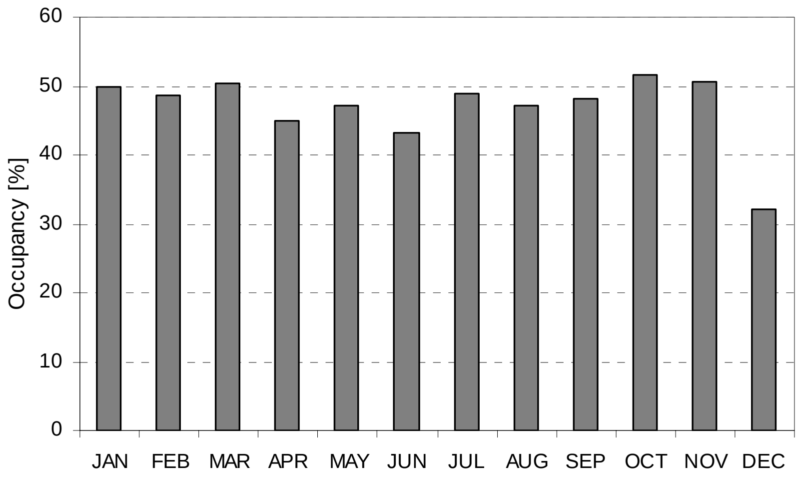


Figure 3-7 Mean monthly occupancy level in VC_NO, averaged over all observed offices

Note that mean occupancy level can vary from room to room. Figure 3-8 shows mean monthly occupancy level for four offices (rooms 111, 116, 122 and 124).

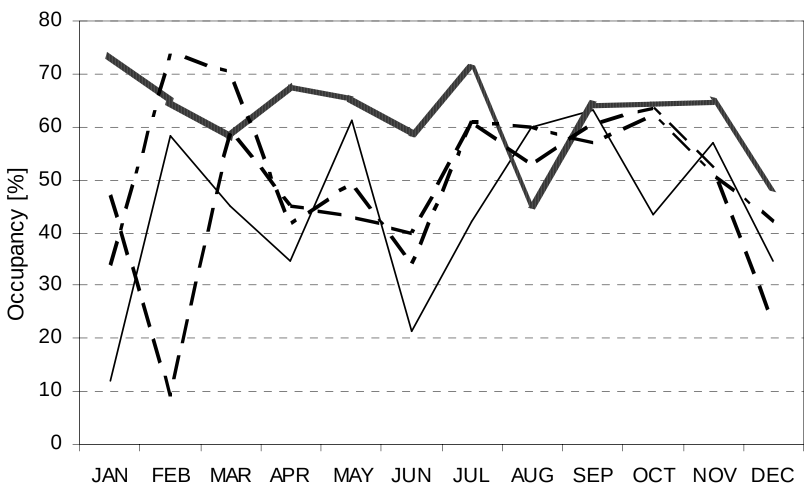


Figure 3-8 Mean monthly occupancy level in 4 offices (111, 116, 122 and 126) averaged over all observed offices of VC_NO

Figure 3-9 shows the mean occupancy level over the course of a reference day (averaged over the entire observation period). Note that this Figure represents the presence in the user's office and not the complex. Moreover, as Figure 3-10 demonstrates, the occupancy patterns in individual offices can vary considerably.

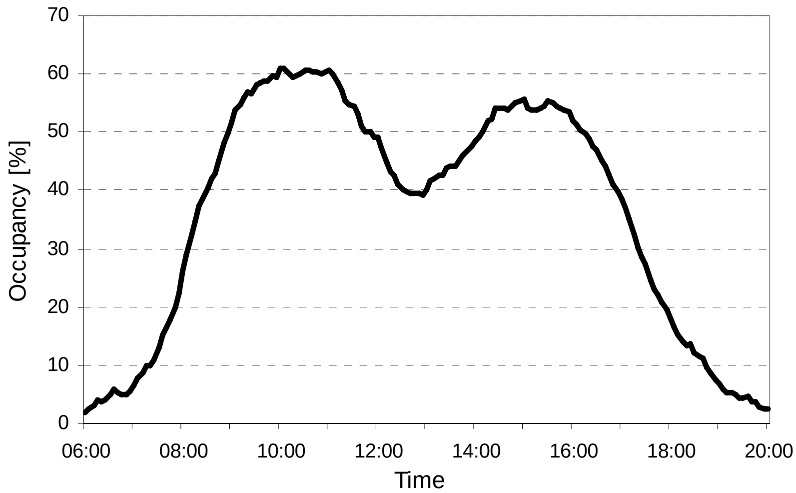


Figure 3-9 *Mean occupancy level over the course of a reference day, averaged over all observed offices of VC_NO*

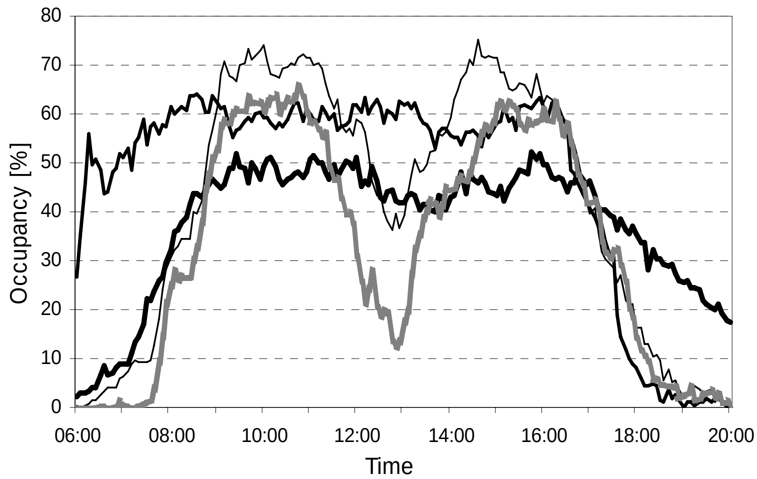


Figure 3-10 *Observed occupancy levels in 4 different offices (111, 116, 122 and 126) in VC_NO over the course of a reference day*

3.4.2 Lighting

3.4.2.1 Light operation

Figure 3-11 illustrates mean lighting electricity load over the course of a reference day averaged over the observed offices in VC_NO. Figure 3-12 shows the observed effective lighting load in the course of a reference day. Obviously, the information in this Figure is about the general light usage tendency in all observed offices. To provide an impression of the differences amongst individual light usage profiles, Figure 3-13 shows the lighting operation in each observed office for the entire monitoring period in the working hours.

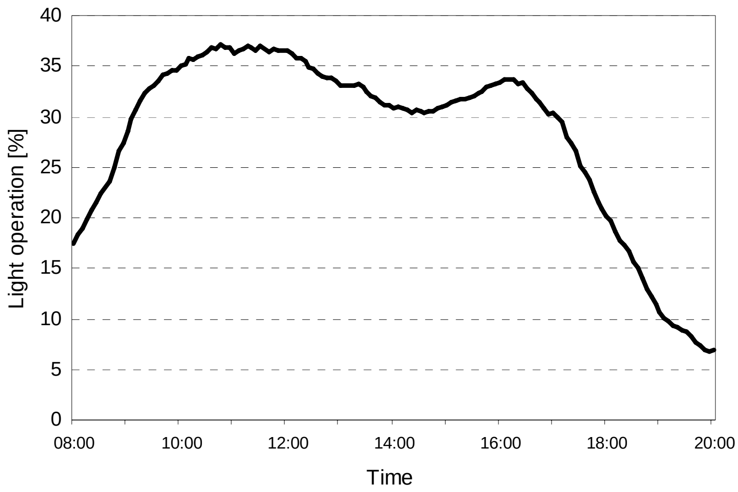


Figure 3-11 *Mean lighting electricity load over the course of a reference day average in the observed offices in VC_NO*

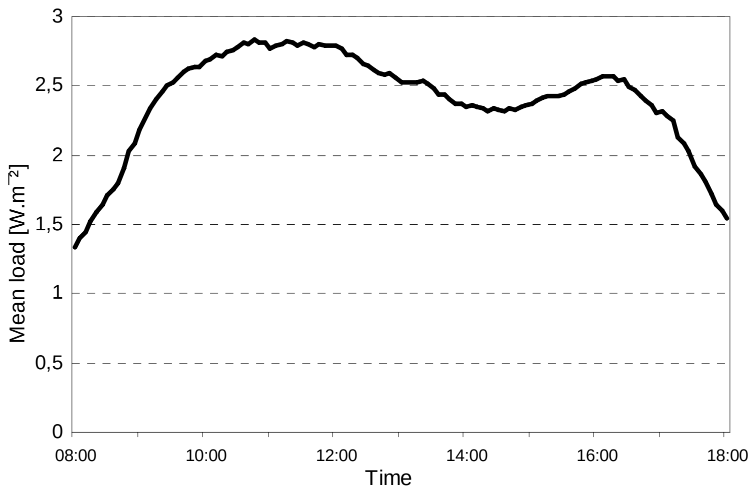


Figure 3-12 *Lighting operation in VC_NO offices*

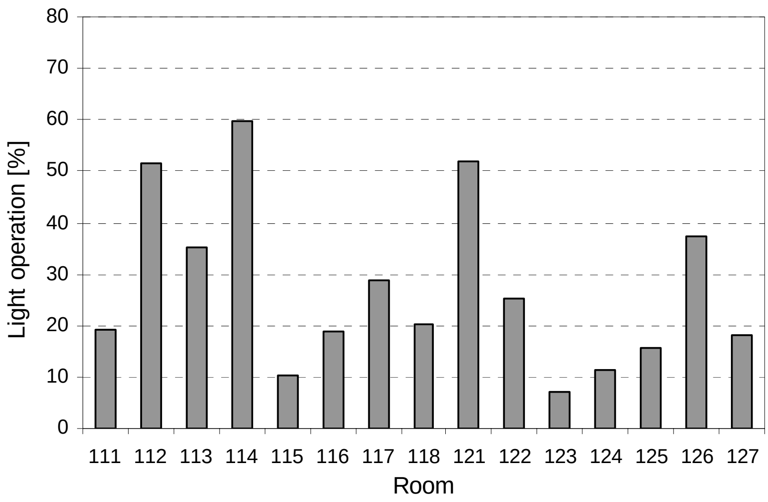


Figure 3-13 *Duration of lighting operation (in percentage of respective overall working hours) in VC_NO offices*

3.4.2.2 Switching lights on upon arrival

Figure 3-14 shows the relative frequency of switching the lights on, upon arrival in office as a function of the prevailing task illuminance level immediately before the arrival. Figure 3-15 is probability of switching the lights on upon arrival in the office as a function of the prevailing task illuminance level, immediately before the arrival.

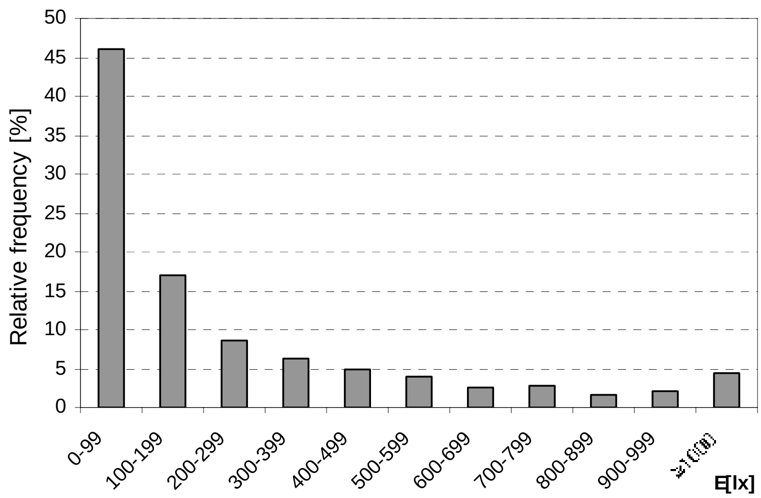


Figure 3-14 *Relative frequency of switching the lights on upon arrival in the office as a function of the prevailing task illuminance level, immediately before the arrival, in VC_NO offices*

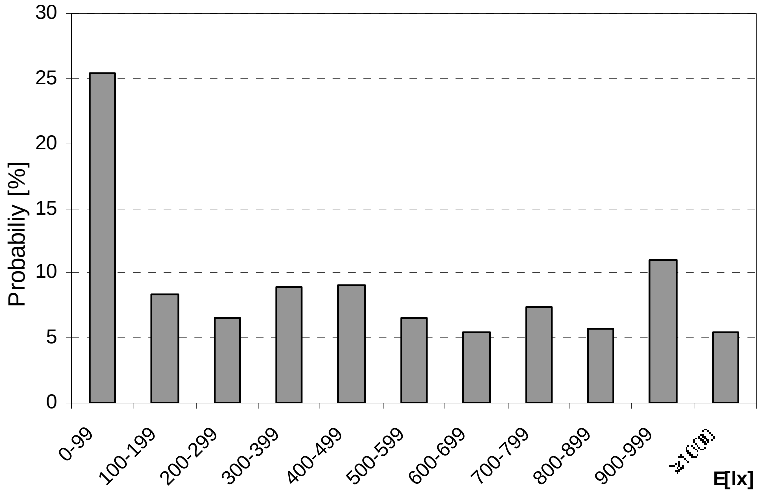


Figure 3-15 *Probability of switching the lights on upon arrival in the office as a function of the prevailing task illuminance level, immediately before the arrival, in VC_NO offices*

3.4.2.3 Switching lights on intermediate

Figure 3-16 shows the relative frequency of intermediate switching lights on as a function of the prevailing task illuminance level. Intermediate in this context means 15 minutes after arrival and 15 minutes before leaving the office. Figure 3-17 shows the normalized relative frequency of intermediate actions "switching light on" by occupants who have been in their offices for more than 15 minutes before and after the occurrence of the action as a function of the prevailing task illuminance level immediately prior to the action's occurrence. Normalization denotes in this context that the actions are related to both occupancy and the duration of the time in which the relevant illuminance ranges (bins) applied.

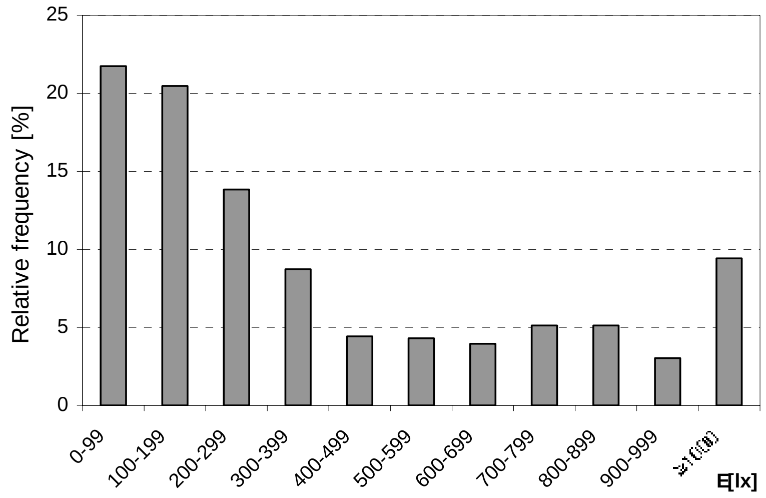


Figure 3-16 *Relative frequency of switching the lights on intermediate as a function of the prevailing task illuminance level in VC_NO offices*

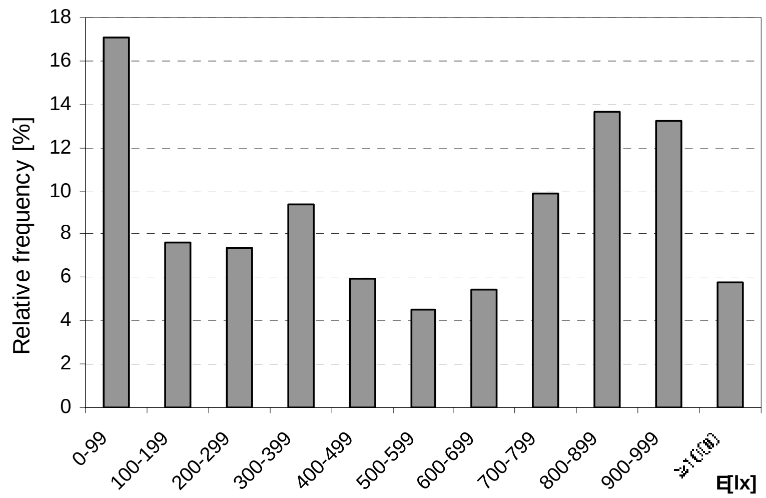


Figure 3-17 *Normalized relative frequency of intermediate light switching on actions as a function of the prevailing task illuminance level in VC_NO offices*

3.4.2.4 Switching the lights off as a function of the duration of absence from the office

Figure 3-18 shows the relative frequency of "switching light off" actions on leaving the office as a function of the time, which the occupants are away from the office. Figure 3-19 shows the probability that an occupant would switch off the lights upon leaving his/her office as a function of the time that passes before he/she returns to the office.

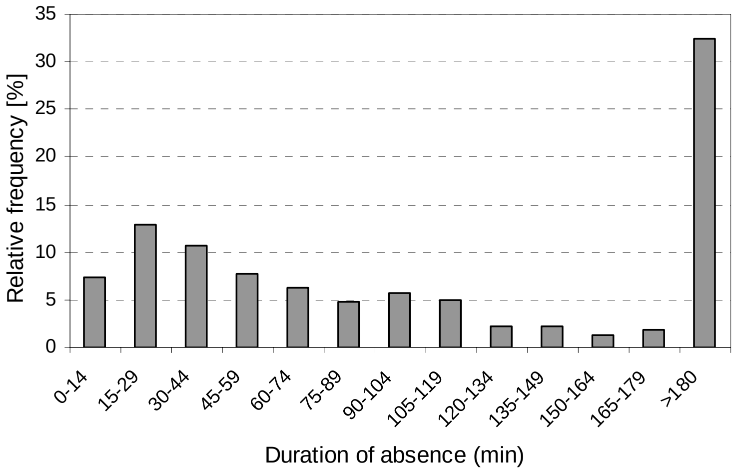


Figure 3-18 *Relative frequency of switching the lights off upon leaving the office in VC_NO offices*

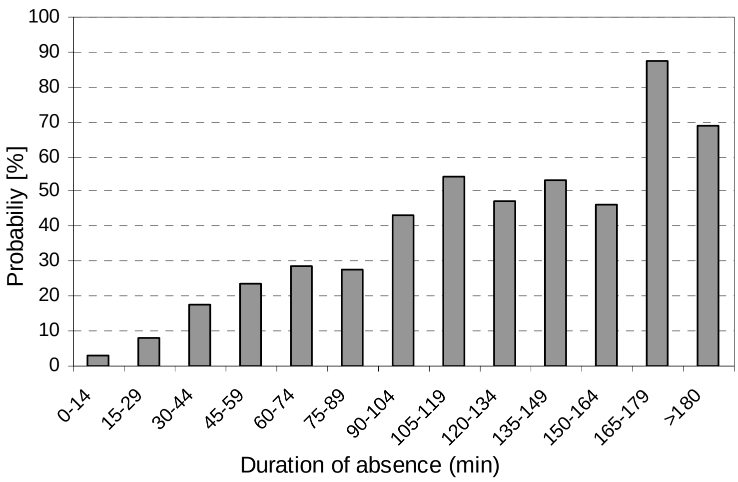


Figure 3-19 *Probability of switching the lights off as a function of the duration of absence from the offices in VC_NO*

3.4.2.5 Switching lights off intermediate

Figure 3-20 shows the 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 in this context means more than 15 minutes after arrival and 15 minutes before leaving the office. Figure 3-21 shows the normalized frequency of the (intermediate) "switching the lights off" actions as a function of the prevailing illuminance level, immediately prior to the action's occurrence. Normalization denotes in this case the consideration of occupancy and the applicable durations of the respective illuminance bins while deriving the actions' frequency.

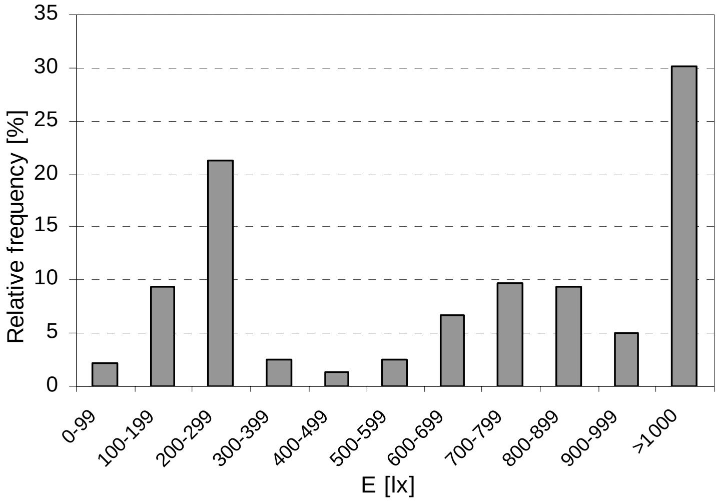


Figure 3-20 *Relative frequency of switching the lights off in VC_NO offices as a function of the prevailing illuminance level, immediately prior to the action's occurrence*

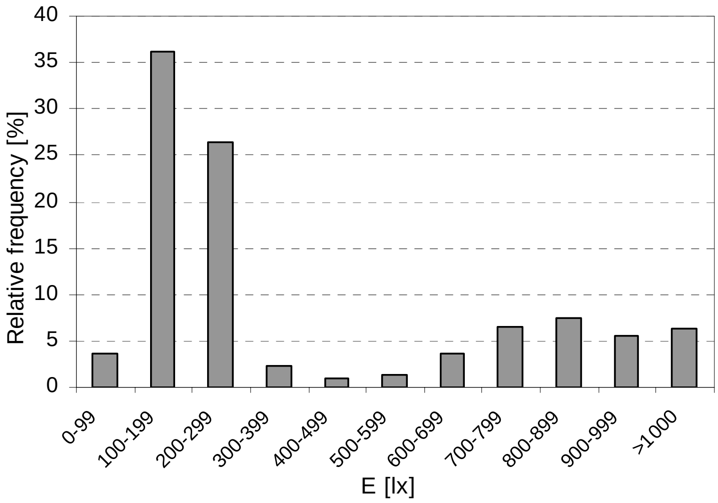


Figure 3-21 *Normalized relative frequency of switching the lights off in VC_NO offices as a function of the prevailing illuminance level, immediately prior to the action's occurrence*

3.4.3 Shading

3.4.3.1 Mean monthly shade deployment degree

Figure 3-22 represents the mean monthly shade deployment degree in VC_NO, averaged over the observed offices in year 2005.

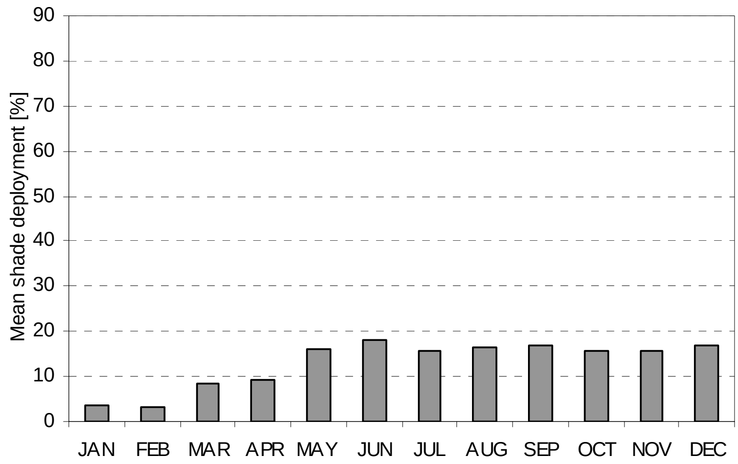


Figure 3-22 Mean monthly shade deployment degree in VC_NO averaged over the observed offices in year 2005

3.4.4 Energy consideration

3.4.4.1 Energy saving potential in light system

Figure 3-23 and Figure 3-24 illustrate the potential for reduction of electrical energy use for lighting in VC_NO. Thereby, three (cumulative) energy saving scenarios are computationally derived. The first scenario requires that the lights are automatically switched off after 10 minutes if the office is not occupied. The second scenario implies, in addition, that lights are switched off, if the daylight-based task illuminance level equals or exceeds 500 lx. Finally, the third scenario assumes furthermore an automated dimming regime, whereby luminaires are dimmed down so as to maintain a task illuminance level of 500 lx while minimizing the electrical energy use for lighting.

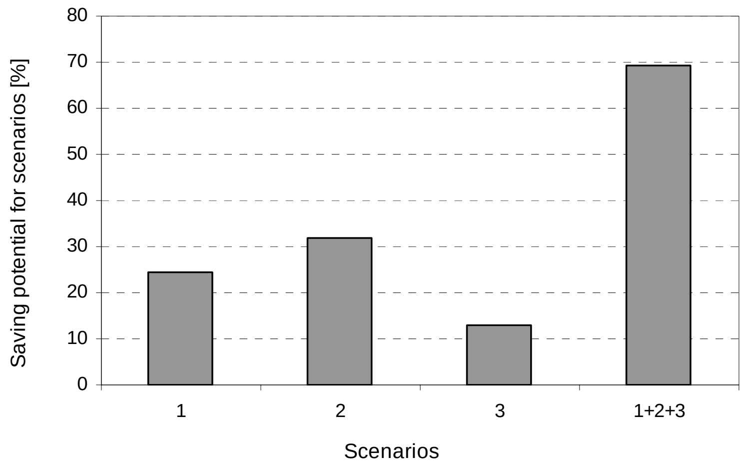


Figure 3-23 *Electricity energy saving potential of luminaires in percentage by scenarios in VC_NO offices*

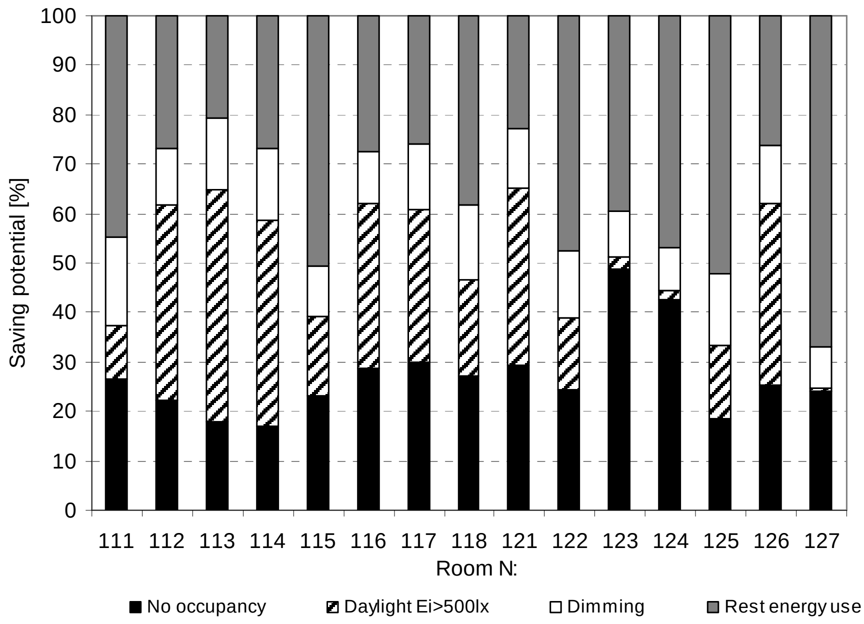


Figure 3-24 *Saving potential in electrical energy use for lighting in 15 offices in VC_NO for the 3 scenarios*

3.4.4.2 Energy saving potential for fans, heating, and cooling

To calculate energy saving potential in 'fans' (provider of heating and cooling in the offices), 'heating energy' and 'cooling energy', two separate scenarios are considered; first scenario requires that the fans are switched on automatically half an hour before the occupant arrives at the office. They are in operation during the time the occupant is present and switched off half an hour after his/her departure. The second scenario is similar, with one exception: the fans continue to operate after an occupant leaves the office, if the subsequent period of absence is not more than four hours.

Electrical energy saving potential for fans

Figure 3-25 illustrates the potential for reduction of electrical energy used in fans in VC_NO for the two scenarios. It is calculated based on presence of the occupants. Figure 3-26 shows the saving potential of electrical energy in office fans in 15 offices of VC_NO for the second scenario.

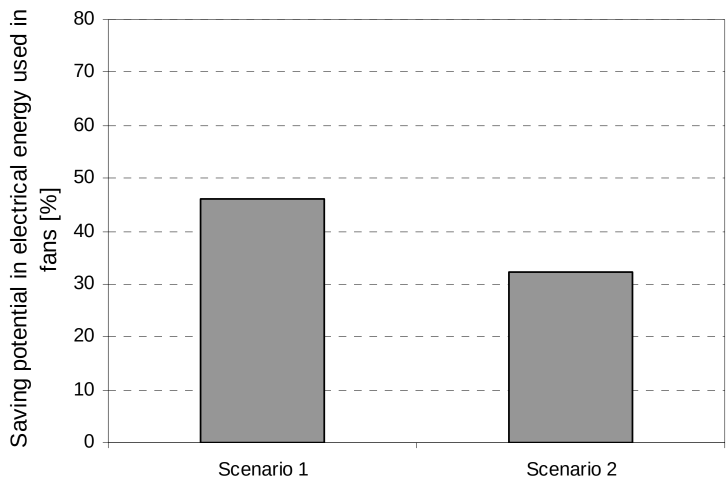


Figure 3-25 *Saving potential for electrical energy in office fans of VC_NO for the two scenarios*

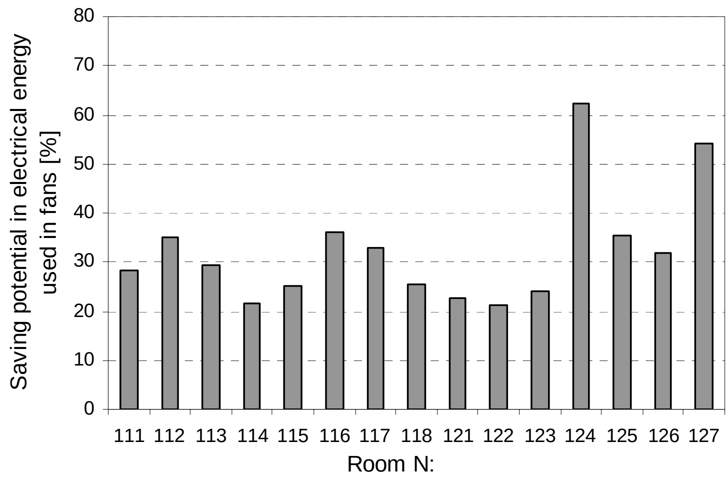


Figure 3-26 *Saving potential for electrical energy in office fans of 15 offices of VC_NO for the second scenario*

Energy saving potential for heating

Figure 3-27 illustrates saving potential in heating energy use expressed as the time (in %) when the heating system could be turned off in VC_NO for the two scenarios. Figure 3-28 shows saving potential in 15 offices of VC_NO for the second scenario.

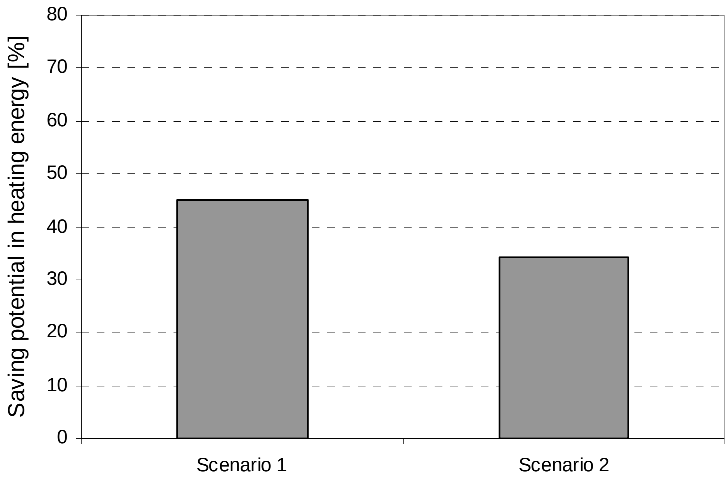


Figure 3-27 *Saving potential for heating energy in VC_NO for the two scenarios (expressed as the time –in %- when the heating system could be switched off)*

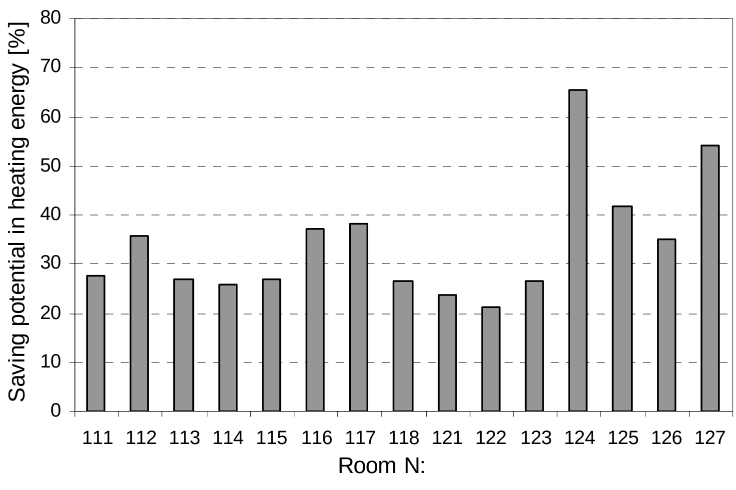


Figure 3-28 *Saving potential for heating energy in 15 offices of VC_NO for the second scenario*

<u>Energy saving potential for cooling</u>

Figure 3-29 illustrates saving potential in heating energy use expressed as the time (in %) when the heating system could be turned off in VC_NO for the two scenarios. Figure 3-30 shows saving potential in 15 offices of VC_NO for the second scenario.

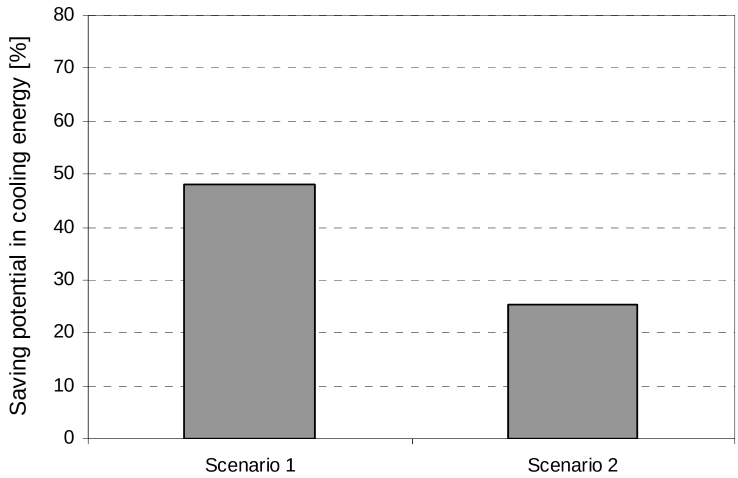


Figure 3-29 *Saving potential for cooling energy in VC_NO for the two scenarios (expressed as the time –in %- when the heating system could be switched off)*

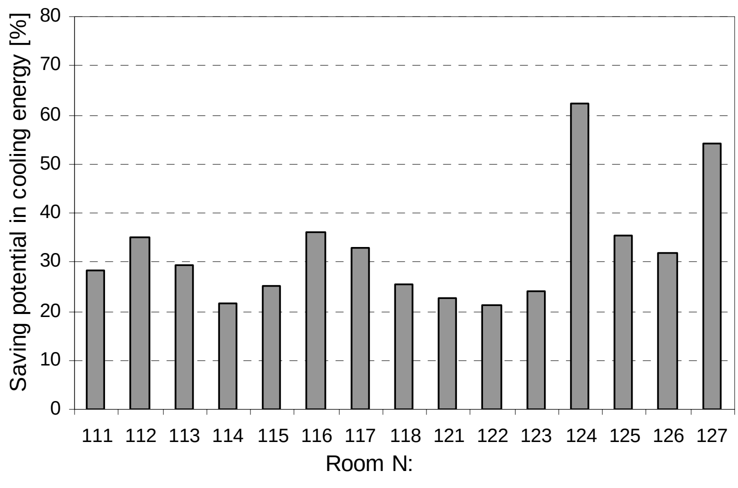


Figure 3-30 *Saving potential for cooling energy in 15 offices of VC_NO for the second scenario*

3.5 VC_SW

3.5.1 Occupancy

Figure 3-31 illustrates the mean monthly occupancy level in VC_SW, averaged over all observed offices, over the observed period (2005) in percentage. The data in this and the following occupancy figures is for working days (from 8:00 to 20:00).

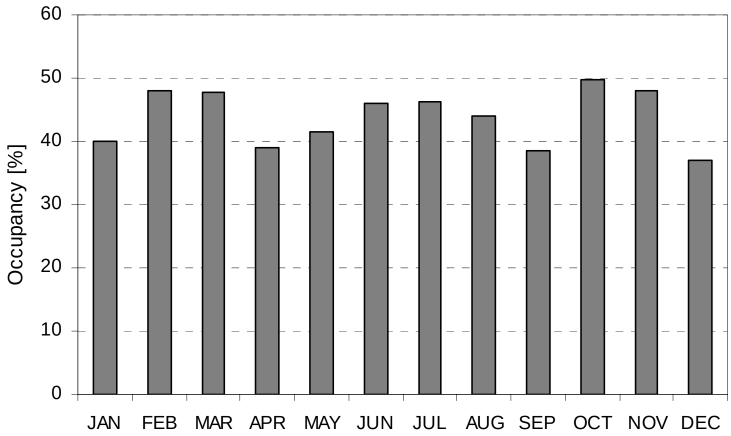


Figure 3-31 Mean monthly occupancy level in VC_SW, averaged over all observed offices

Note that mean occupancy level can vary from room to room. Figure 3-32 shows mean monthly occupancy level for rooms 212, 213, 221 and 225.

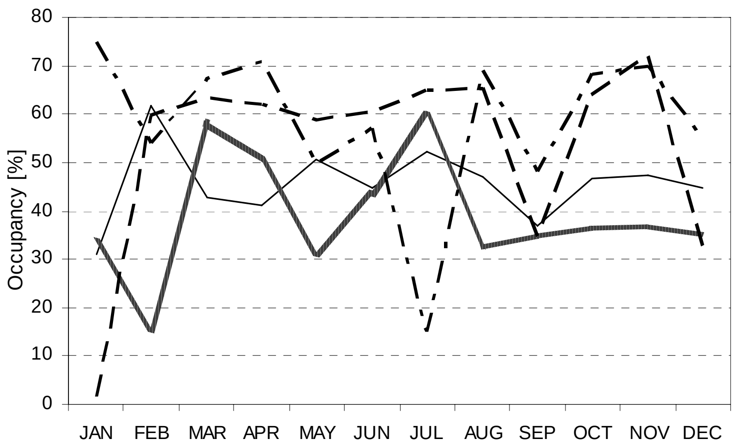


Figure 3-32 Mean monthly occupancy level in 4 offices (212, 213, 221 and 225) averaged over all observed offices of VC_SW

Figure 3-33 shows the mean occupancy level over the course of a reference day (averaged over the entire observation period). Note that this Figure represents the presence in the user's office and not the complex. Moreover, as Figure 3-34 demonstrates, the occupancy patterns in individual offices can vary considerably.

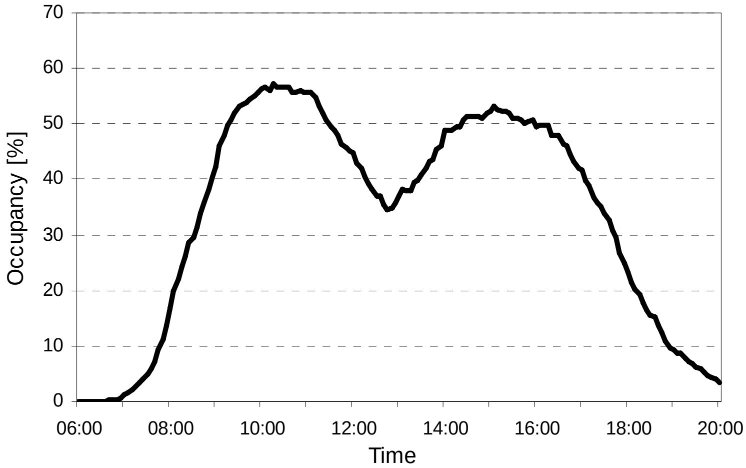


Figure 3-33 *Mean occupancy level in VC_SW over the course of a reference day, averaged over the observed offices*

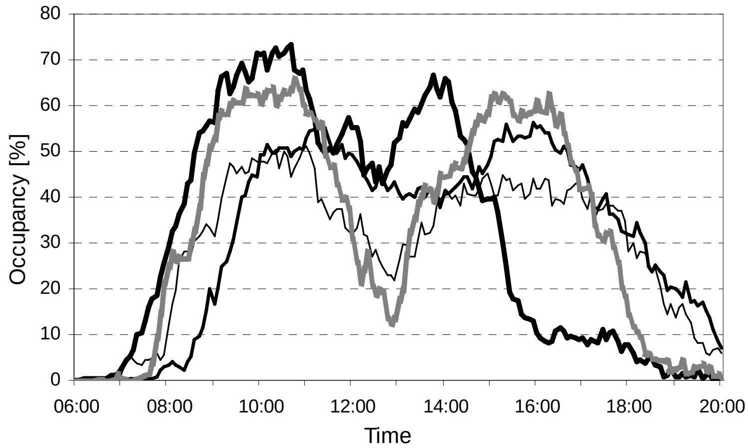


Figure 3-34 *Observed occupancy levels in 4 different offices in VC_SW over the course of a reference day*

3.5.2 Lighting

3.5.2.1 Light operation

Figure 3-35 illustrates Mean lighting electricity load over the course of a reference day averaged over the observed offices in VC_SW. Figure 3-36 shows the observed effective lighting load in the course of a reference day. Obviously, the information in this Figure is about the general light usage tendency in all observed offices. To provide an impression of the differences amongst individual light usage profiles, Figure 3-37 shows the lighting operation in each observed office for the entire monitoring period in the working hours.

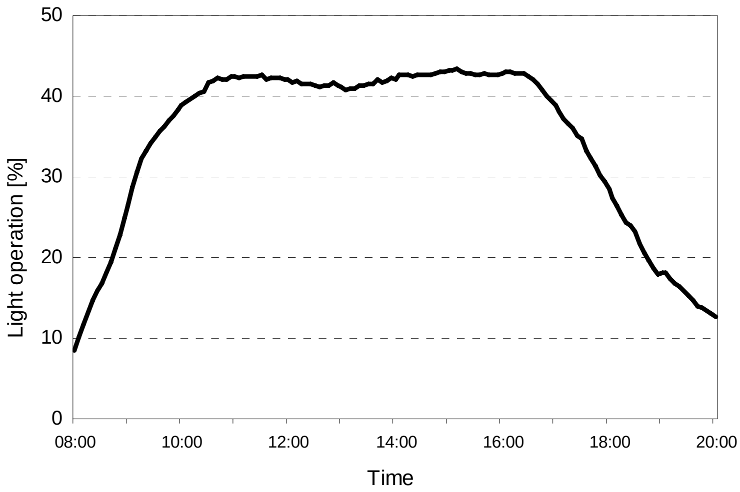


Figure 3-35 *Mean lighting electricity load over the course of a reference day averaged over the observed offices in VC_SW*

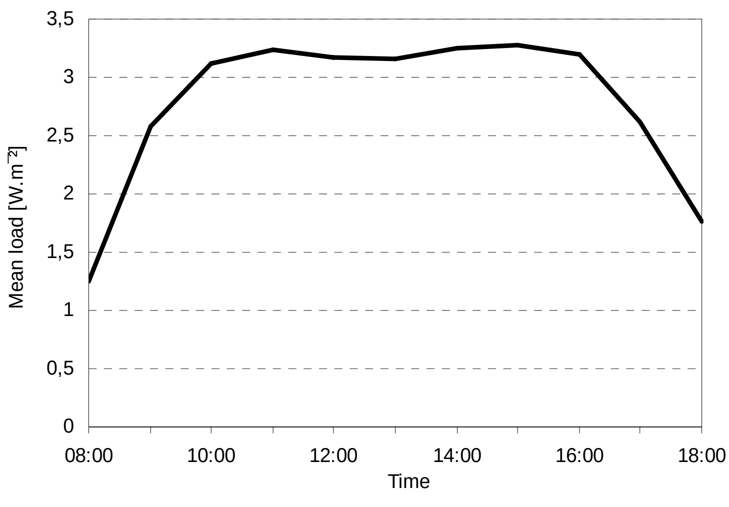


Figure 3-36 *Lighting operation in VC_SW offices*

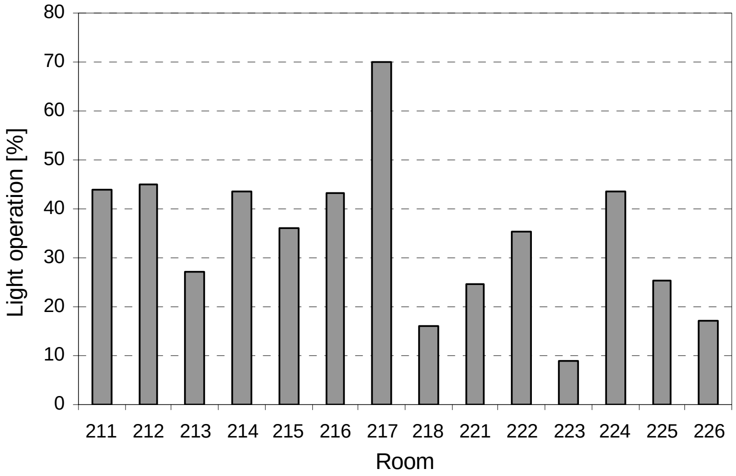


Figure 3-37 *Duration of lighting operation (in percentage of respective overall working hours) in VC_SW offices*

3.5.2.2 Switching lights on upon arrival

Figure 3-38 shows the relative frequency of switching the lights on, upon arrival in office as a function of the prevailing task illuminance level immediately before the arrival. Figure 3-39 is probability of switching the lights on upon arrival in the office as a function of the prevailing task illuminance level, immediately before the arrival.

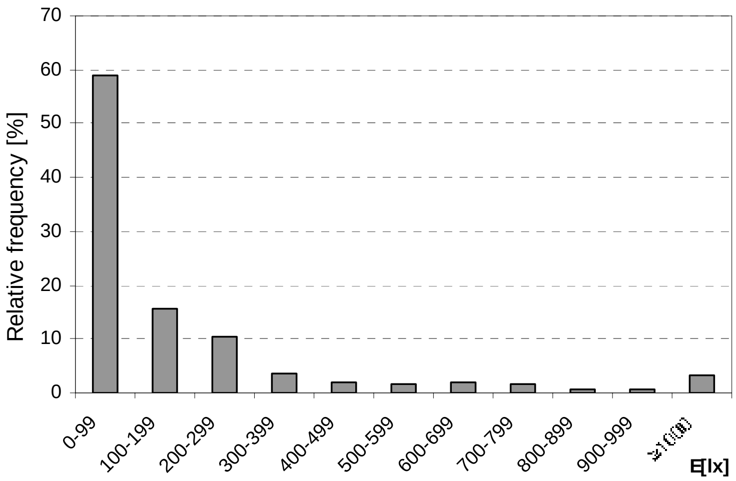


Figure 3-38 *Relative frequency of switching the lights on upon arrival in the office as a function of the prevailing task illuminance level, immediately before the arrival, in VC_SW*

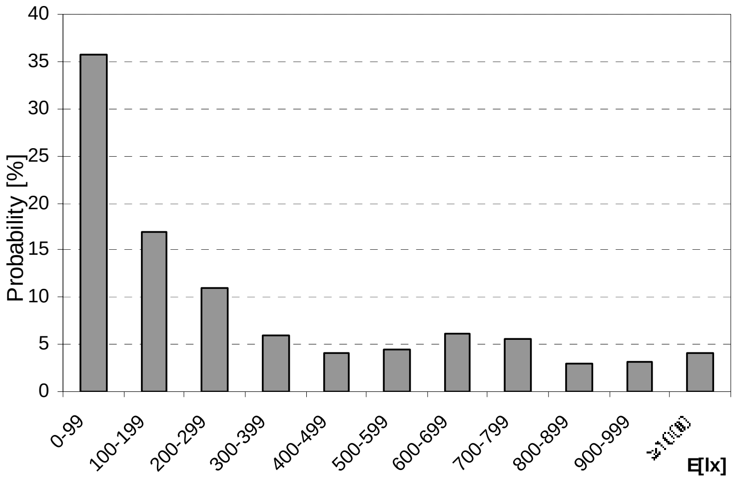


Figure 3-39 *Probability of switching the lights on upon arrival in the office as a function of the prevailing task illuminance level, immediately before the arrival, in VC_SW*

3.5.2.3 Switching lights on intermediate

Figure 3-40 shows the relative frequency of intermediate switching lights on as a function of the prevailing task illuminance level. Intermediate in this context means more than 15 minutes after arrival and 15 minutes before leaving the office. Figure 3-41 shows the normalized relative frequency of intermediate actions "switching the lights on" by occupants who have been in their offices for about 15 minutes before and after the occurrence of the action as a function of the prevailing task illuminance level immediately prior to the action's occurrence. Normalization denotes in this context that the actions are related to both occupancy and the duration of the time in which the relevant illuminance ranges (bins) applied.

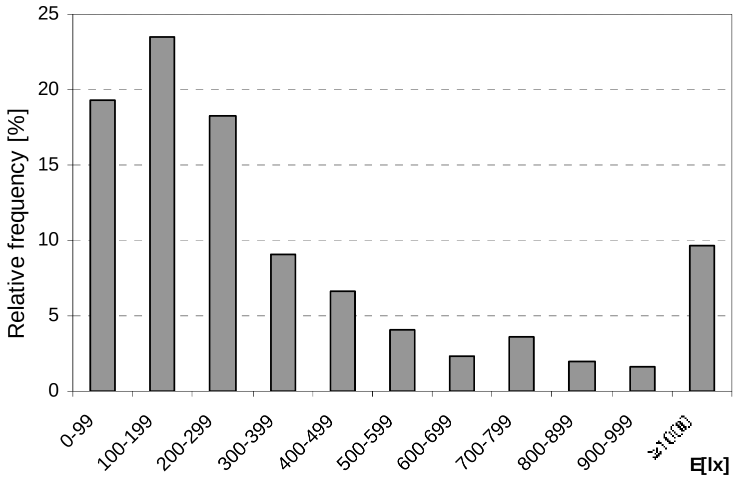


Figure 3-40 *Relative frequency of switching the lights on intermediate as a function of the prevailing task illuminance level in VC_SW*

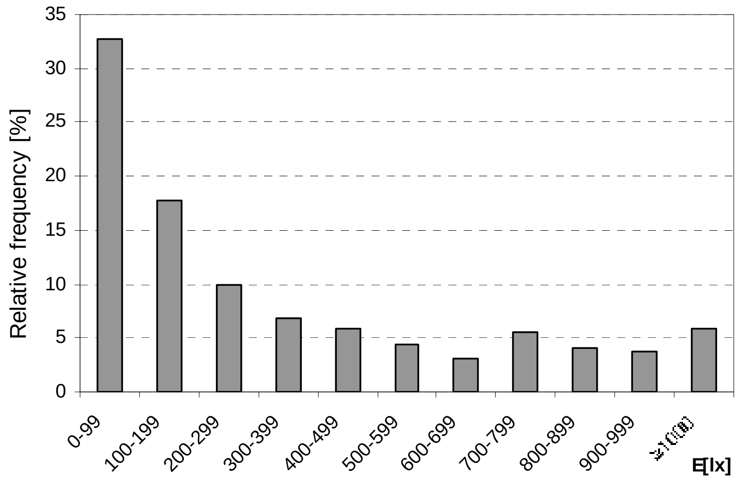


Figure 3-41 *Normalized relative frequency of intermediate light switching on actions as a function of the prevailing task illuminance level in VC_SW*

3.5.2.4 Switching the lights off as a function of the duration of absence from the office

Figure 3-42 shows the relative frequency of "switching the lights off" actions on leaving the office as a function of the time, which the occupants are away from the office. Figure 3-43 shows the probability that an occupant would switch off the lights upon leaving his/her office as a function of the time that passes before he/she returns to the office.

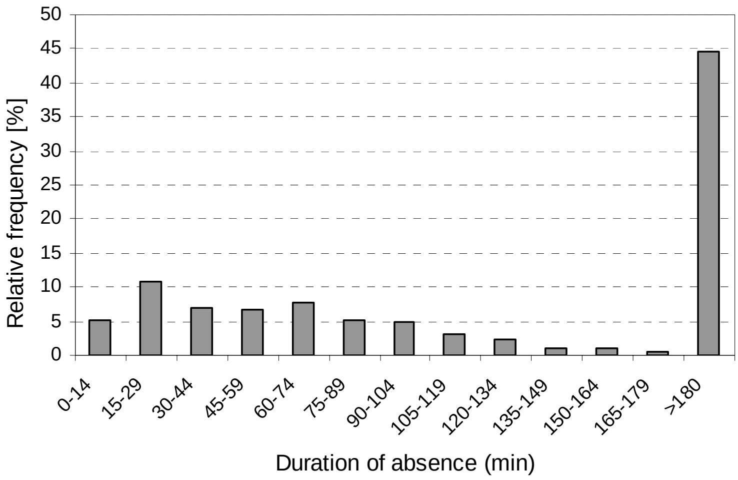


Figure 3-42 *Relative frequency of switching the lights off upon leaving the office in VC_SW*

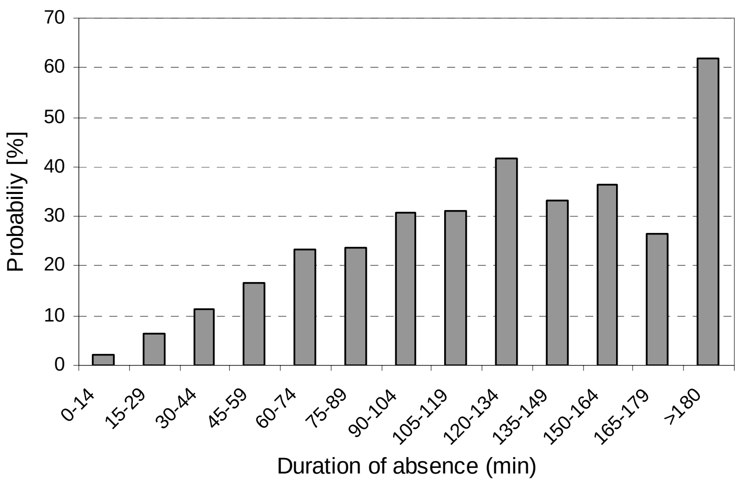


Figure 3-43 *Probability of switching the lights off as a function of the duration of absence from the offices in VC_SW*

3.5.2.5 Switching lights off intermediate

Figure 3-44 shows the 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 in this context means more than 15 minutes after arrival and 15 minutes before leaving the office. Figure 3-45 shows the normalized frequency of the (intermediate) "switching the lights off" actions as a function of the prevailing illuminance level, immediately prior to the action's occurrence. Normalization denotes in this case the consideration of occupancy and the applicable durations of the respective illuminance bins while deriving the actions' frequency.

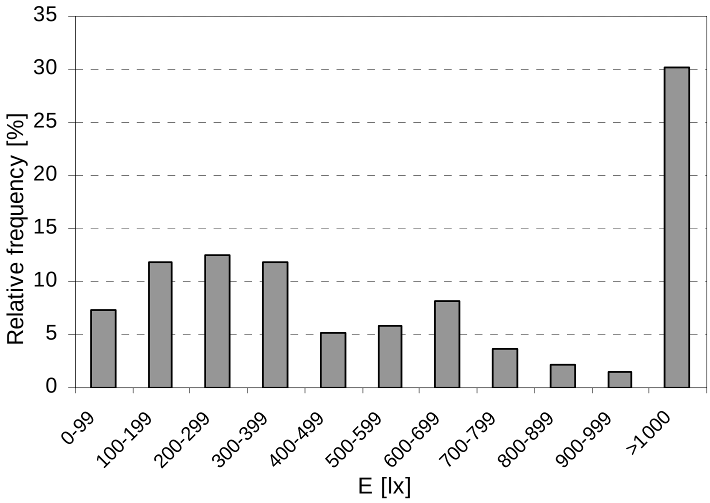


Figure 3-44 *Relative frequency of switching the lights off in VC_SW offices as a function of the prevailing illuminance level, immediately prior to the action's occurrence*

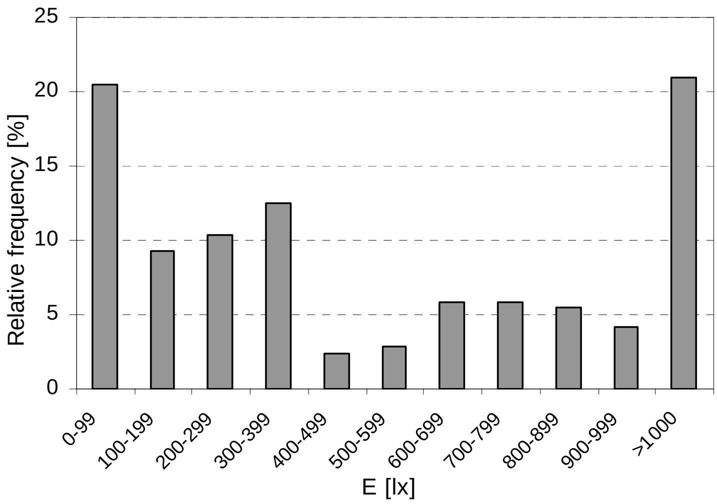


Figure 3-45 *Normalized frequency of switching the lights off in VC_SW offices as a function of the prevailing illuminance level, immediately prior to the action's occurrence*

3.5.3 Shading

3.5.3.1 Mean monthly shade deployment degree

Figure 3-46 represents the mean monthly shade deployment degree in VC_SW, averaged over the observed offices in year 2005.

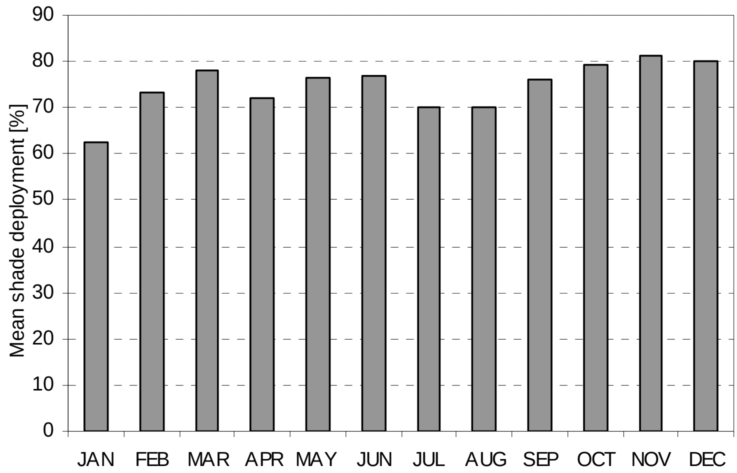


Figure 3-46 *Mean monthly shade deployment degree in VC_SW averaged over the observed offices in year 2005*

3.5.4 Energy consideration

3.5.4.1 Energy saving potential in light system

Figure 3-47 and Figure 3-48 illustrate the potential for reduction of electrical energy use for lighting in VC_SW. Thereby, three (cumulative) energy saving scenarios are computationally derived. The first scenario requires that the lights are automatically switched off after 10 minutes if the office is not occupied. The second scenario implies, in addition, that lights are switched off, if the daylight-based task illuminance level equals or exceeds 500 lx. Finally, the third scenario assumes furthermore an automated dimming regime, whereby luminaires are dimmed down so as to maintain a task illuminance level of 500 lx while minimizing the electrical energy use for lighting.

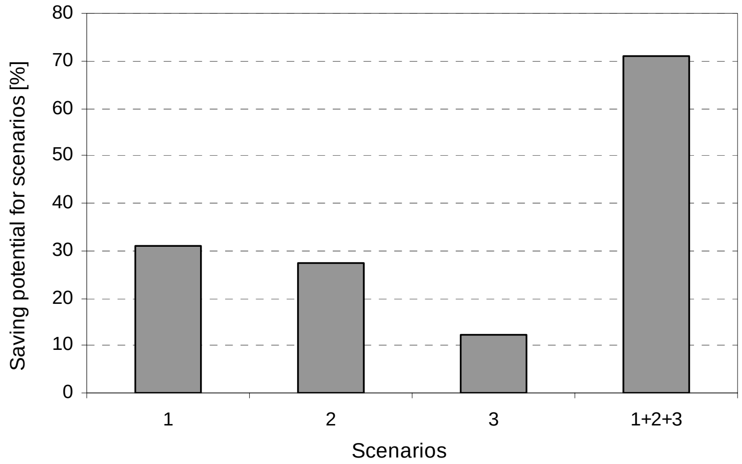


Figure 3-47 *Electricity energy saving potential of luminaires in percentage by scenarios in VC_SW offices*

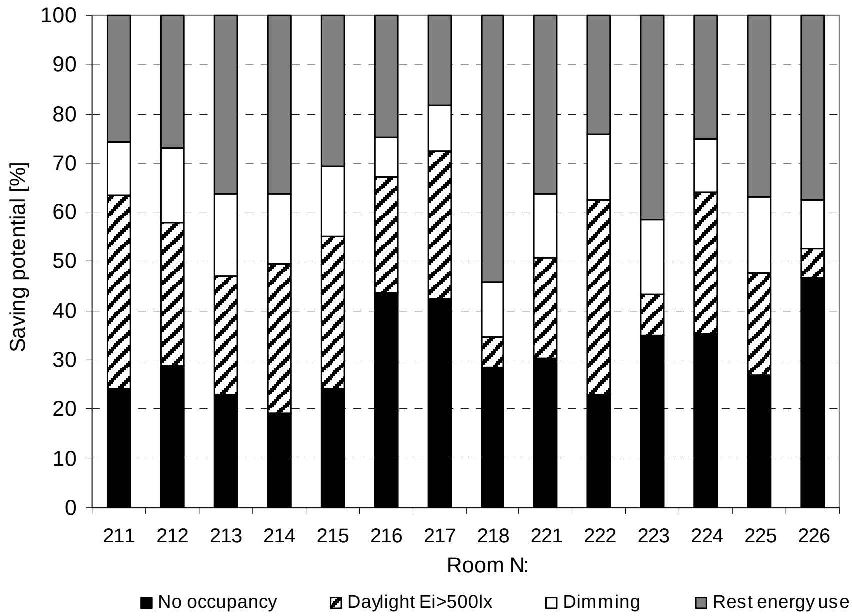


Figure 3-48 *Saving potential in electrical energy use for lighting in 14 offices of VC_SW for the 3 scenarios*

3.5.4.2 Energy saving potential for fans, heating, and cooling

To calculate energy saving potential in fans (provider of heating and cooling in the offices), heating energy and cooling energy, two separate scenarios are considered; first scenario requires that the fans are switched on automatically half an hour before the occupant arrives at the office. They are in operation during the time the occupant is present and switched off half an hour after his/her departure. The second scenario is similar, with one exception: the fans continue to operate after an occupant leaves the office, if the subsequent period of absence is not more than four hours.

Electrical energy saving potential for fans

Figure 3-49 illustrates the potential for reduction of electrical energy used in fans in VC_SW for the two scenarios. It is calculated based on presence of the occupants. Figure 3-50 shows the saving potential of electrical energy in office fans in 14 offices of VC_SW for the second scenario.

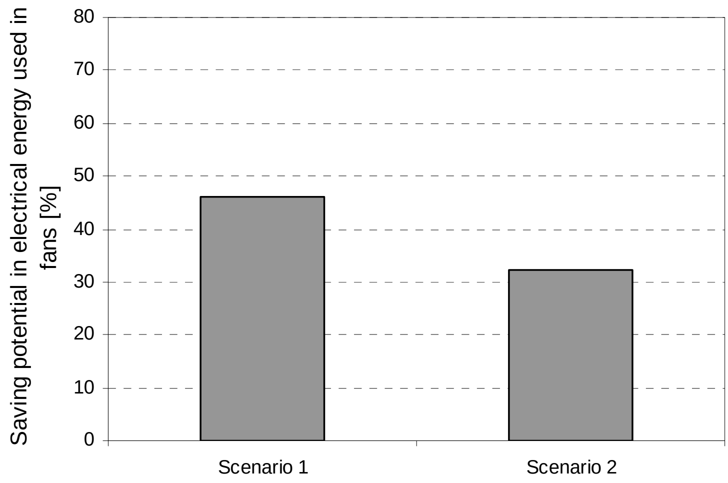


Figure 3-49 Saving potential percentages for electrical energy in office fans of VC_SW for the two scenarios

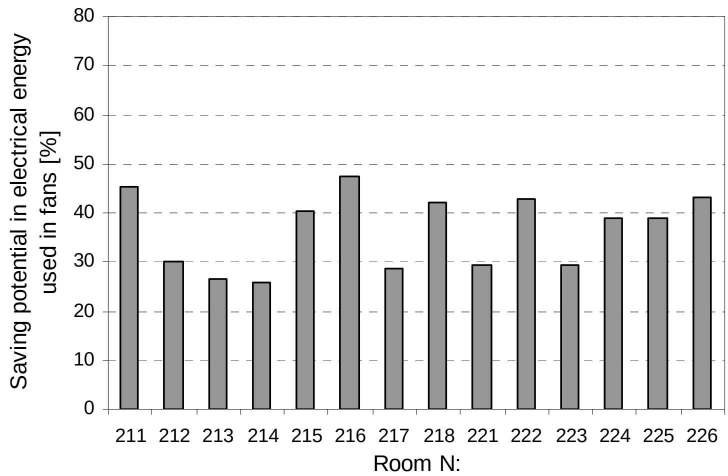


Figure 3-50 Saving potential percentages for electrical energy in office fans of 14 offices of VC_SW for the second scenario

Energy saving potential for heating

Figure 3-51 illustrates saving potential in heating energy use expressed as the time (in %) when the heating system could be turned off in VC_SW for the two scenarios. Figure 3-52 shows saving potential in 14 offices of VC_SW for the second scenario.

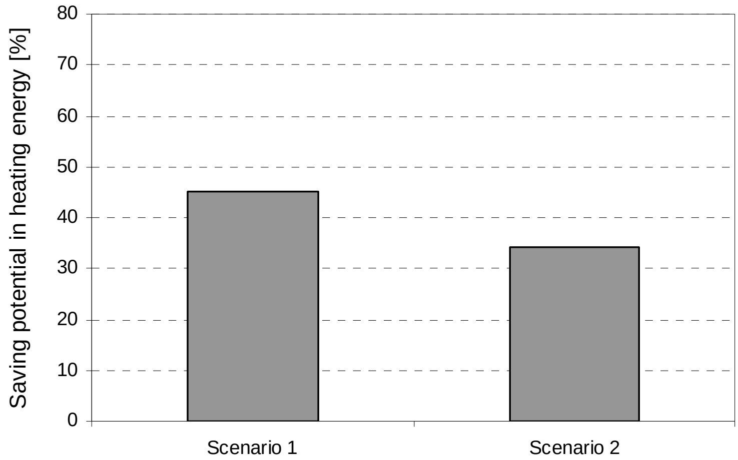


Figure 3-51 *Saving potential for heating energy in VC_SW for the two scenarios (expressed as the time –in %- when the heating system could be switched off)*

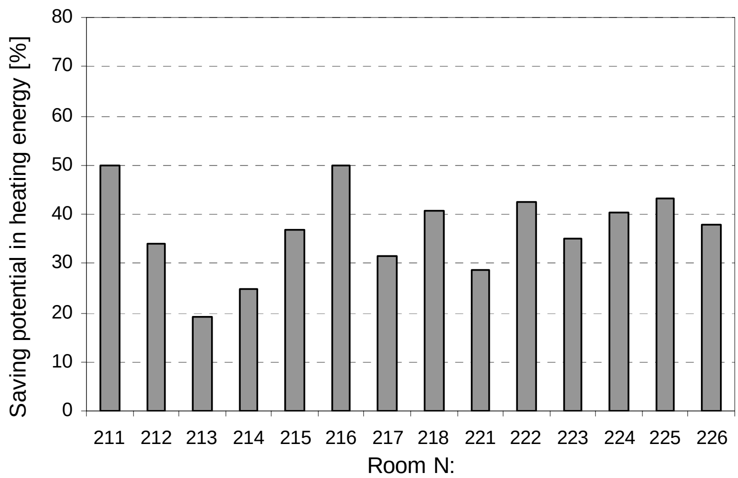


Figure 3-52 *Saving potential for heating energy in 14 offices of VC_SW for the second scenario*

Energy saving potential for cooling

Figure 3-53 illustrates saving potential in heating energy use expressed as the time (in %) when the heating system could be turned off in VC_SW for the two scenarios. Figure 3-54 shows saving potential in 14 offices of VC_SW for the second scenario.

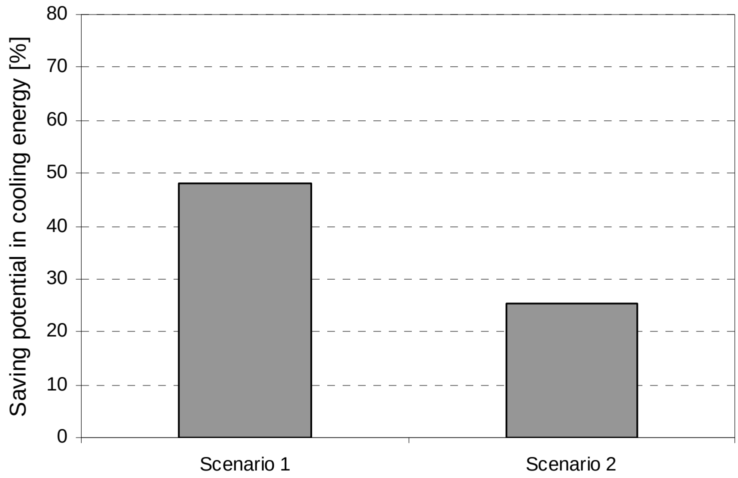


Figure 3-53 *Saving potential for cooling energy in VC_SW for the two scenarios (expressed as the time –in %- when the heating system could be switched off)*

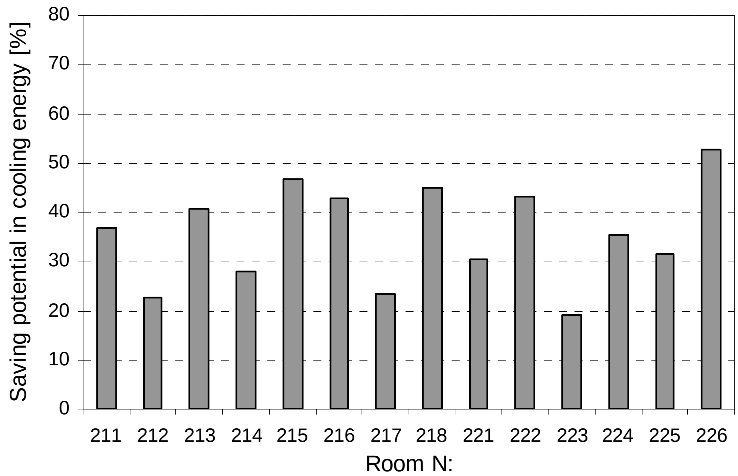


Figure 3-54 *Saving potential for cooling energy in 14 offices of VC_SW for the second scenario*

4 Discussion

4.1 Interviews

Figure 3-1 shows that 35 percent of the occupants found the air quality of the offices bad and very bad and the same percent were not satisfied with the possibility of ventilation in the rooms, however, the fan devices work nonstop along the working period time. The fact that the windows are not operable looks to play an important roll in the feeling because most of the answers settled this fact as reason.

33 percent of the answers stated that the room is warm in winter and 45 percent stated that the room is warm in summer (see Figure 3-2). Our observation did not show a frequently use of the thermostats, therefore the high temperature in winter can be explained by that. The level of the floors (12^{th} and 13^{th} floors) and possibility of receiving direct sunlight especially in direction of southwest and lake of external shades and the operation quality of the shades can be other reasons for the high temperature and being annoyed by direct sunlight (see Figure 3-3). The observation of mean monthly shade deployment in VC_NO and VC_SW shows a high difference of about 65% that can be explained by presence of direct sunlight in south-west direction and trouble in operating the shades.

4.2 Energy consumption data

The fact that energy cost is about 30 percent of the maintenance and operation costs of the complex is a good reason to find and study other costs of the complex. However, energy issues are environmentally very important.

Table 3-2 and Figure 3-5 show that only a small percentage of energy cost corresponds lighting in the offices and office devices, where as many concerns from facility managers and research groups go to reducing that and not to other means of energy consumption.

Table 3-4 and Figure 3-6 show that cooling energy has an important roll in energy costs and it is almost as much as heating energy cost. It is because producing unit cooling energy is three times more expensive as for heating energy. Considering the location of the complex (Vienna, Austria) which has a long winter and a very short summer, makes the point very important for the building system designers and the architects.

4.3 Behavior

4.3.1 Occupancy

Figure 4-1 that is comparison between occupancy levels in the two cases does not show a major difference between the two directions (north and south-west) in case of presence periods. Figure 4-2 shows mean occupancy level over the course of a reference day average in all observed offices (VC_NO+VC_SW).

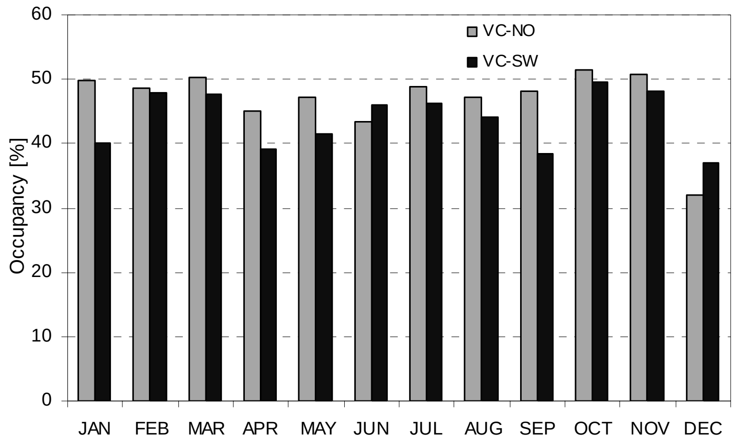


Figure 4-1 *Mean monthly occupancy level in VC_NO and VC_SW, averaged over all observed offices*

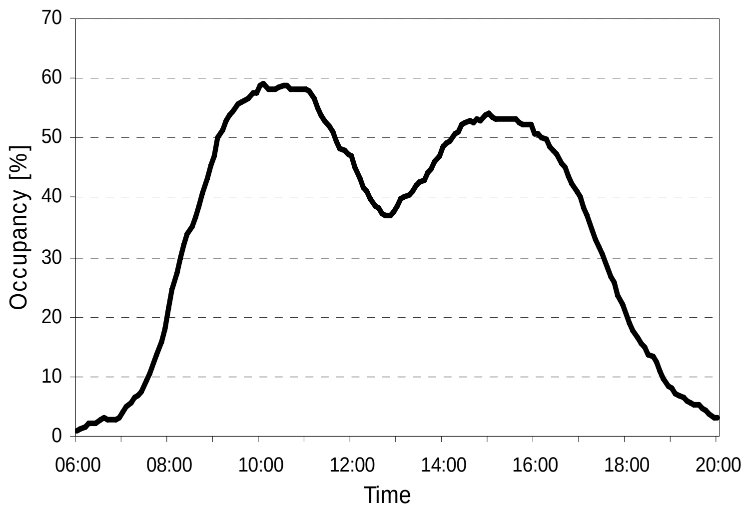


Figure 4-2 *Mean occupancy level in VC_NO+VC_SW over the course of a reference day, averaged over all observed offices*

The monitored occupancy in VC_NO+VC_SW (Figure 4-2) and the obviously related people and lighting loads (Figure 4-5) reveal a pattern similar to that of many other office buildings and as such can be used for simulation runs in terms of corresponding hourly schedules (Figure 4-3, Figure 4-4 and Figure 4-7). Such simulations can be used, for example, to explore the impact of thermal improvement measures on the building's energy use (Mohammadi 2007). The maximum occupancy level is comparatively low. Moreover, the differences in both occupancy levels (Figure 3-7, Figure 3-9, Figure 3-31 and Figure 3-33) and lighting operation (Figure 3-6 and 3-29) in various offices of VC_NO and VC_SW suggest the possibility of a more realistic simulation scenario using software agents to represent occupancy states in different offices in probabilistic terms. On a more general view, the observations regarding this building suggest that the environmental systems in a considerable number of office buildings may be "over-designed", in a sense that they are designed for occupancy levels that seldom occur.

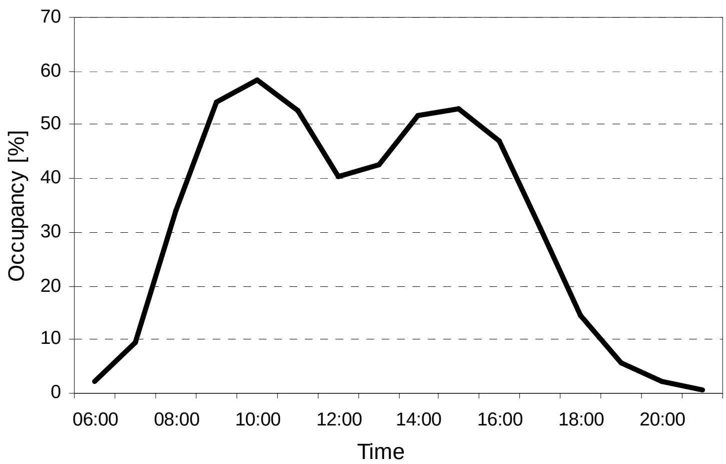


Figure 4-3 *Illustrative simulation input data regarding mean hourly occupancy level for VC_NO+VC_SW*

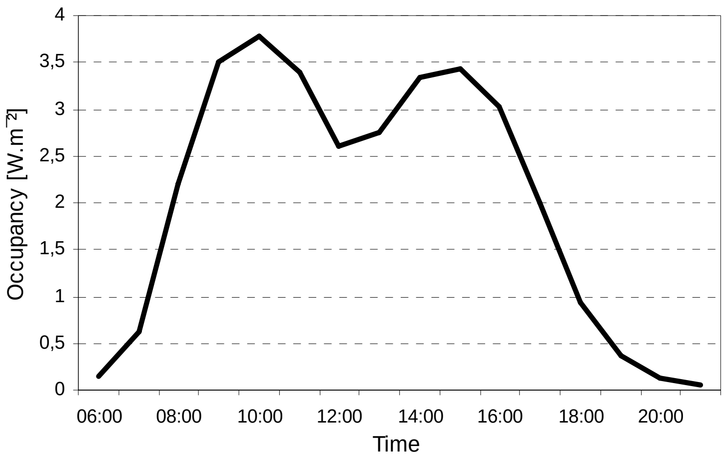


Figure 4-4 *Illustrative simulation input data regarding mean hourly people (sensible) load for VC_NO+VC_SW*

4.3.2 Lighting

Figure 4-5 illustrates the percentage of lighting operation over the course of a reference day in VC_NO and VC_SW respectively. Figure 4-6 shows the intensity of light operation in the two cases. Figure 4-7 and Figure 4-8 represent Illustrative simulation input data regarding mean hourly lighting load in VC_NO and VC_SW. Figure 4-9 shows a comparison between light operation percentage between VC_NO and VC_SW, the increased percentage of light use can be explained by state of shades; mean monthly shade deployment degree in VC_SW which has a South-west direction is about 65% more than VC_NO which has a North direction (see Figure 4-15).

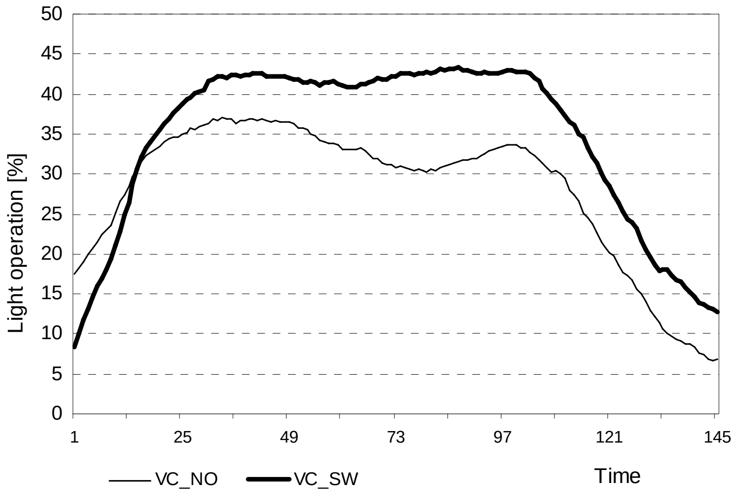


Figure 4-5 *Light operation level in VC_NO and VC_SW*

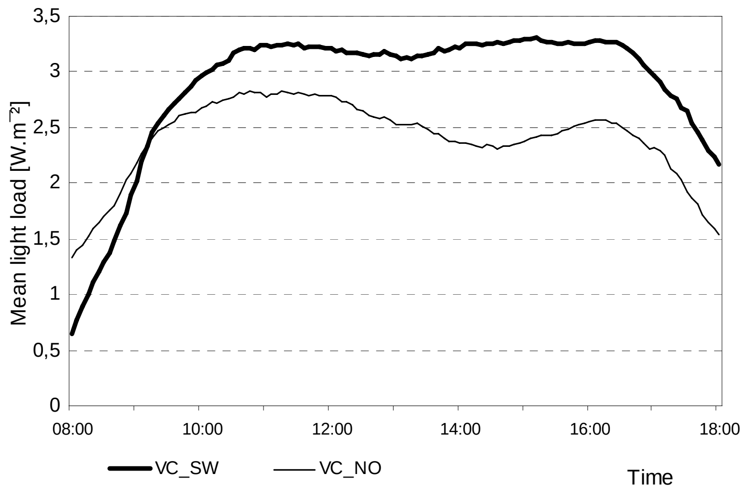


Figure 4-6 *Lighting operation load in VC_NO and VC_SW offices*

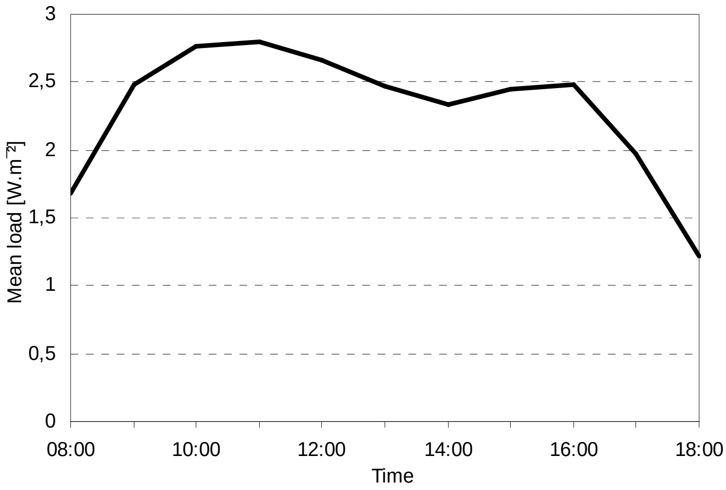


Figure 4-7 *Illustrative simulation input data regarding mean hourly lighting load in VC_NO*

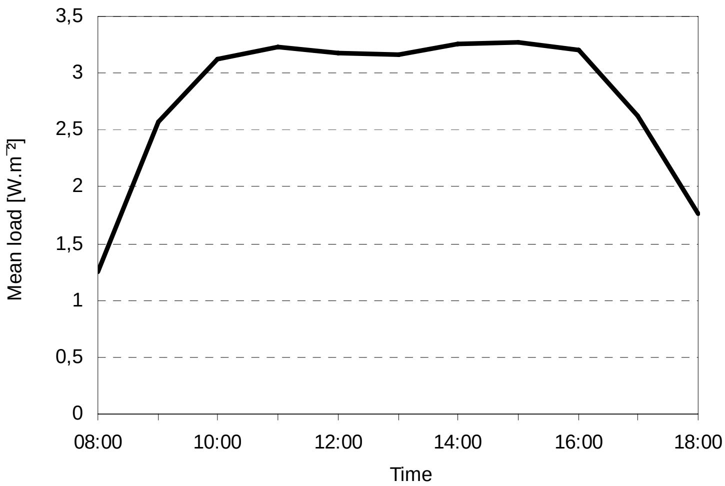


Figure 4-8 *Illustrative simulation input data regarding mean hourly lighting load in VC_SW*

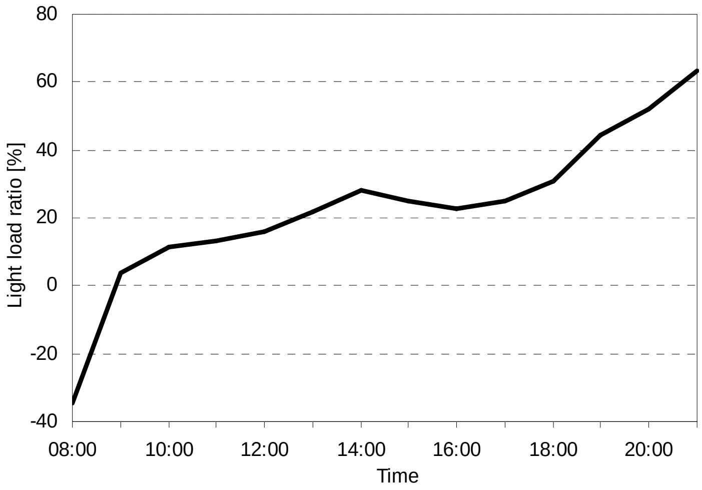


Figure 4-9 *Comparison of mean hourly lighting loads in VC_SW to VC_NO*

Concerning the dependency of the action "switching on the lights" on prevailing illuminance levels, the clear patterns suggest that only illuminance levels below 100 lx are likely to trigger actions at a non-random rate (see Figure 4-10).

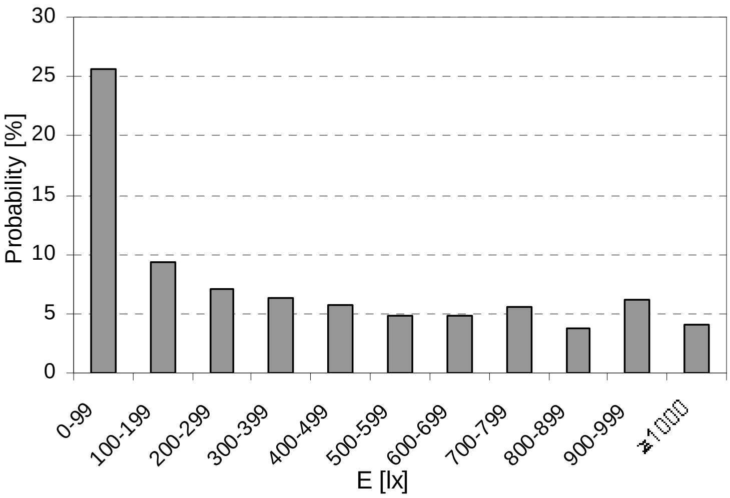


Figure 4-10 *Probability of switching the lights on upon arrival in the office as a function of the prevailing task illuminance level immediately before the arrival in VC_NO and VC_SW offices*

Figure 4-11 shows normalized number of “switching light on” actions upon arrival in VC_NO and VC_SW respectively. The graph does not show a major difference between the two cases. Figure 4-12 represents normalized relative frequency of intermediate light switching on actions in VC_NO+VC_SW. Like Figure 4-10 (Probability of switching the lights on upon arrival in the office as a function of the prevailing task illuminance level immediately before the arrival in VC_NO and VC_SW offices) it suggests that only illuminance less than 100 lx are likely to trigger the switching on actions at a non random rate.

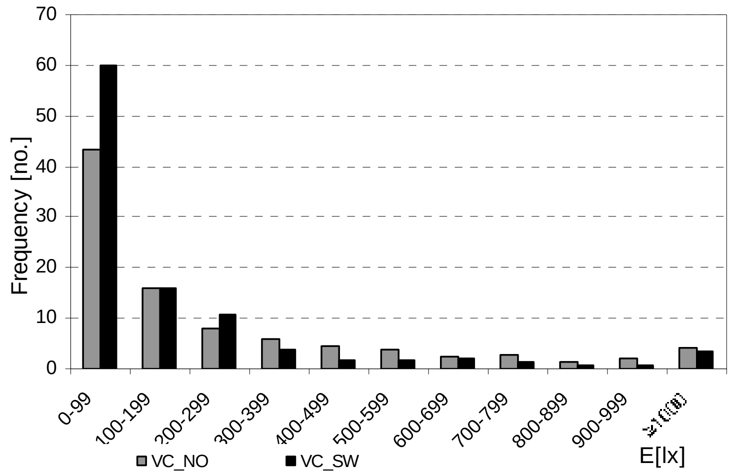


Figure 4-11 *Frequency number of actions "switching the lights on" per office upon arrival in VC_NO and VC_SW offices*

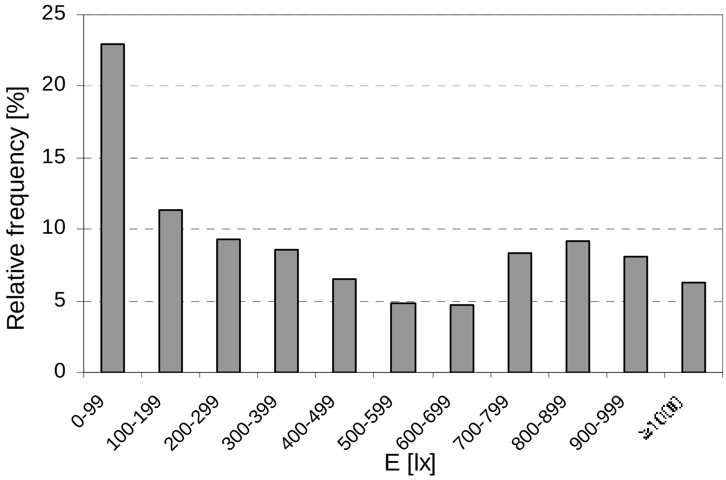


Figure 4-12 *Normalized relative frequency of intermediate light switching on actions in VC_NO+VC_SW*

Figure 4-13 shows normalized number of “switching light on” intermediate actions in VC_NO and VC_SW offices. The number of actions in this case does not show a major difference between the two cases.

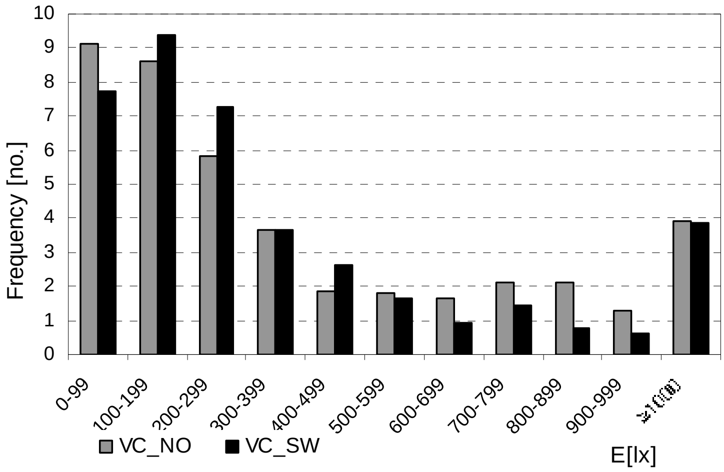


Figure 4-13 *Frequency number of actions “intermediate switching the lights on” in VC_NO and VC_SW offices*

As to the action "switching the lights off", a clear relationship to the subsequent duration of absence is evident (Figure 4-14). Moreover comparing graphs of the two facades in this case shows a very similar pattern for VC_NO and VC_SW (Figure 3-19 and Figure 3-43). However switching the lights off as a function of the prevailing illuminance level in the two cases does not show a clear pattern (Figure 3-21 and Figure 3-45).

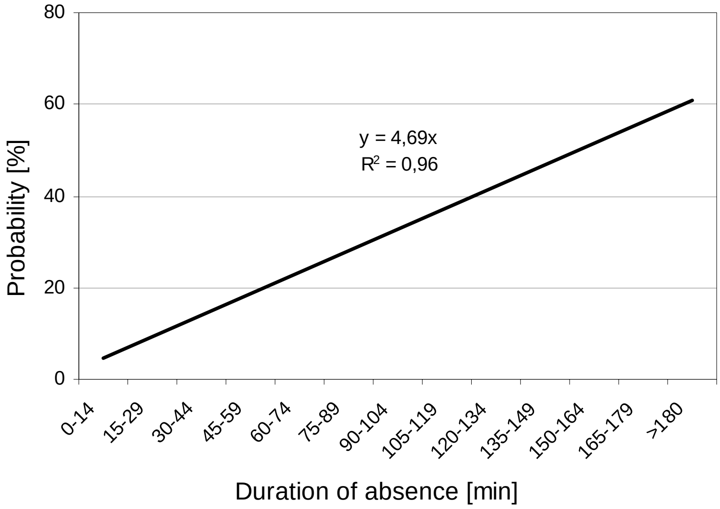


Figure 4-14 *Probability of switching the lights off as a function of the duration of absence from the offices in VC_NO+VC_SW*

The mean monthly shade deployment for each facade, clearly related to the orientation of the observed offices (VC_NO to north and VC_SW to south-west). This explains the higher deployment level of about 65 percent for VC_SW in comparison to VC_NO (Figure 4-15).

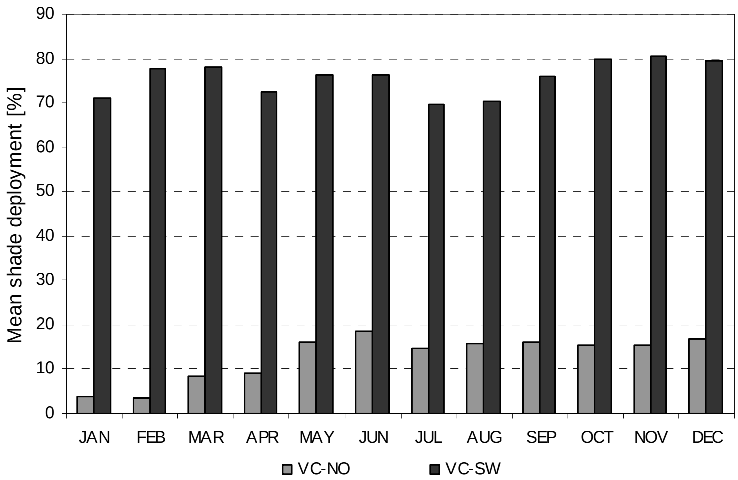


Figure 4-15 *Mean monthly shade deployment degree in VC_NO and VC_SW*

4.4 Building performance simulation

4.4.1 Energy plus

Energy Plus was used to simulate annual energy consumption and energy saving potential (see Figure 4-16). The input data used to set the program is given in appendix 7.4 “Input for Energy plus”.

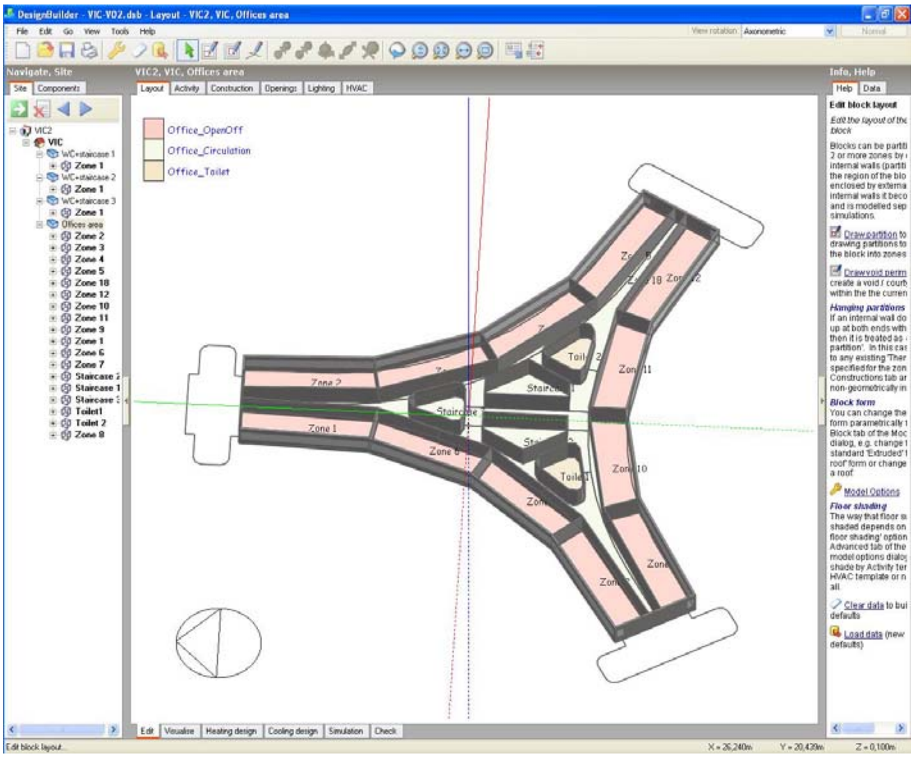


Figure 4-16 Energy plus interface (Design builder)

Table 4-1 and Table 4-2 show the heating and cooling design capacity simulated by Energy Plus.

Table 4-1 Heating energy demand and heating design capacity simulation of floor 12th in the coldest day of year 2005 by Energy plus

Block	Steady-State Heat Loss (kW)	Design Capacity (kW)
Floor 12	303	363

Table 4-2 Cooling energy demand and Cooling design capacity simulation of floor 12th in the warmest day of year 2005 by Energy plus

Block	Steady-State Heat gain (kW)	Design Capacity (kW)
Floor 12	161	210

Summary of annual heating and cooling energy demand simulated by the program is in the

Table 7-8.

Table 4-3 Annual energy demand in 12th floor and in all offices simulated by Energy plus

	Heating (MWh)	Cooling (MWh)
Annual energy demand in 12th floor	188	47
Annual energy demand in all offices of the complex	10,902	2,726

4.5 Energy impact

4.5.1 Energy saving potential in luminaires

The percentage of saving potential in electrical energy use for lighting of the sampled offices is significant (Figure 3-24 and Figure 3-25, Figure 3-48 and Figure 3-49). To estimate the saving potential in electrical energy use for office lighting, three (cumulative) energy saving scenarios were considered: i) lights are automatically switched off after 10 minutes if the office is not occupied; ii) lights are switched off, if the daylight-based task illuminance level equals or exceeds 500 lx; iii) an automated dimming regime is applied, whereby luminaires are dimmed down so as to maintain a task illuminance level of 500 lx while minimizing the electrical energy use for lighting.

The overall cumulative energy saving potential for all sampled offices is 70% for VC_NO+VC_SW (Figure 4-17). This would imply, that in the VC complex, annually roughly 127,000 € could be saved by a comprehensive retrofit of the office lighting system toward dynamic consideration of occupancy patterns and daylight availability. (Note that a lighting system retrofit and the resulting electrical energy use reduction would increase the heating loads and decrease the cooling loads. Previous studies have shown that, given the magnitude of required cooling loads in office buildings, the overall thermal implications of a lighting retrofit are positive both in energetic and monetary terms. (Mohammadi 2006a))

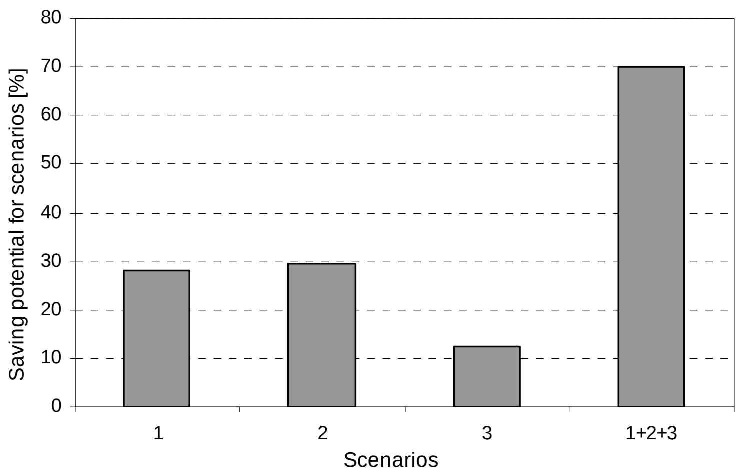


Figure 4-17 Electricity energy saving potential of luminaires in percentage by the scenarios in VC_NO+VC_SW offices

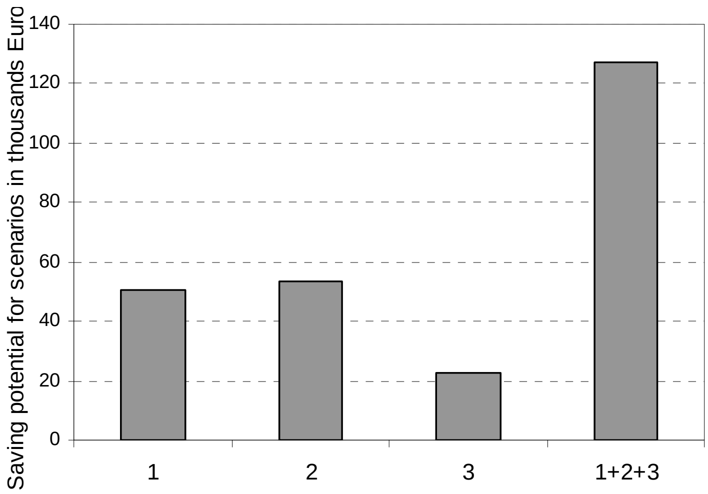


Figure 4-18 *Electricity energy saving potential of luminaires in thousand Euros by the scenarios in VC_NO+VC_SW offices*

Table 4-4 *Saving potential (electrical energy for lighting) for the scenarios*

		Energy saving scenarios			
Building	Saving potential in	1	2	3	1+2+3
VC_ NO + VC_SW	%	28	30	13	71
	$kWh.m^{-2}. a^{-1}$	6.8	7.2	3.0	17.0
	$€.m^{-2}. a^{-1}$	0.53	0.56	0.24	1.32

Figure 4-18 shows the saving potential percentage of operation time in fans, heating and cooling system by considering occupancy and the second scenario mentioned in sections 3.4.4.2 and 3.5.4.2.

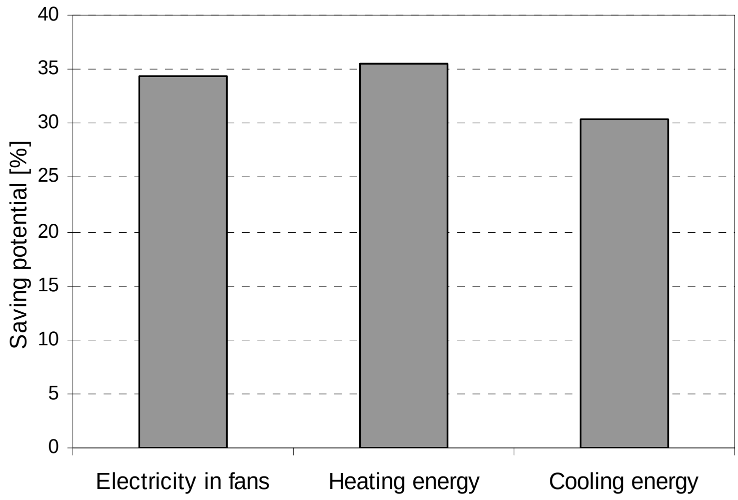


Figure 4-19 *Saving potential percentages of electrical energy in terms of operation time in office fans, heating energy and cooling energy in VC_NO+VC_SW for the second scenario*

Based on the observation of occupancy for both cases, a simulation program (Energy plus) used to estimate energy saving potential. It was assumed that 33% of the offices are not occupied, however the temperature in the these offices is not allowed to go under 16º and above 30º, so that half an hour working of fans before the user comes to the office can provide fresh air and desirable temperature. Table 4-5 shows energy use of the floor 12 when all devices are working, energy use with the mentioned condition and percentage of heating and cooling energy saving potential.

Table 4-5 *Energy use of the floor 12 when all devices are working, energy use with the mentioned condition and percentage of heating and cooling energy saving potential*

VC_NO+VC_SW	Heating (kWh)	Cooling (kWh)
Full floor energy use	187963.9	46990.88
One-third of offices off	156204.2	37701.95
Energy saving potential	20.33 %	24.64 %

Based on above information and the real energy consumption, Figure 4-20 shows the amount of saving potential of electrical energy for fans, heating and cooling in the offices of the complex.

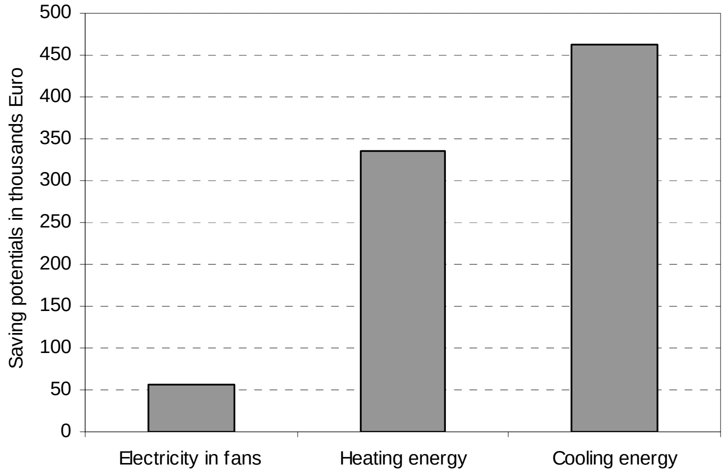


Figure 4-20 *Estimated value amount of saving potential for electrical energy used in fans, Heating energy and cooling energy of office devices for the whole VC_NO+VC_SW For the second scenario*

5 Conclusion

The work presented an empirical study on user control actions in an office complex in Vienna, Austria. The results imply the possibility of identifying general patterns of user control behavior as a function of indoor and outdoor environmental parameters such as illuminance and irradiance. The compound results of the case study are expected to lead to the development of robust occupant behavior models that can improve the reliability of computational building performance simulation applications (a summary of the graphs is presented in section 4: Discussion). It also addresses more important aspects of energy consumption to provide better understanding of means of energy use in an office building.

In case of presence of occupants in the offices, the results suggest a more realistic view in building system design. On a more general level, our observations regarding this building suggest that the environmental systems in a considerable number of office buildings may in fact be "over-designed", in a sense that they are dimensioned for occupancy levels that seldom occur.

Concerning the dependency of the action "switching on the lights" on prevailing illuminance levels, the clear patterns suggest that only illuminance levels below 100 lx are likely to trigger actions at a non-random rate.

A clear relationship between switching the lights off actions and the duration of absence from the offices is evident.

Lighting operation and mean monthly shade deployment verify the roll of direction of the widows, were as lighting use in southwest direction is more than north. It is explained by considering the state of shades for the two cases: people have to keep shades closed to protect working place from direct sunlight and they do not open them because it is not easy to operate the shades. On the other hand, people in north façade have the shades most of the times open and they close it only in case of direct sunlight that occasionally happen.

The results of the study of the lighting saving potential show that up to 70 % of lighting energy used for the lighting in office could be saved. Moreover a better-designed use of daylight would provide more comfort and energy saving.

Considering the presence of the occupants, about 30% of electricity energy used in fans, 25 % of heating energy consumption and 20 % of cooling energy consumption (in a conservative calculation) can be saved by providing more intelligent controllers for building systems considering behavior of the occupants.

List of publications

Mohammadi A, Kabir E, Mahdavi A, Pröglhöf C, 2007, "Modelling user control of lighting and shading devices in office buildings: An empirical case study" IBPSA 2007 Conference, Beijing, China

Kabir E, Mohammadi A, Mahdavi A, Pröglhöf C, 2007, "How do people interact with buildings environmental systems? An empirical case study of an office building" IBPSA 2007 Conference, Beijing, China

Mahdavi A, Mohammadi A, Kabir E, Lambeva L, 2007a, "An empirically-based approach toward user control action models in buildings", ECPPM 2007 Conference, Maribor, Slovenian

Mahdavi A, Mohammadi A, Kabir E, Lambeva L, 2007b, "User control actions in buildings: Patterns and impact", CLIMA 2007 Conference, Helsinki, Finland

Mahdavi A, Mohammadi A, Lambeva L, Suter G, Kabir E, Pröglhöf C, 2007c, "People as power plant: Energy implications of user behavior in office buildings"; in "IEWT 2007 – 5th International energy science conference" at Vienna University of Technology, Vienna, Austria, P. 178 - 179

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7 Appendices

7.1 General information about the complex

In 1966, the Austrian Federal Government made an offer to an international organization to construct an international headquarters center in Vienna. In 1967, the Federal Government and the Municipality of Vienna, in a joint decision, designated an area on the left bank of the Danube as the site of the Center. An international competition for the design of the buildings at Vienna's Donaupark was organized by the Government of Austria in 1968. It produced worldwide interest among architects and resulted in 288 submissions. At conclusion, the Austrian architect, Johann Staber was designated the winner and announced in 1970 by the Federal Chancellor of Austria. Construction began in 1972 under the general direction of the "Internationaler Amtssitz und Konferenzzentrum Wien (IAKW)"; the center was inaugurated in August 1979.[1]


Figure 7-1 selected site (left), Construction site (right)

The complex covers an area of 180,000 m² and has extraterritorial status. Maintenance and operating costs for the complex were about $19.5 million or €15.5 million in year 2003. The complex comprises about 4,500 offices, 9 conference rooms. In 2004, it accommodated about 3,600 international civil servants from about 100 countries. The Y-shaped office towers are between 48 m and 120 m high. The construction costs of approximately € 640.000.000, were shared by the Federal Government (65%) and the Municipality of Vienna (35%)(Vienna International center website).

[1] http://www.unvienna.org/unov/en/vichistory.html?print


Figure 7-2 construction site (left), today's view (right)

Total net area of the floors, including kindergarten, checkpoints, Technical Floors and fire house is almost 230,000 m^2. The office towers of the complex named from A to G and they are formed as following:

Table 7-1 Sub areas

Tower	Floors	Height (m)	Office area (m²)	Total area (m²)
A	28	109	18,581	47,882
B	11	54	7,800	19,348
C	8	45	2,362	36,704
D	22	90	15,339	38,754
E	15	67	11,125	24,144
F	10	51	3,899	55,702
G	6	38	1,361	24,561

The area of kindergarten, checkpoints, technical floors building "J" (no office area) and fire house is 3,441 (m²).

Out of 92 floors, 26 floors are technical floors in which various air-conditioning plants and other technical facilities are located and 66 floors are office floors.

Each floor has 234 window modules and the same number of air-conditioning units and accommodates about 55-70 offices or staff. The number of the total Air-conditioning units installed at every window module in all the office towers is 15,500. The spacing of window modules is constant of 88 cm, centre to centre, in all these office floors (Der-Petrosian 2006).

7.2 Deriving missed external environmental data of Weather station

Table 7-2 First quarter of year 2005, comparing collected data of WS_BPI and WS_VC

Correlation	Equation
R^2(WS) = 0.2447	Y=0.4405X+0.4419
R^2 (RHe) = 0.9637	Y=1.0606X-2.2745
R^2 (T) = 0.9861	Y=0.9713X-0.1796
R^2 (SR) = 0.9439	Y=0.9179X+4.9831

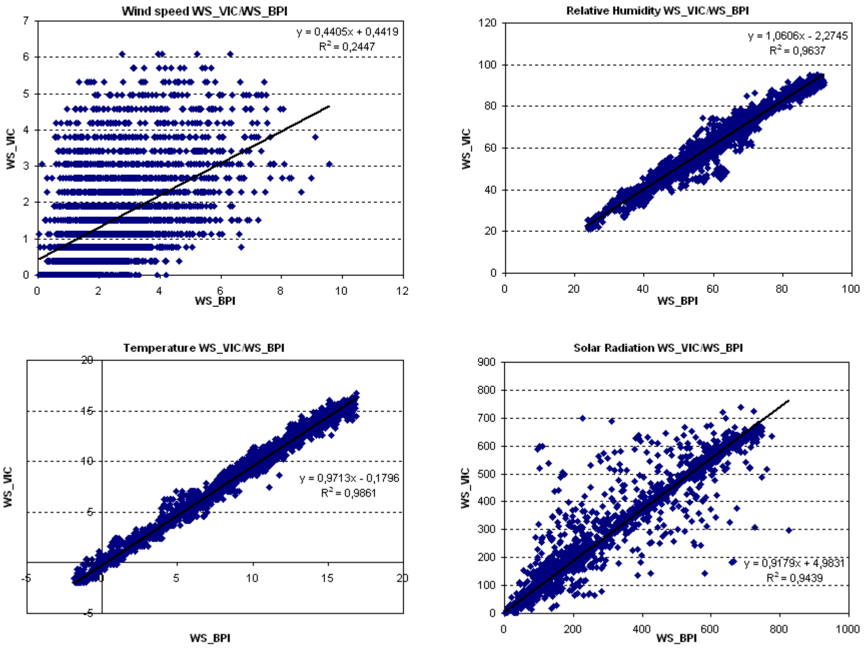

Figure 7-3 Comparing parameters of weather stations for first quarter in VC and BPI; Wind speed, relative humidity, temperature and solar radiation

Table 7-3 Second quarter of year 2005, comparing collected data of WS_BPI and WS_VC

Correlation	Equation
R^2(WS) = 0.4373	Y=0.654X+0.0963

R^2 (RHe) = 0.9365	Y=1.0943X-1.5571
R^2 (T) = 0.982	Y=0.9548X+0.2848
R^2 (SR) = 0.8432	Y=0.826X+12.645

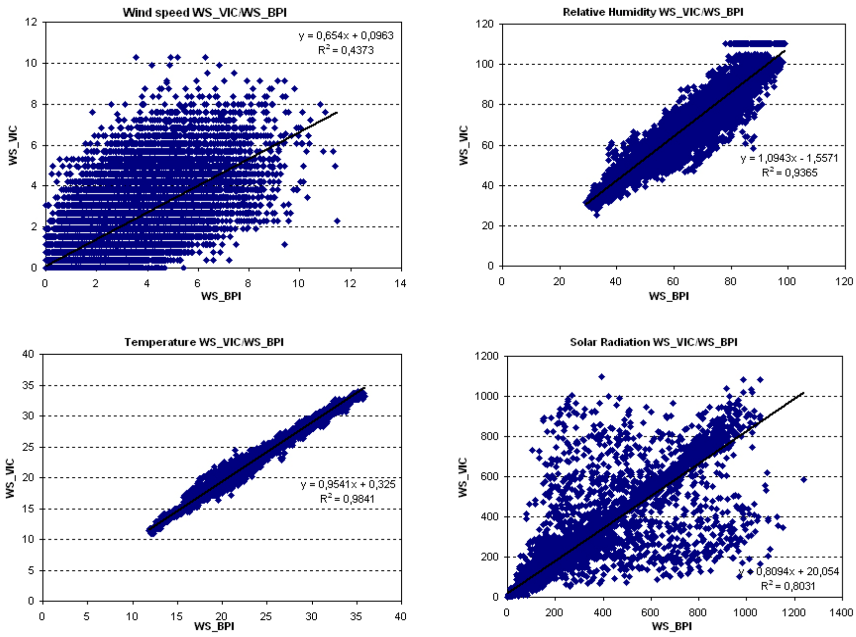

Figure 7-4 *Comparing parameters of weather stations for second quarter in VC and BPI; Wind speed, relative humidity, temperature and solar radiation*

Table 7-4 *Third quarter of year 2005, comparing collected data of WS_BPI and WS_VC*

Correlation	Equation
R^2(WS) = 0.3762	Y=0.6256X+0.3809
R^2 (RHe) = 0.9532	Y=1.0799X-3.074
R^2 (T) = 0.9819	Y=0.965X+0.0214
R^2 (SR) = 0.9382	Y=0.8876X+5.5741

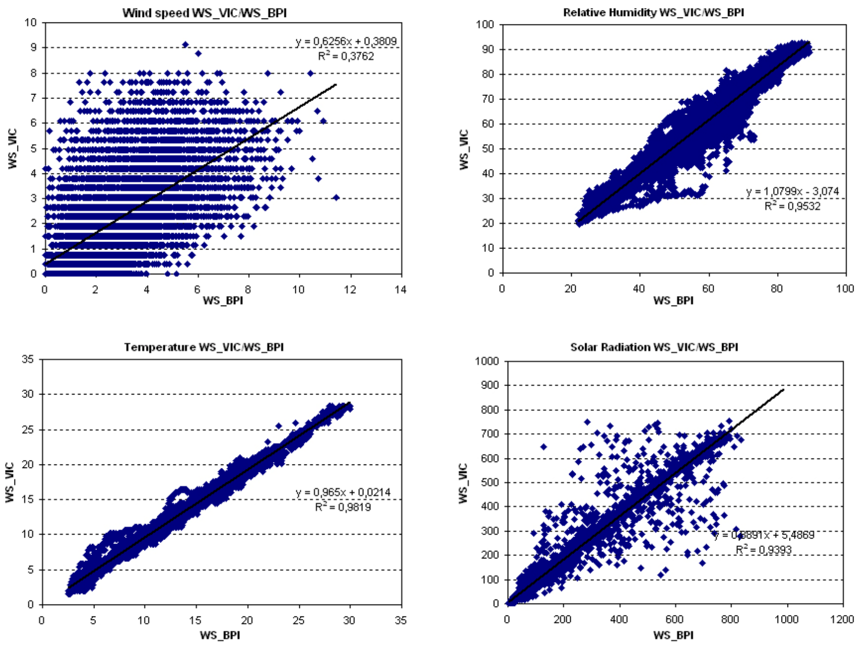

Figure 7-5 *Comparing parameters of weather stations for third quarter in VC and BPI; Wind speed, relative humidity, temperature and solar radiation*

Forth quarter: Complete data was recorded.

As mentioned before, there are very good correlations between values of WS_VIC and WS_BPI for temperature and relative humidity, there is also a good correlation for solar radiation but correlation for wind speed is not good enough to be applied as formula and to generate values for WS_VIC. So the equations for temperature, relative humidity and solar radiation were used to derive missing values in periods we have no data for WS_VIC.

The next step was to compare average hourly values for wind speed. The results are summarized in Table 2-5 and figures 2-11 and 2-12.

Table 7-5 *Wind speed, comparing collected data of WS_BPI and WS_VC*

Correlation	Equation
R^2 (WS)-First quarter = 0.4001	Y=0.6076X+0.0131
R^2 (WS)-First quarter = 0.505	Y=0.7684X+0.0046
R^2 (WS)-First quarter = 0.6292	Y=0.849X+0.4787

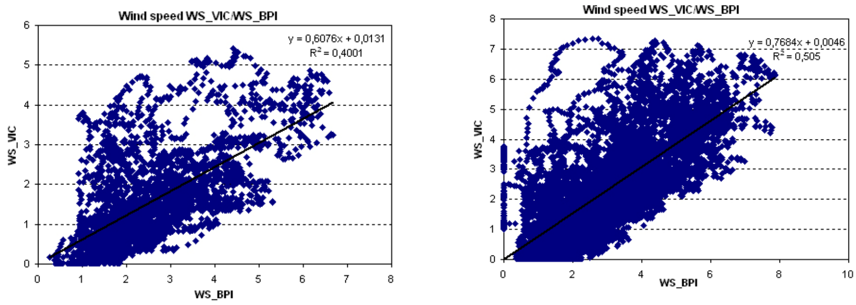

Figure 7-6 *Comparing wind speed, recorded data of weather stations in VC and BPI*

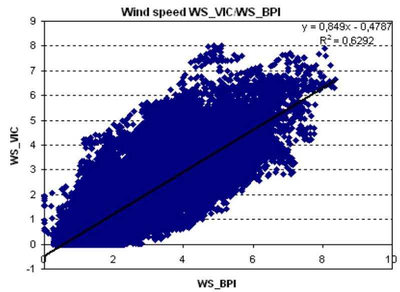

Figure 7-7 *Comparing wind speed, recorded data of weather stations in VC and BP*

7.3 Energy consumption data

Tables 2-12 to 2-17 show detail energy consumption in buildings "D" and "E" which used for the analysis and predictions (Der-Petrosian 2006).

Table 7-6 Energy consumption for space HEATING in buildings D+E

Year	1	3	4	5
	Total heating energy consumed	Net heating energy consumed in OFs	Total office area heated	Electrical energy consumed for air circulation
	mWh	mWh	Sq.m	mWh
2005	6,400	6,100	53,371	643

Table 7-7 Energy consumption for space COOLING in buildings D+E

Year	1	2	3	4	5
	Total cooling energy consumed	Electrical energy consumed for air circulation	Electrical energy for generating chilled water in UTS	Total electrical energy consumed	Total area cooled in office floors
	mWh	mWh	mWh	mWh	Sq.m
2005	3,390	650	1,550	4,040	53,371
2004	3,310	650	1,550	3,960	53,371
2003	3,900	650	1,550	4,550	53,371
2002	3,500	650	1,550	4,150	53,371

Table 7-8 Energy consumption for LIGHTING and OFFICE DEVICES in buildings D+E

Year	1	2	4
	Total electrical energy consumed for Lighting	Total electrical energy consumed for Office devices	Electrical energy consumed for Lighting in office floors
	mWh	mWh	mWh

2005	1,020	850	930
2004	1,020	850	930
2003	1,020	850	930
2002	1,020	850	930

Table 7-9 Buildings Utilities Consumption in 2005 for buildings D+E in mWh

Utility	JAN	FEB	MAR	APR	MAY	JUN	JUL
*Electric	240	230	240	220	233	230	231
**Heating	1,566	1,200	980	700	250	250	150
Cooling	0	0	0	140	450	400	580

Utility	AUG	SEP	OCT	NOV	DEC	Total
*Electric	240	220	230	225	230	2,769
**Heating	140	380	700	1,100	1,600	9,016
Cooling	680	400	150	0	0	2,800

* Including all uses of electricity

**including warm water

Table 7-10 Cost of HEATING and COOLING in buildings D+E

Year	1	2	2	2
	Unit Cost of Heating energy	Unit Cost of Cooling energy	Unit Cost of electrical energy	Unit Cost of Gas
	Euro/kWh	Euro/kWh	Euro/kWh	Euro/m³
2005	0.059	0.180	0.078	0.276
2004	0.059	0.208	0.054	0.276
2003	0.049	0.159	0.055	0.276
2002	0.058	0.155	0.055	0.276

Table 7-11 Operation time of utilities in building D, 2005

	Heating	Cooling	Offices' Lights	Corridors' lights
JAN	*		7:00-19:00	6:00-21:00
FEB	*		7:00-19:00	6:00-21:00
MAR	*		7:00-19:00	6:00-21:00
APR	*		7:00-19:00	6:00-21:00
MAY	*	*	7:00-19:00	6:00-21:00
JUN		*	7:00-19:00	6:00-21:00
JUL		*	7:00-19:00	6:00-21:00
AUG		*	7:00-19:00	6:00-21:00
SEP	*	*	7:00-19:00	6:00-21:00
OCT	*		7:00-19:00	6:00-21:00
NOV	*		7:00-19:00	6:00-21:00
DEC	*		7:00-19:00	6:00-21:00

7.4 Input for Energy plus

Constructions: External wall in offices: U =0.18 W/m2, External wall in staircases: U =2.79 W/m2, Internal wall in offices: U =0.64 W/m2. Floors and ceilings are considered as adiabatic.

Openings: Windows: U = 2, 93 W/m2, Glazing 54 %

Activity: WC+ Staircase 1, WC+ Staircase 1 (no toilet): Activity status – 'walking about', Occupancy density: 0.03 people /m2, Occupancy 5 days per week, 8:00 - 17:00, Temperatures: day -15ºC, night – 12ºC, Lighting level: 300 lx.

WC+ Staircase 1 (with toilet): Activity status – 'standing/walking', Occupancy density: 0.11 people /m2, Occupancy 5 days per week, 8:00 -17:00, Temperatures: day -17.5ºC, night – 13.5ºC, Lighting level: 300 lx

Offices: Activity status – 'typing', Occupancy density: 0.07 people /m2, Occupancy 5 days per week, 8:00 -17:00

Temperatures: heating: day -23ºC, night – 19ºC; cooling: day -24ºC, night – 25ºC, Lighting level: 500 lx

Computer heat gains: 10 W/m2

Staircase 1, Staircase 2, Staircase 3, Zone 18 (corridor): Activity status – 'standing/walking', Occupancy density: 0.11 people /m2, Occupancy 5 days per week, 8:00 -17:00, Temperatures: heating: day -23ºC, night – 19ºC; cooling: day - 24ºC, night – 25ºC, Lighting level: 300 lx, Equiment: 2 W/m2

Toilet 1, toilet 2: Activity status – 'standing/walking', Occupancy density: 0.03 people /m2, Occupancy 5 days per week, 8:00 -17:00, Temperatures: day -20ºC, night – 19ºC, Lighting level: 300 lx

Lighting: T8 Fluorescent, low frequency control gea, Gains from lighting 13.2 (300lx) - 22 W/m2 (500lx)

HVAC: All systems work 5 days per week, from 7:00-18:30, WC+ Staircase 1, WC+ Staircase 1 (no toilet), No ventilation system, no heating, no cooling, WC+ Staircase 1 (with toilet), Ventilation system, air exchange rate: 4 * h^{-1}

Offices, corridor: All heated and air-conditioned. Mechanical ventilation system, air exchange rate 3 * h^{-1}

Staircases, All heated. Mechanical ventilation system, air exchange rate 1.3 * h^{-1}

Toilets: All heated. Mechanical ventilation system, air exchange rate 10 * h^{-1}