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User Control Actions in Buildings: A Case Study of Shading

A master's thesis submitted for the degree of
“Master of Science”

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Vienna, 27.06.2006

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Affidavit

I, **Haydar Sukru Tokel**, hereby declare

1. That I am the sole author of the present Master Thesis, "User Control Actions in Buildings: A Case Study of Shading", 48 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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ABSTRACT

User Control Actions in Buildings: A Case Study of Shading

This thesis describes the results of a research to find out how users interact with shading and lighting devices in an office building in Vienna, Austria. The aim of the research is to explore the parameters that lead occupants to change shade positions. For this purpose, changes in shading on the southwest and north façades of the building were observed by capturing images of the whole façade. Weather conditions were registered by the weather station mounted on the top of the building. Inside the building, 15 rooms on the southwest façade and 14 rooms on the north façade were selected. Users' operation of lighting was captured in each room. Data over a period of twelve months was collected and analyzed. The relationship between users' behavior and environmental parameters was studied. The potential for energy saving through the use of occupancy sensors was explored.

Keywords: Building control system, user behavior, shading, lighting

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1. INTRODUCTION

1.1 Motivation

Users of buildings interact with multiple control devices whenever they enter their spaces. Lighting, heating, and cooling are examples of the systems, with which users interact. By adjusting devices, they aim to bring about desired condition in their working or living places. The adjustments may depend on various factors such as culture, gender, physiological or psychological needs of users. Building type and location also influence variations of user behavior. As desired conditions are different for different users, empirical information can support the operation of a building control system. Also, performance simulation applications could benefit from the results before or during the design phase of buildings, which can reduce the cost of operation and improve comfort.

1.2 Simulation and Operation

Building performance simulation applications can predict energy performance of a building before construction. By adding the users' behavior to the input data, more accurate simulations may be performed.

Building operation systems gain more importance in recent years. If they are operated in a conscious way, energy consumption could be reduced while increasing users' comfort. Facility management services deal with operation of buildings. They may reduce costs of operation by using results of such studies.

1.3 Case Study of User Control Actions

To illustrate the level of user-system-interactions in buildings, a case study is presented. Some 200 architecture students were asked to register their control actions in log-books. For instance, any actions regarding opening, closing or adjusting systems in the building were logged by the occupants.

These students, living in Vienna, Austria are studying Architecture. Their age was between 20 to 25 years. The survey includes user actions registered over a period of 3 days. The percentage of males and females participated in the survey is almost equal.

People were asked to fill log-books (see Figure 1). Log-books have columns including place (home or office), systems of lighting (on/off), shading (open/close), heating (increase/decrease), window (open/close) and additional remarks. Rows are filled with the time of prevailing user action.

Please document your control actions regarding building systems (heating, ventilation, light and shade), including location and time.

LOG-BOOK

Name Matr.Nr.

Date	Time	Place		System				Additional Remarks	Date	Time	Place		System				Additional Remarks
		Home (living place)	Office (work place)	Light [On+ /Off −]	Shading [+(Open)/−(Close)]	Heating [Increase+/Decrease−]	Window [Open+ /Close −]	Motivation, Situation, etc.			Home (living place)	Office (work place)	Light [On+ /Off −]	Shading [+(Open)/−(Close)]	Heating [Increase+/Decrease−]	Window [Open+ /Close −]	Motivation, Situation, etc.
17/04	13:52	X		O	+			50% Open									
	13:56		X	Off			+	Window Open									
	13:58			On				14:50									
								18/06					On				
													Off				

Figure 1: Log-book sample page

Data from 200 log-books was saved in excel sheets. In these sheets, user actions of a person were grouped and listed to find out the total number of specific actions per day (see Figure 2).

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
Date:	Sex		Light		Shading		Heating		Window		Light	Shad	Heati	Wind	Place		Light	Shading	Heating	Window
		Intervals	On+	Off -	Open+	Close-	Increase+	Decrease-	Open+	Close -	Total	Total	Total	Total	Home/Other		Total per day	Total per day	Total per day	Total per day
06.05.2005	F	7:00-10:00	1	1	1			1	1		2	1	1	1	H	Name:				
06.05.2005	F	10:00-13:00	4	2		1					6	1	0	0	O					
06.05.2005	F	13:00-16:00	2	3						1	5	0	0	1	O					
06.05.2005	F	16:00-19:00									0	0	0	0	O					
06.05.2005	F	19:00-22:00					1				0	0	1	0	H		13	2	2	2
07.05.2005	F	7:00-10:00	2	1			1			1	3	0	1	1	H					
07.05.2005	F	10:00-13:00		2					1		2	0	0	1	H					
07.05.2005	F	13:00-16:00	1			1					1	1	0	0	O					
07.05.2005	F	16:00-19:00		2	1			1		1	2	1	1	1	H					
07.05.2005	F	19:00-22:00							1		0	0	0	1	H		8	2	2	4
07.05.2005	F	7:00-10:00	1					1	1		1	0	1	1	H					
07.05.2005	F	10:00-13:00	2			1				1	2	1	0	1	O					
07.05.2005	F	13:00-16:00		3							3	0	0	0	O					
07.05.2005	F	16:00-19:00	1		1		1		1		1	1	1	1	O					
07.05.2005	F	19:00-22:00		1							1	0	0	0	O		8	2	2	3
06.05.2005	F	7:00-10:00									0	0	0	0		Name:				
06.05.2005	F	10:00-13:00									0	0	0	0						
06.05.2005	F	13:00-16:00									0	0	0	0						

Figure 2: Excel sheet example showing control actions data for a student

The results of the analysis of the log-books are presented below. In Figure 3, average number of operations, of lighting, shading, heating and windows are presented. According to this figure, the participants operated lighting devices more often than other systems.

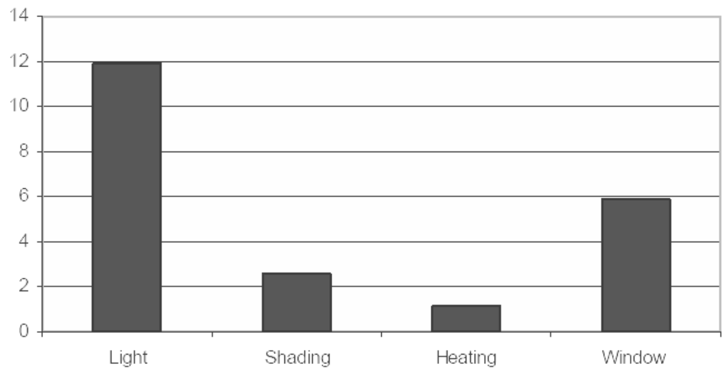


Figure 3: Average number of actions of a student for each system per day

Figure 4 illustrates the average number of all actions in 3 hour periods during the day. In the morning hours and evening hours, the number of actions increases.

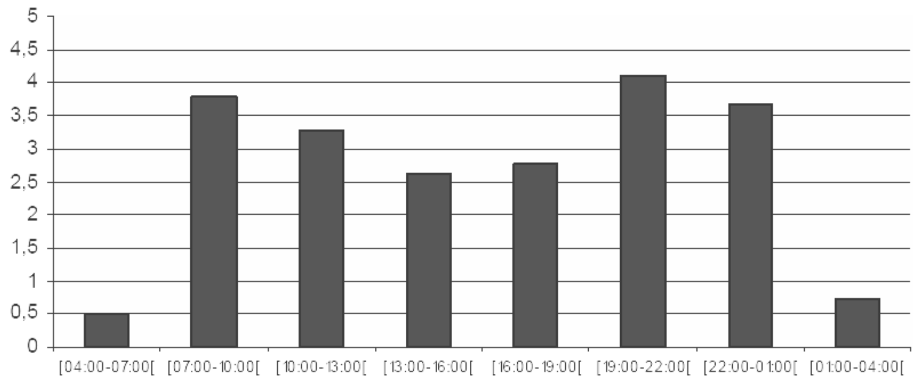


Figure 4: The number of control action as a function of the time of the day

Figure 5 illustrates lighting control actions as a function of the time of the day. Figure 6 illustrates window operations as a function of the time of the day.

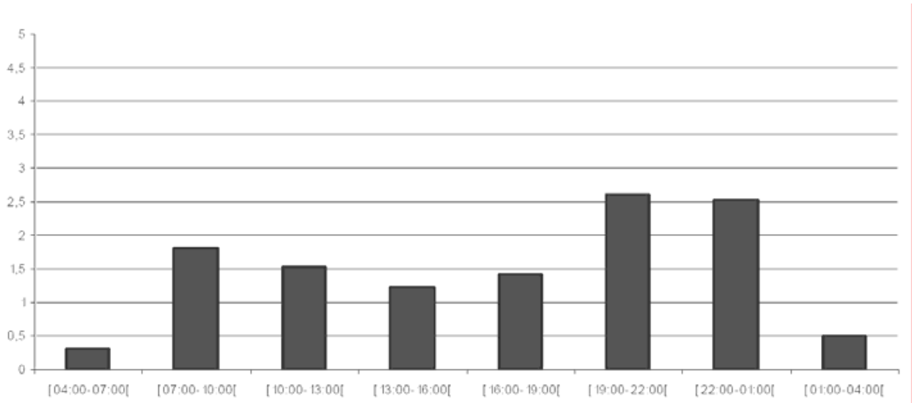


Figure 5: Lighting control actions as function of the time of the day

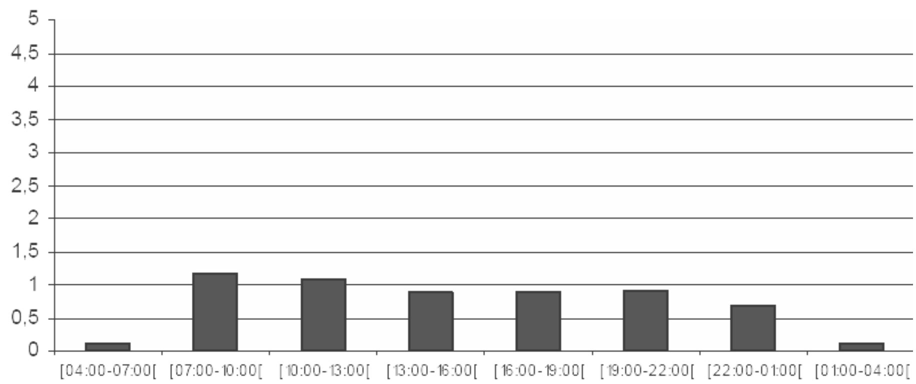


Figure 6: Window operations as a function of the time of the day

These results showed that the participants tended to interact with lighting systems more frequently during evening and early night hours. The frequency of the interaction with shading system was higher during morning hours and early evening hours. Overall the importance and frequency of user control actions in buildings could be demonstrated.

1.2 Background

There have been a number of publications on control-oriented occupant behavior. Control actions regarding lighting, heating, ventilating etc. were analyzed in past research. There are also papers written on a specific action such as shade positions. Rubin commented that people set the position of blinds consciously (Rubin et al. 1984). The blind position of choice seems to be a result of weighing positive and negative effects over a period as long as weeks or months whereas diurnal blind operations are rare (Rea 1978). Lindsay found that individual manual blind manipulation varies from never to daily in the same facade and is more frequent at the extremes of a working day (Lindsay and Littlefair 1993).

These research results help to understand occupant behavior and use it for simulation projects for certain places. However, more long-term monitoring results with higher resolution are necessary. Specifically, there is a lack of such data in the context of Austria.

2. METHODOLOGY

2.1 Building Selection

The research presented in this paper is a small part of a larger effort dealing with different control actions in an office building in Vienna Austria: Vienna International Center (VIC). VIC has about 4,500 office rooms, 9 conference rooms and, in 2004, accommodates about 3,600 international civil servants from about 100 countries.

Figure 7: Vienna International Center (VIC)

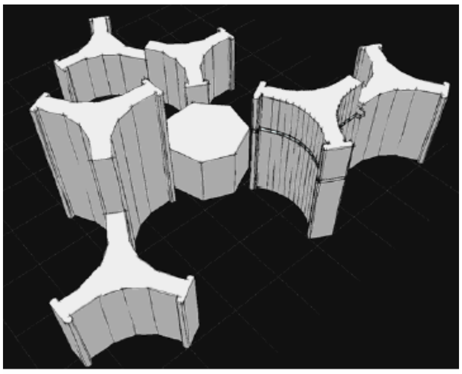


Figure 8: VIC Building 3D Model

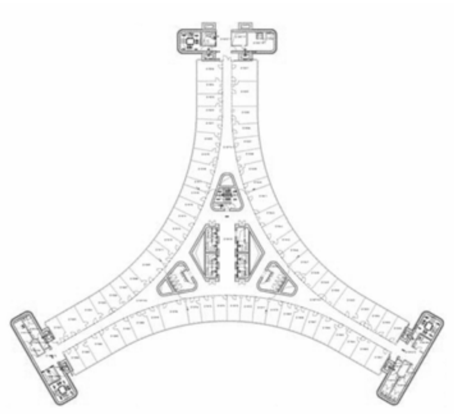


Figure 9: VIC Building Floor Plan

2.2 Selection of the Systems

Shading is one of the analyzed systems in this building. It affects operation costs of lighting, heating, and cooling. Occupants change the status of these devices because of environmental parameters and personal desires. As operation costs are reduced by conscious adjustment, shading devices can be positioned for optimum lighting and more comfort. Shading devices in VIC building are controlled manually. Rooms have 3 or 4 blinds (see Figure 10).

Lighting is another important system in building operation. With lighting typically accounting for 30% to 50% of energy use in most buildings, finding ways to increase lighting efficiency can result in significant savings (SWMCB 2002). Rooms in VIC are lit with 9 or 12 fluorescent fixtures. One fluorescent fixture draws about 43W.

Figure 10: An office room in VIC with 12 fluorescent fixtures and 4 blinds

2.3 Selection of the Rooms

On the southwest façade of the building, 15 rooms were selected: 9 rooms on the 3rd floor and 6 rooms on the 4th floor. On the north façade, 14 rooms were selected: 8 rooms on the 3rd floor and 6 rooms on the 4th floor. Inside rooms, sensors were installed for logging further control actions. These are the rooms where occupants from different countries regularly work.

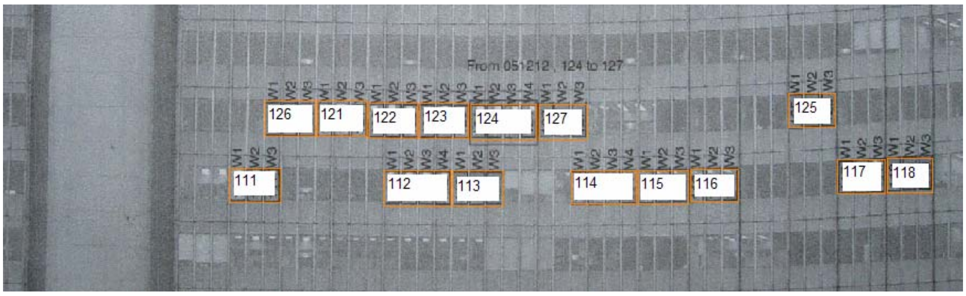


Figure 11: Selected rooms on the North façade

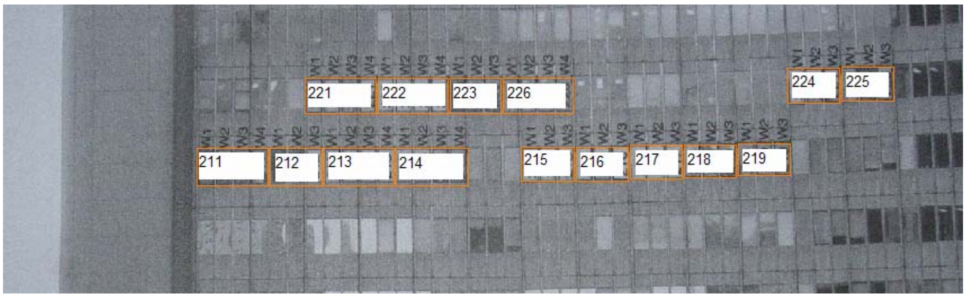


Figure 12: Selected rooms on the Southwest façade

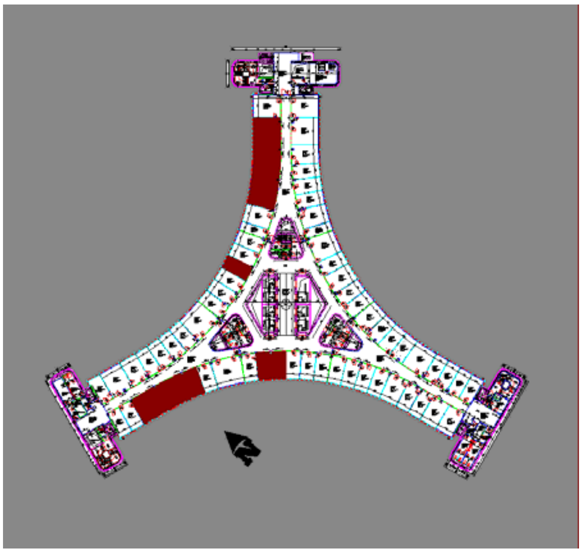


Figure 13: Plan of the 4th floor showing selected rooms

2.4 Data Collection

The data for the research is collected with three equipments: *i)* Weather station *ii)* Digital cameras *iii)* Occupancy/ light status loggers

Weather station collects data parallel to monitoring of user actions (see Figure 14). Weather conditions such as temperature, humidity, global solar irradiance were collected with the station mounted on the top of the building (Mahdavi et al. 2006). Data taken from the station was saved in a server for further analysis.

One digital camera was installed in front of both façades for capturing the image of the façade every 10 min. over a period of one year. The images were transferred to a server for further processing. Images have high-resolution for detailed analysis of shade positions.

Changes in status of light were captured by a dedicated sensor. (see Figure 15). These devices were hanged under the fixtures to register the status of the lights (on/off). Occupancy/ light status logger collected data of lighting devices in rooms, so that relationship between occupancy and status of lighting devices could be documented.

Figure 14: Weather Station mounted on the roof

Figure 15: Occupancy/light status logger

2.5 Data Processing

After collection of one year's weather station and camera data, the following process was done:

Images of façades were analyzed by using an image-processing software (Lechleitner 2005). This program was written as a plug-in of the software Labview. Images of both façade were processed in this software. Figure 16 illustrates user interface of the software. On the left, names of the windows are listed and the image of the façade is on the right. All window frames were defined and labeled.

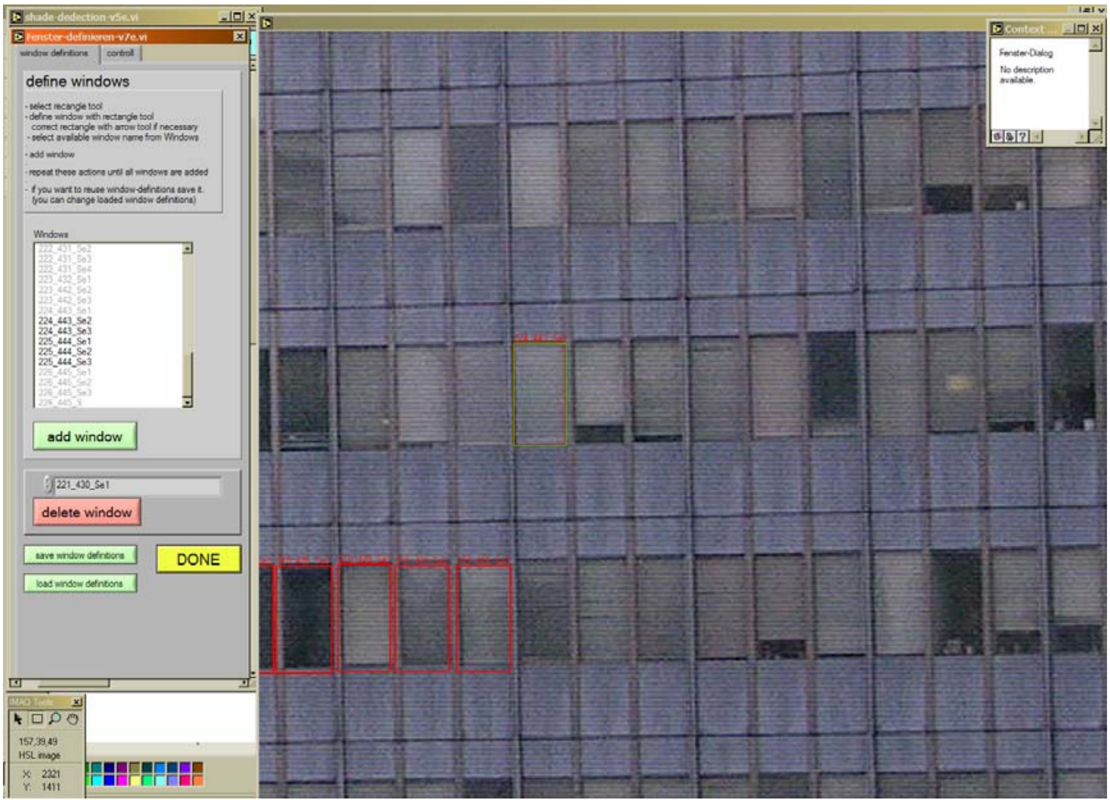


Figure 16: Image-processing Software

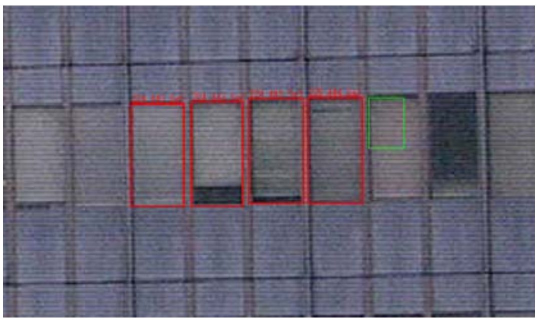


Figure 17: Definition of window frames

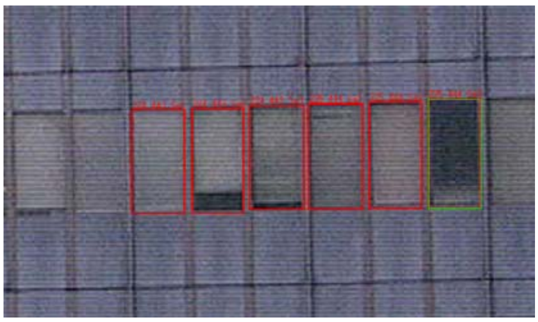


Figure 18: Defined window frames

After the definition of window frames, positions of blinds were defined. Figure 19 illustrates windows of two selected rooms. The positions of blinds were defined by clicking the mouse button of the computer. In Figure 20, positions of blinds were defined and the percentage is defined for each blind.

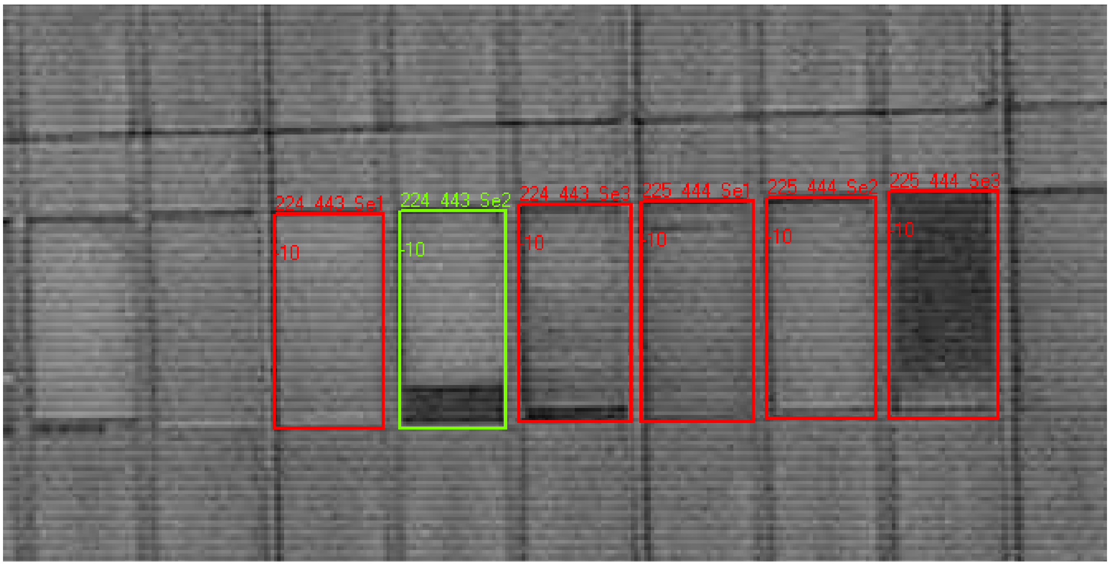


Figure 19: Blind positions before definition

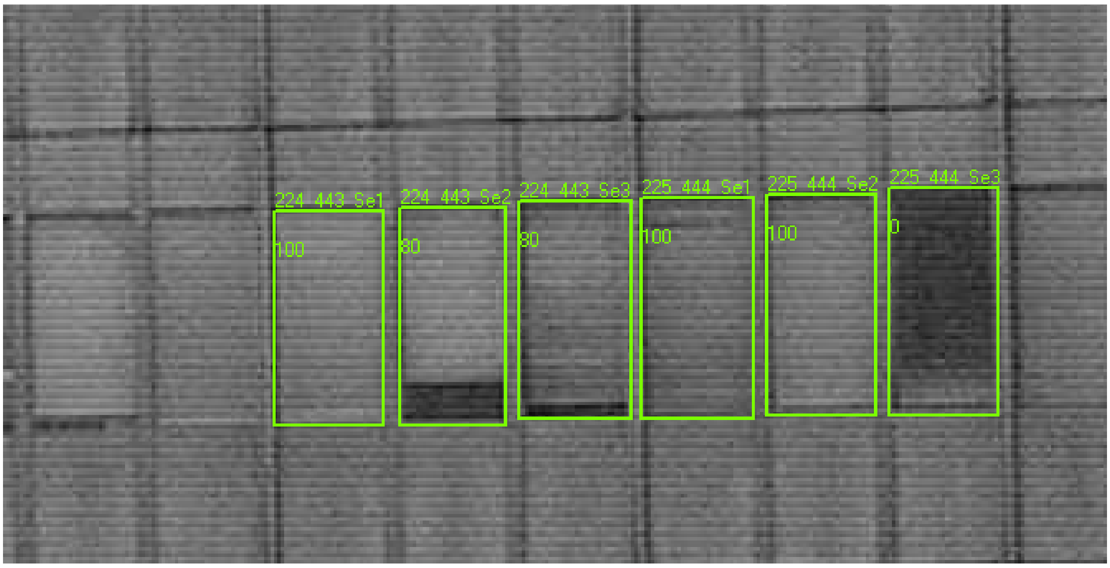
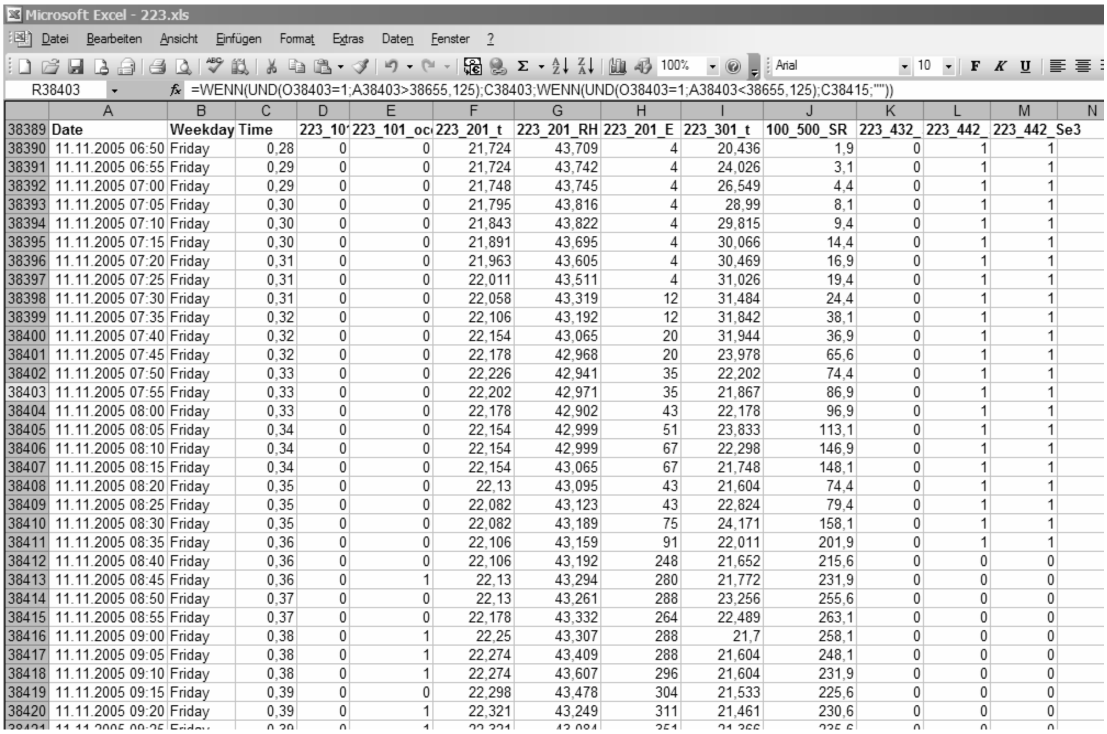


Figure 20: Blind positions and percentage of closed blinds

Data taken from image-processing was analyzed in a second software; Senselect (Pröglhof 2005). Senselect converts data into document form for further analysis and provides combining the data from different sensors. Subsequently, different data types from sensors, weather station and shades positioning can be collected in one file for finding further analysis. In Figure 21, data for shade positions after the Senselect-process is illustrated. The three columns from right show percentage of shading of three windows of room 223.

Data taken from the weather station, such as horizontal irradiation (in W.m^{-2}), was transferred to the server with the manufacturer's software and processed in Senselect like the previous data. Vertical and horizontal irradiance are illustrated in Figure 21 for 5 min. periods parallel to user actions. Date and time of adjustments of blinds were recorded in these sheets.


Microsoft Excel - 223.xls

Datei Bearbeiten Ansicht Einfügen Format Extras Daten Fenster ?

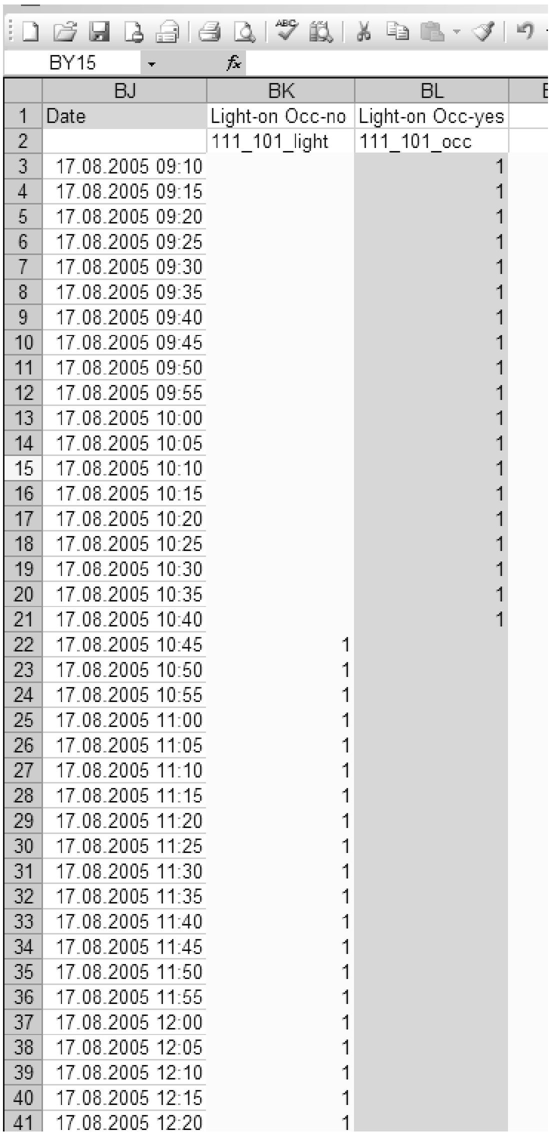
R38403 =WENN(UND(O38403=1;A38403>38655,125);C38403;WENN(UND(O38403=1;A38403<38655,125);C38415;""))

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
38389	Date	Weekday	Time	223_10	223_101_oc	223_201_t	223_201_RH	223_201_E	223_301_t	100_500_SR	223_432_	223_442_	223_442_Se3	
38390	11.11.2005 06:50	Friday	0,28	0	0	21,724	43,709	4	20,436	1,9	0	1	1	
38391	11.11.2005 06:55	Friday	0,29	0	0	21,724	43,742	4	24,026	3,1	0	1	1	
38392	11.11.2005 07:00	Friday	0,29	0	0	21,748	43,745	4	26,549	4,4	0	1	1	
38393	11.11.2005 07:05	Friday	0,30	0	0	21,795	43,816	4	28,99	8,1	0	1	1	
38394	11.11.2005 07:10	Friday	0,30	0	0	21,843	43,822	4	29,815	9,4	0	1	1	
38395	11.11.2005 07:15	Friday	0,30	0	0	21,891	43,695	4	30,066	14,4	0	1	1	
38396	11.11.2005 07:20	Friday	0,31	0	0	21,963	43,605	4	30,469	16,9	0	1	1	
38397	11.11.2005 07:25	Friday	0,31	0	0	22,011	43,511	4	31,026	19,4	0	1	1	
38398	11.11.2005 07:30	Friday	0,31	0	0	22,058	43,319	12	31,484	24,4	0	1	1	
38399	11.11.2005 07:35	Friday	0,32	0	0	22,106	43,192	12	31,842	38,1	0	1	1	
38400	11.11.2005 07:40	Friday	0,32	0	0	22,154	43,065	20	31,944	36,9	0	1	1	
38401	11.11.2005 07:45	Friday	0,32	0	0	22,178	42,968	20	23,978	65,6	0	1	1	
38402	11.11.2005 07:50	Friday	0,33	0	0	22,226	42,941	35	22,202	74,4	0	1	1	
38403	11.11.2005 07:55	Friday	0,33	0	0	22,202	42,971	35	21,867	86,9	0	1	1	
38404	11.11.2005 08:00	Friday	0,33	0	0	22,178	42,902	43	22,178	96,9	0	1	1	
38405	11.11.2005 08:05	Friday	0,34	0	0	22,154	42,999	51	23,833	113,1	0	1	1	
38406	11.11.2005 08:10	Friday	0,34	0	0	22,154	42,999	67	22,298	146,9	0	1	1	
38407	11.11.2005 08:15	Friday	0,34	0	0	22,154	43,065	67	21,748	148,1	0	1	1	
38408	11.11.2005 08:20	Friday	0,35	0	0	22,13	43,095	43	21,604	74,4	0	1	1	
38409	11.11.2005 08:25	Friday	0,35	0	0	22,082	43,123	43	22,824	79,4	0	1	1	
38410	11.11.2005 08:30	Friday	0,35	0	0	22,082	43,189	75	24,171	158,1	0	1	1	
38411	11.11.2005 08:35	Friday	0,36	0	0	22,106	43,159	91	22,011	201,9	0	1	1	
38412	11.11.2005 08:40	Friday	0,36	0	0	22,106	43,192	248	21,652	215,6	0	0	0	
38413	11.11.2005 08:45	Friday	0,36	0	1	22,13	43,294	280	21,772	231,9	0	0	0	
38414	11.11.2005 08:50	Friday	0,37	0	0	22,13	43,261	288	23,256	255,6	0	0	0	
38415	11.11.2005 08:55	Friday	0,37	0	0	22,178	43,332	264	22,489	263,1	0	0	0	
38416	11.11.2005 09:00	Friday	0,38	0	1	22,25	43,307	288	21,7	258,1	0	0	0	
38417	11.11.2005 09:05	Friday	0,38	0	1	22,274	43,409	288	21,604	248,1	0	0	0	
38418	11.11.2005 09:10	Friday	0,38	0	1	22,274	43,607	296	21,604	231,9	0	0	0	
38419	11.11.2005 09:15	Friday	0,39	0	0	22,298	43,478	304	21,533	225,6	0	0	0	
38420	11.11.2005 09:20	Friday	0,39	0	1	22,321	43,249	311	21,461	230,6	0	0	0	

Figure 21: Excel sheet illustrating all data for room 223

Data from light status logger (on/off) and occupancy sensor (present/absent) was analyzed with manufacturer's software and sent to Senselect. After this process, another data sheet was created (see Figure 22).

In Figure 13, occupancy and status of lights are shown on the left for different rooms. Columns present information of date, time and name of the room. The number "1" refers to the time period of lighting of 5 min. The number "1" on the left refers to 5 min. time of lighting without occupancy in the room. The column on the right shows the time of lighting with occupancy in the room. The total time of lighting without occupancy could be calculated from these sheets for 29 rooms.



	BJ	BK	BL
1	Date	Light-on Occ-no	Light-on Occ-yes
2		111_101_light	111_101_occ
3	17.08.2005 09:10		1
4	17.08.2005 09:15		1
5	17.08.2005 09:20		1
6	17.08.2005 09:25		1
7	17.08.2005 09:30		1
8	17.08.2005 09:35		1
9	17.08.2005 09:40		1
10	17.08.2005 09:45		1
11	17.08.2005 09:50		1
12	17.08.2005 09:55		1
13	17.08.2005 10:00		1
14	17.08.2005 10:05		1
15	17.08.2005 10:10		1
16	17.08.2005 10:15		1
17	17.08.2005 10:20		1
18	17.08.2005 10:25		1
19	17.08.2005 10:30		1
20	17.08.2005 10:35		1
21	17.08.2005 10:40		1
22	17.08.2005 10:45	1	
23	17.08.2005 10:50	1	
24	17.08.2005 10:55	1	
25	17.08.2005 11:00	1	
26	17.08.2005 11:05	1	
27	17.08.2005 11:10	1	
28	17.08.2005 11:15	1	
29	17.08.2005 11:20	1	
30	17.08.2005 11:25	1	
31	17.08.2005 11:30	1	
32	17.08.2005 11:35	1	
33	17.08.2005 11:40	1	
34	17.08.2005 11:45	1	
35	17.08.2005 11:50	1	
36	17.08.2005 11:55	1	
37	17.08.2005 12:00	1	
38	17.08.2005 12:05	1	
39	17.08.2005 12:10	1	
40	17.08.2005 12:15	1	
41	17.08.2005 12:20	1	

Figure 22: Excel sheet showing 5 min. time periods of lighting with and without occupancy

2.6 Hypotheses

After analysis of the data of lighting and shading systems, the relationships between control actions and possible contributing influence factors were explored. Results of shading positions and weather station data were compared. Data taken from sensors in rooms was expected to give additional information on occupant behavior. The main research questions were: *i)* Is there a relationship between the degree of shades deployment and natural parameters such as incident global horizontal irradiance *ii)* Is it possible to reduce operation costs of lighting by installing occupancy sensors?

3. ILLUSTRATIVE RESULTS

3.1 Shading

3.1.1 Shades Deployment Results for Total Façades

Occupants of the VIC building used their manual control to influence the setting of their blinds. A total of 140 blind changes on the north, 1132 changes on the southwest façade were recorded over a period of one year in 29 offices. The graphs below illustrate the number of actions in terms of horizontal irradiance classes for Southwest and North façades.

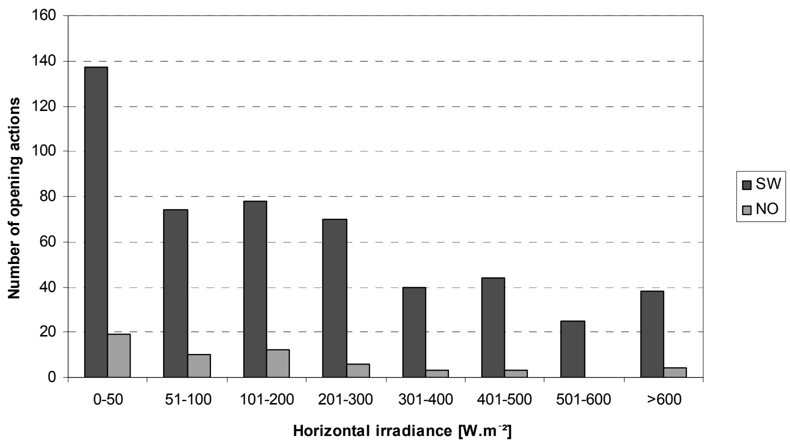


Figure 23: The number of opening actions in terms of horizontal irradiance classes

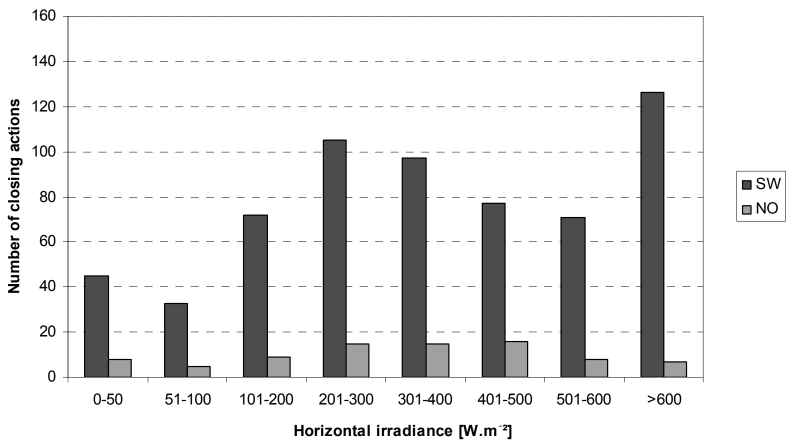


Figure 24: The number of closing actions in terms of horizontal irradiance classes

Figure 25 illustrates that users tend to open shades by lower irradiance values on the Southwest façade. By higher values, there is a visible reduction in the frequency. By low irradiance classes between 0 and 50 W.m^{-2}, occupants open shades more frequently than by other classes. By higher values (more than 300 W.m^{-2}), the frequency falls.

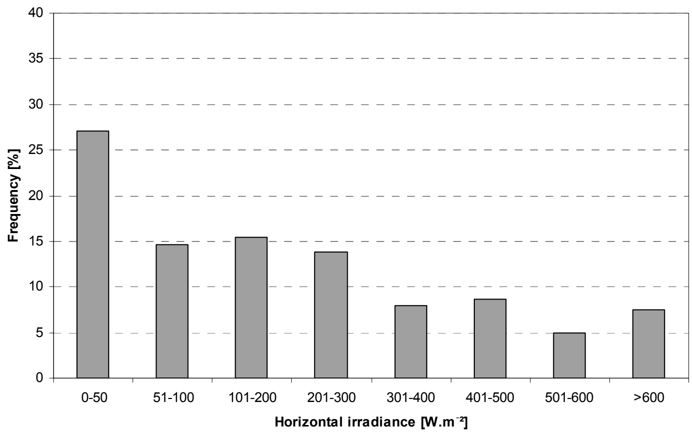


Figure 25: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in Southwest façade

Figure 26 illustrates the frequency of opening the shades versus horizontal global irradiance in North façade. The number of user actions of opening shades decreases while horizontal irradiance rises. The highest frequency level is registered by irradiance classes between 0 and 50 W.m^{-2}. For 300 W.m^{-2} and higher classes, frequency obviously falls.

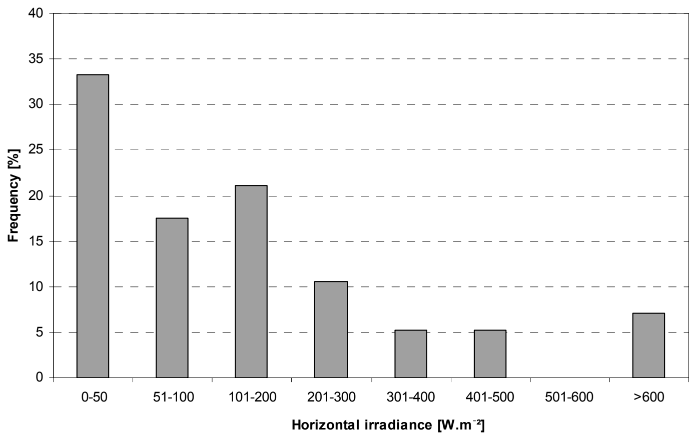


Figure 26: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in North façade

In Figure 27, frequency distribution of closing shades versus horizontal irradiance reaches highest value by irradiance classes of more than 600 W.m^{-2}. Due to relative high frequency values by around 300 W.m^{-2}, there is a relationship for supporting the hypothesis.

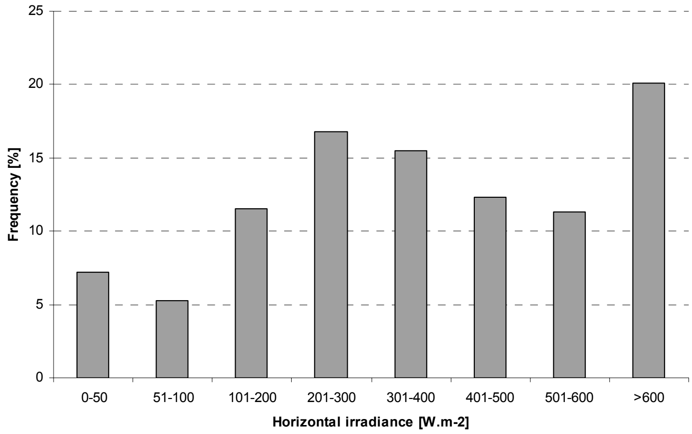


Figure 27: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in Southwest façade

In Figure 28, users tend to close shades by irradiance classes between 200 and 500 W.m^{-2}. After 500 W.m^{-2}, the frequency is lower than expected. The irradiance value barely gets higher than 500 W.m^{-2} on the North façade.

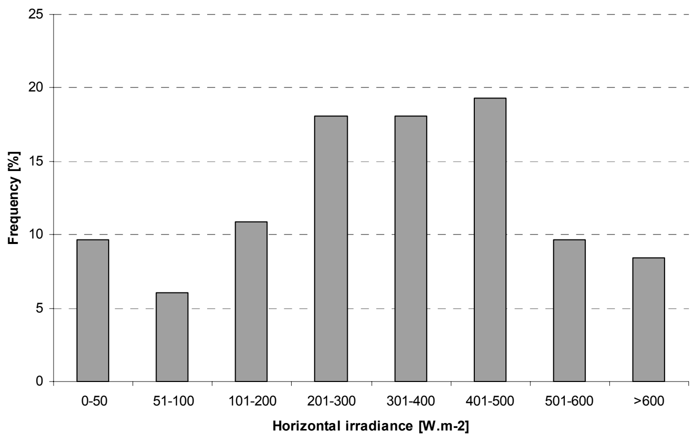


Figure 28: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in North façade

3.1.2 Shades Deployment Results for Office Rooms

After the illustration of shading results over a period of one year for total façades, results for office rooms are illustrated. As the number of registered actions in rooms on the North façade is less than the number of actions in other rooms, shades deployment results of rooms of North façade are not presented.

The relationship between the frequency of opening actions and horizontal irradiance was analyzed for all rooms. Figure 29 illustrates the relationship between opening actions and horizontal irradiance for total façade in Southwest.

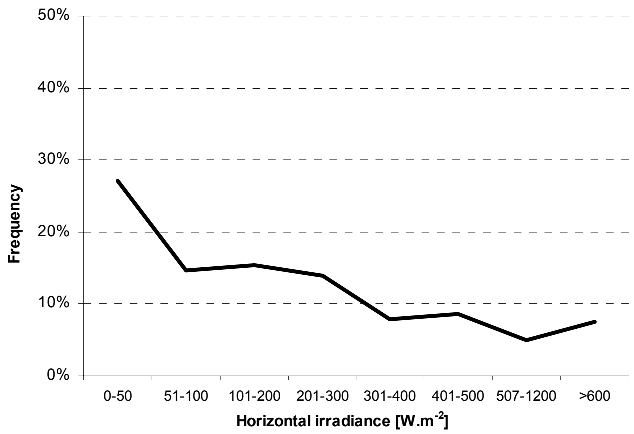


Figure 29: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in Southwest façade

Figure 30 illustrates the relationship between closing actions and horizontal irradiance for total façade in Southwest.

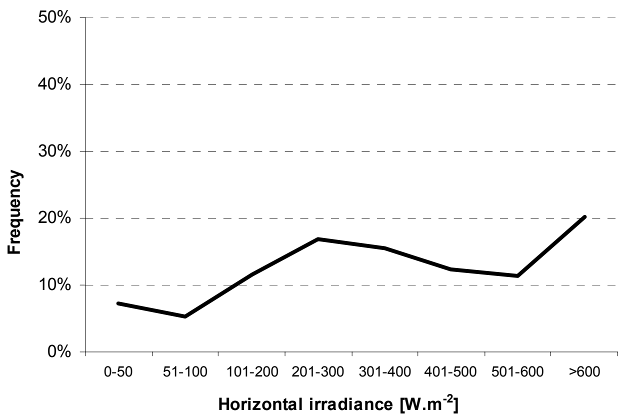


Figure 30: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in Southwest façade

The graphs below illustrate the relationship between opening actions and horizontal irradiance. Results are varied for different rooms. However, the relationship is visible if considered in total (see Figure 31, Figure 32).

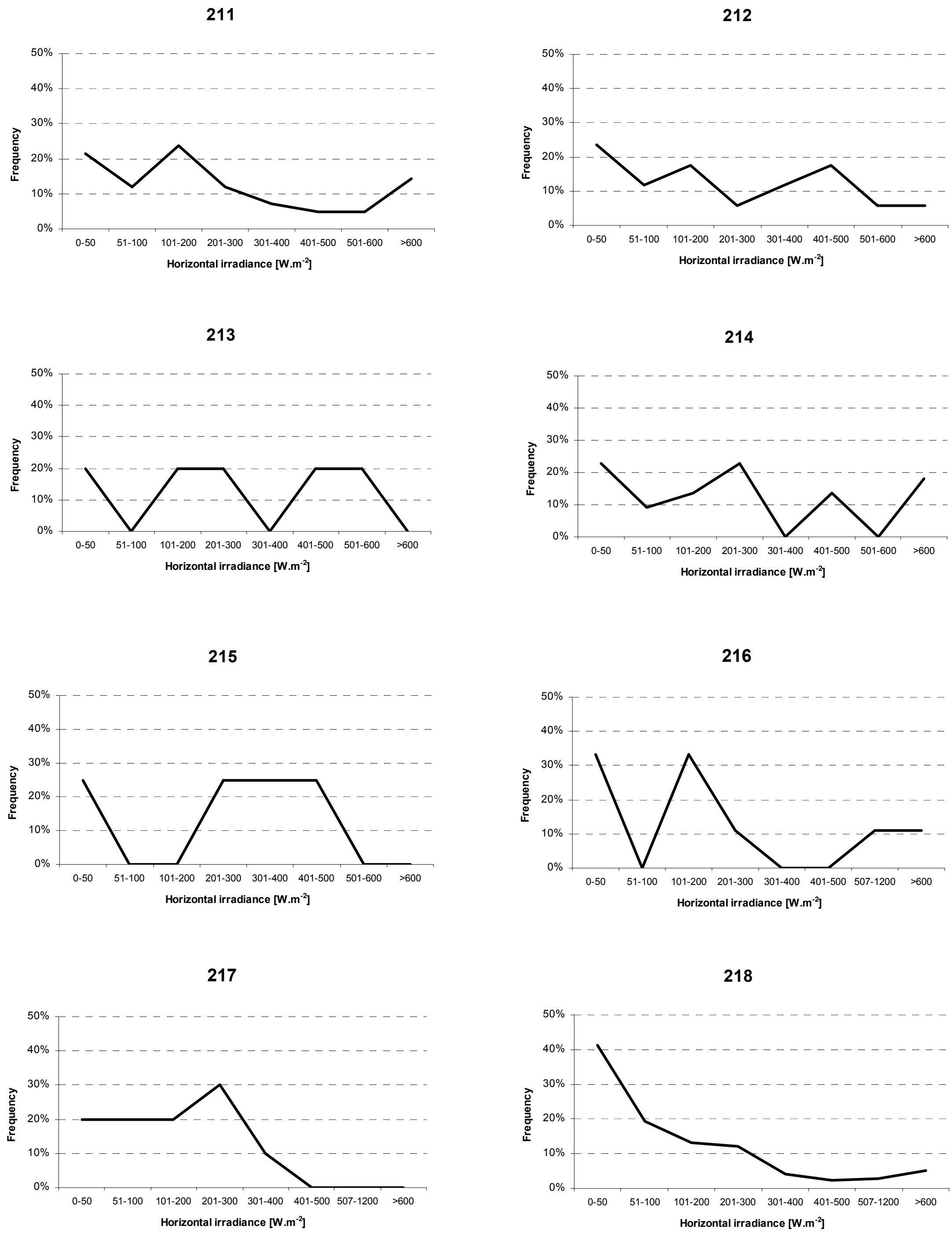


Figure 31: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in Southwest façade for rooms 211-218

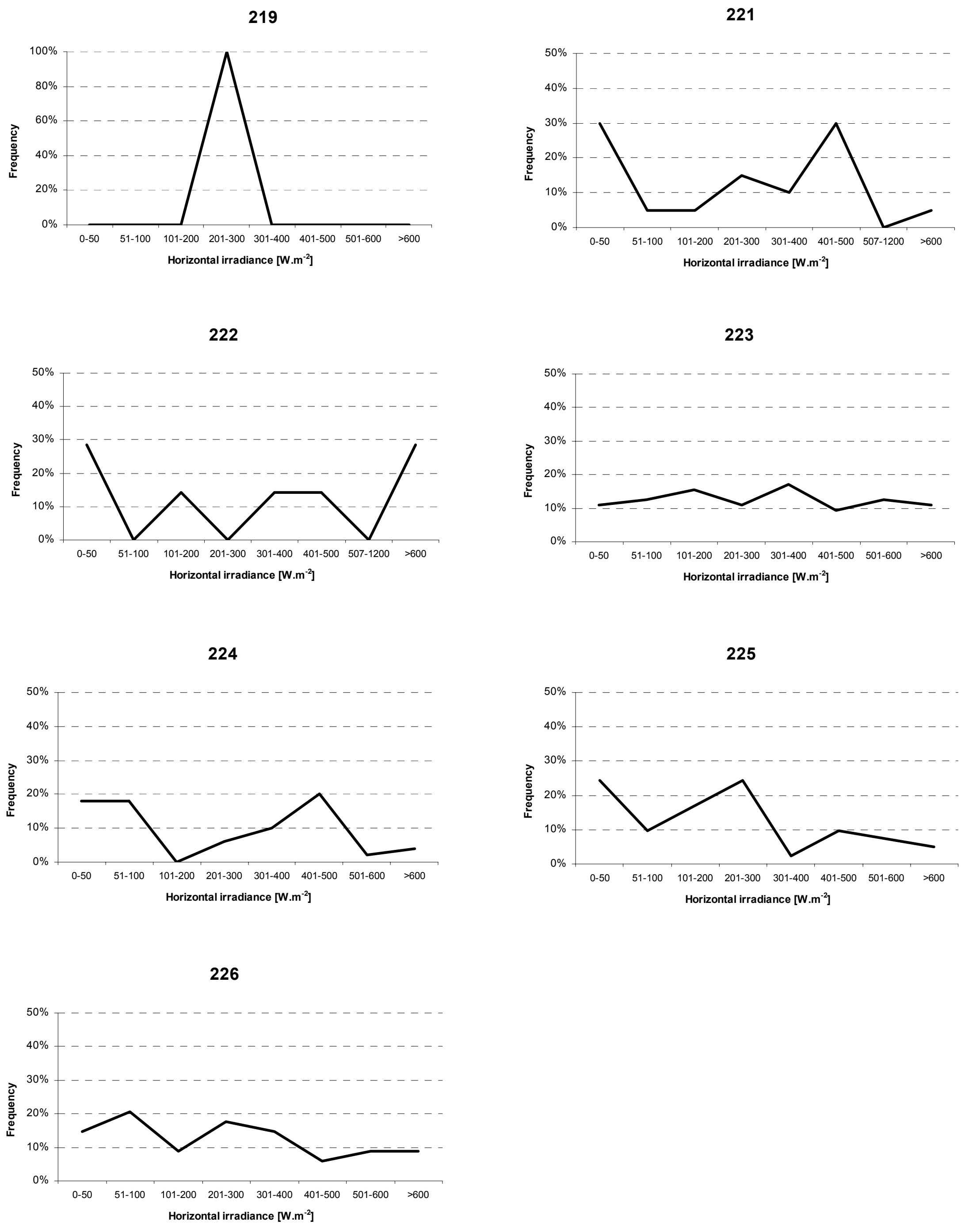


Figure 32: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in Southwest façade for rooms 219-226

Figure 33 illustrates the relationship between closing actions and horizontal irradiance for office rooms. Results are varied for different rooms. In most cases, frequency of closing shades rises by the increase of horizontal irradiance.

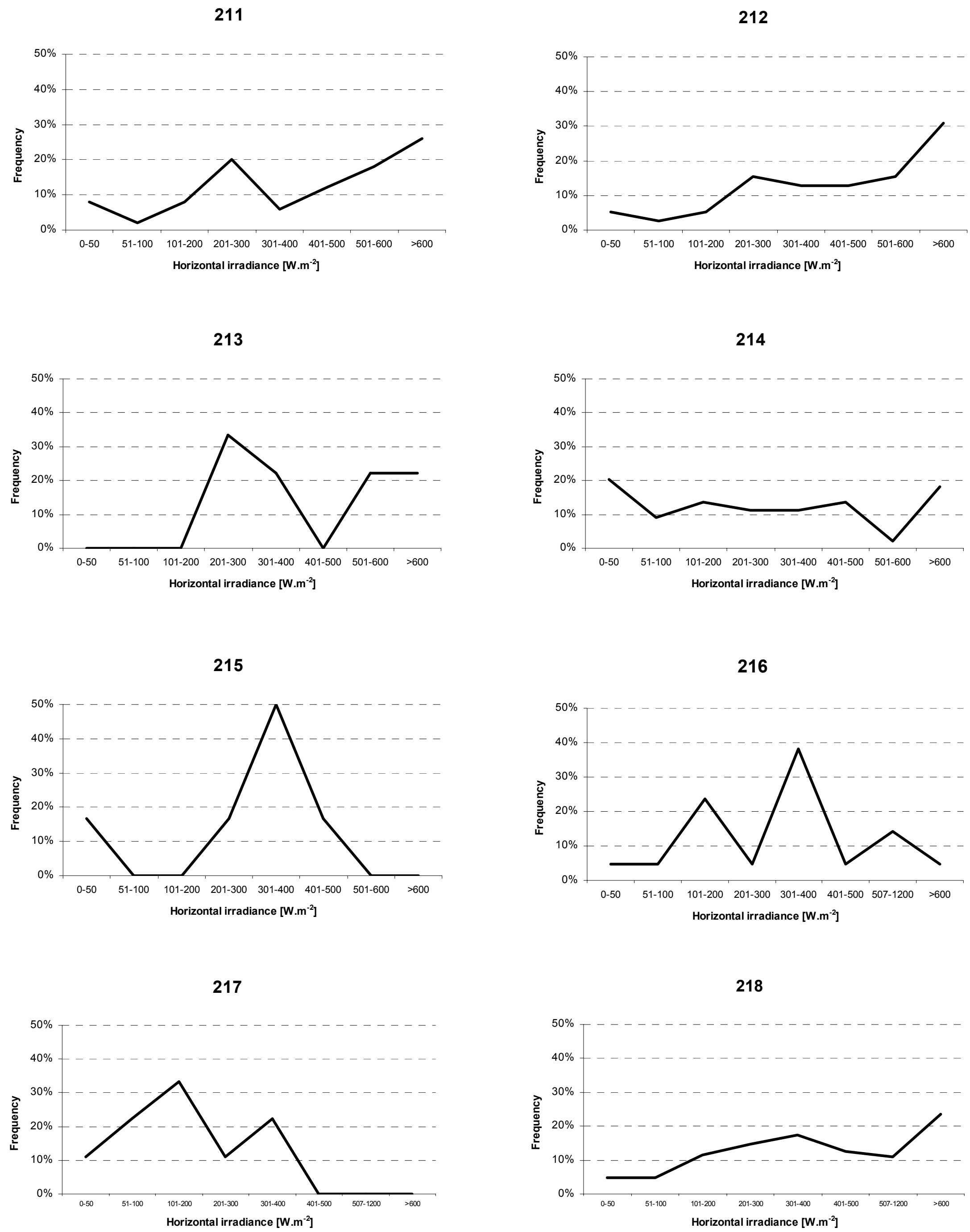


Figure 33: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in Southwest façade for rooms 211-218

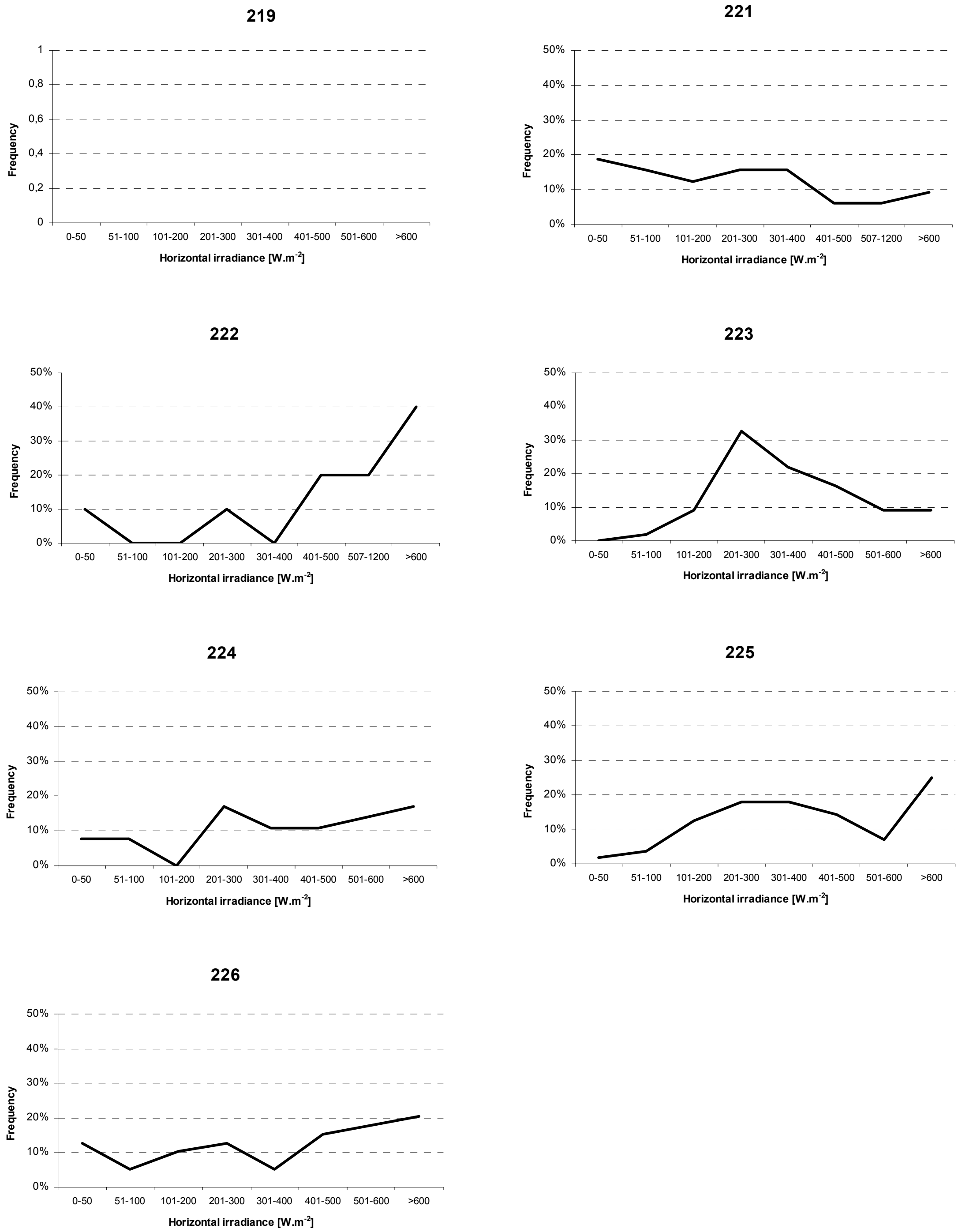


Figure 34: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in Southwest façade for rooms 218-226

5 rooms were selected for a detailed illustration. The relationship between opening-closing actions and horizontal irradiance is illustrated. Figure 35 illustrates the frequency distribution of opening shades over a period of one year for room 211 on the Southwest façade. There is not a remarkable relationship in Figure 35. However, the frequency of opening actions is high by irradiance classes between 0 and 50 W.m^{-2}. Between 100 and 200 W.m^{-2}, frequency reaches its highest value in this illustration. Occupants tend to close shades by higher horizontal irradiance values (see Figure 36). Although there is an unexpected increase of frequency between 200 and 300 W.m^{-2}, the relationship between frequency distribution of closing shades and horizontal irradiance is visible in this graph.

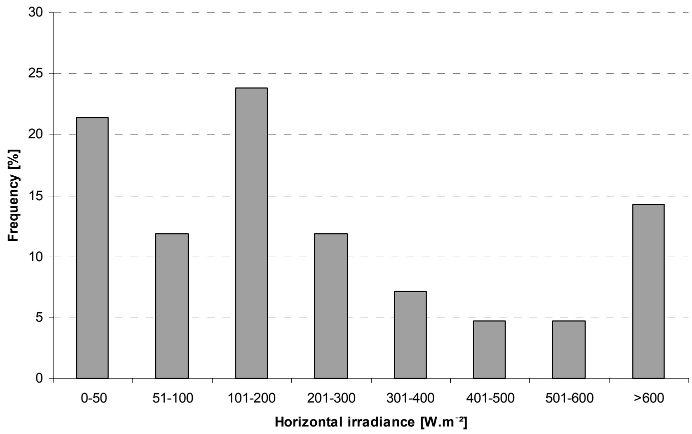


Figure 35: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in room 211 over a period of one year

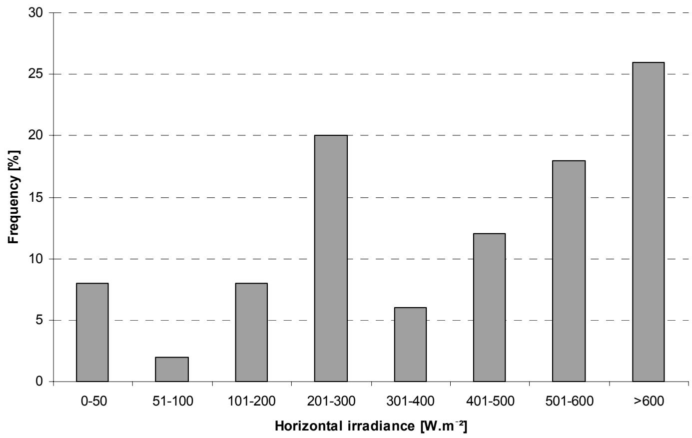


Figure 36: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in room 211 over a period of one year

The frequency of opening and closing actions as a function of the time of the day is illustrated below for room 211. Figure 37 presents user's tendency of opening shades during the day. The number of opening actions is considered in one hour periods. The frequency of opening shades is higher in the afternoon and early evening between 16 and 17 o'clock.

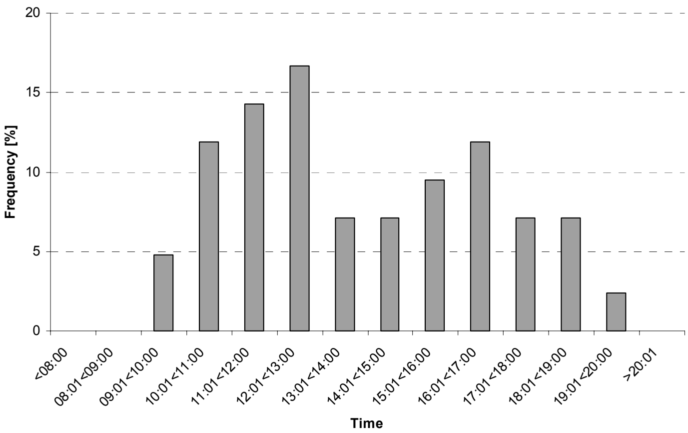


Figure 37: Frequency distribution of the event "opening shades" grouped in terms of one hour periods of the day for room 211 over a period of one year

In Figure 38 illustrates that users tend to close shades between 11 and 12 o'clock more often than the rest of the day. Frequency is also high between 14 and 15 o'clock.

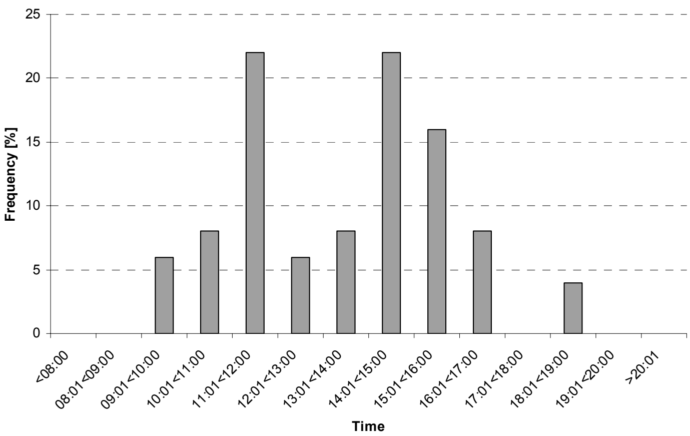


Figure 38: Frequency distribution of the event "closing shades" grouped in terms of one hour periods of the day for room 211 over a period of one year

The following 4 figures illustrate results for shades deployment of room 212. Figure 39 illustrates that occupants open shades by lower irradiance values. There is not a clear relationship in this illustration because of increases of frequency by irradiance classes between 100 and 200 W.m^{-2}. Between 400 and 500 W.m^{-2}, frequency is also high.

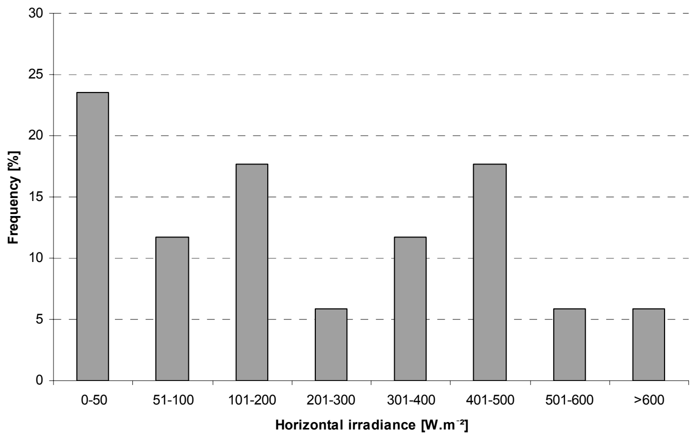


Figure 39: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in room 212 over a period of one year

Figure 40 presents the relationship between frequency of closing actions and horizontal irradiance for room 212 over a period of one year. The relationship is remarkable. A linear function of frequency versus irradiance values can be drawn for this graph. By 600 W.m^{-2} and higher classes, frequency of closing shades rises up to 30%.

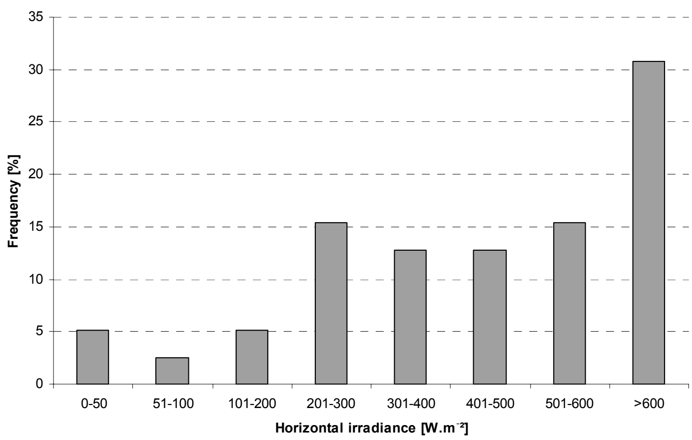


Figure 40: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in room 212 over a period of one year

Figure 41 illustrates time periods in which occupant's tendency of opening shades shows an increase. Between 17 and 18 o'clock, frequency is higher than the rest of the day. No opening actions are registered during morning hours. Also frequency is very low in the afternoon.

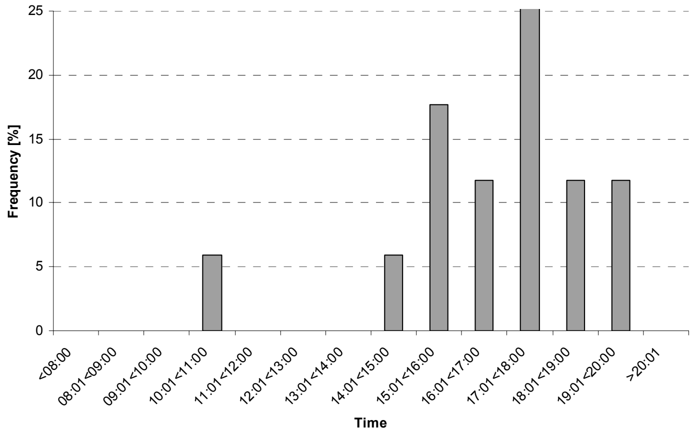


Figure 41: Frequency distribution of the event "opening shades" grouped in terms of one hour periods of the day for room 212 over a period of one year

Figure 42 illustrates that occupants of room 212 tended to close shades between 11 and 12 o'clock more often. Frequency of closing shades is higher between 14 and 15 o'clock than the frequency registered for the rest of the day. Number actions rises by begin of the day and falls by the end of the day.

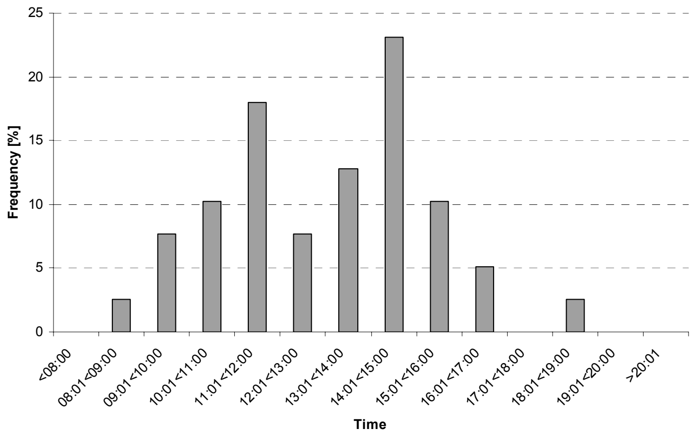


Figure 42: Frequency distribution of the event "closing shades" grouped in terms of one hour periods of the day for room 212 over a period of one year

The following four figures illustrate shades deployment results of room 223. Figure 43 illustrates that occupants open shades by irradiance classes between 100 and 400 W.m^{-2} more frequently.

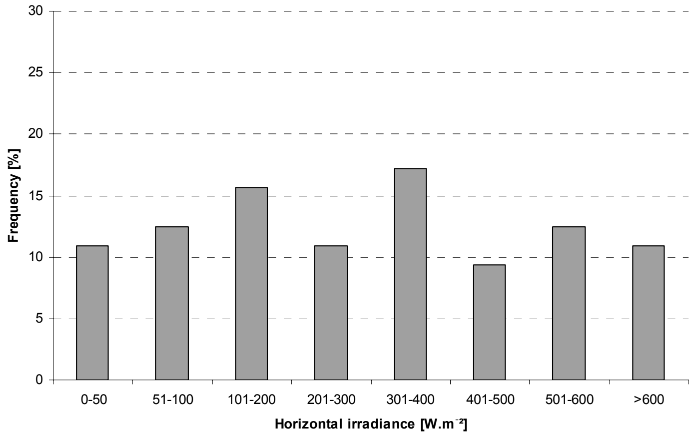


Figure 43: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in room 223 over a period of one year

Figure 44 shows that occupants tend to close shades more often by irradiance classes between 200 and 300 W.m^{-2}. Frequency falls while horizontal irradiance rises.

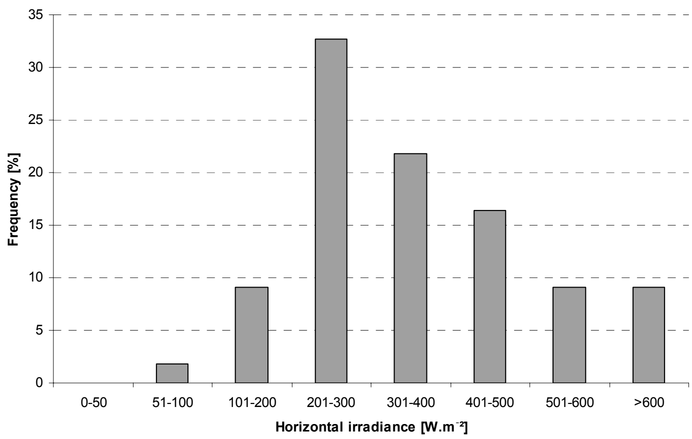


Figure 44: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in room 223 over a period of one year

Figure 45 illustrates time periods in which occupant's tendency of opening shades shows an increase. In morning hours, the frequency is higher than the rest of the day. Frequency of opening shades falls after 11 o'clock. However, there is an increase between 14 and 15 o'clock.

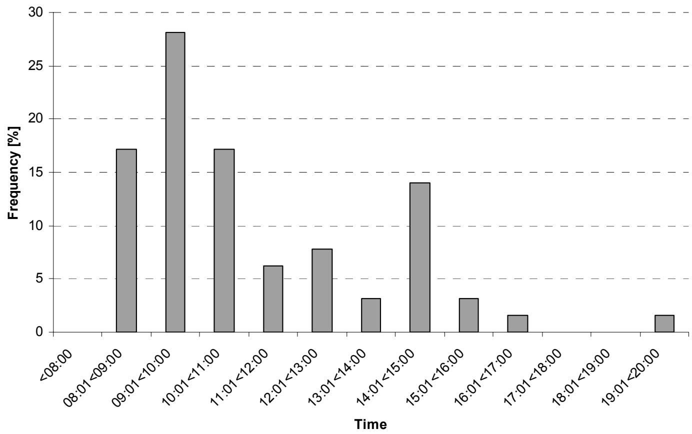


Figure 45: Frequency distribution of the event "opening shades" grouped in terms of one hour periods of the day for room 223 over a period of one year

In Figure 46, frequency of closing shades rises from 8 o'clock until 14 o'clock and falls beginning from 14 o'clock. After 15 o'clock, occupants' tendency of closing shades is low.

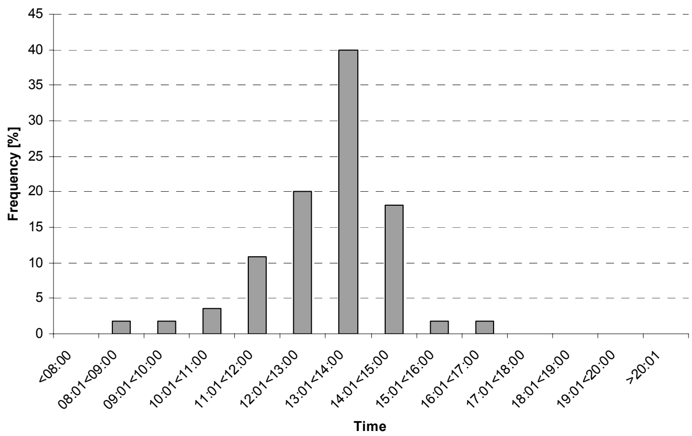


Figure 46: Frequency distribution of the event "closing shades" grouped in terms of one hour periods of the day for room 223 over a period of one year

The following four figures illustrate shades deployment results of room 225. Figure 47 illustrates the frequency distribution of opening shades in terms of horizontal irradiance over a period of one year. By irradiance classes between 0 and 300 W.m^{-2}, the frequency is relative high. Beginning from 400 Wm^{-2}, the frequency falls.

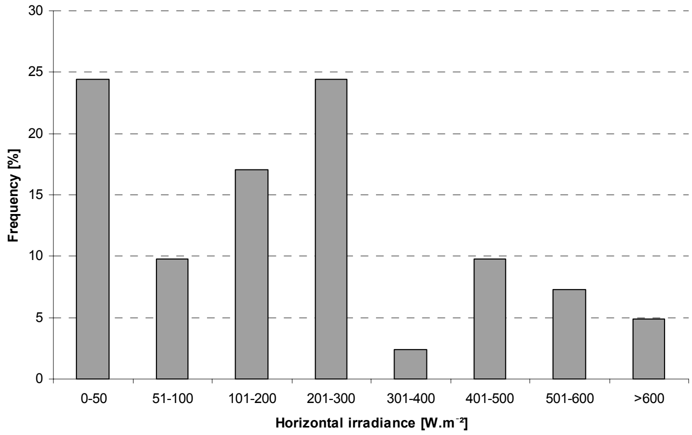


Figure 47: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in room 225 over a period of one year

Figure 48 presents same relationship for closing actions. Occupants of room 225 tend to open shades more frequently by more than 600 Wm^{-2}. Frequency of closing actions rises by irradiance classes from 0 to 400 Wm^{-2}. There is a relationship between frequency distribution of closing shades and horizontal irradiance due to the low frequency registered between 500 and 600 Wm^{-2}.

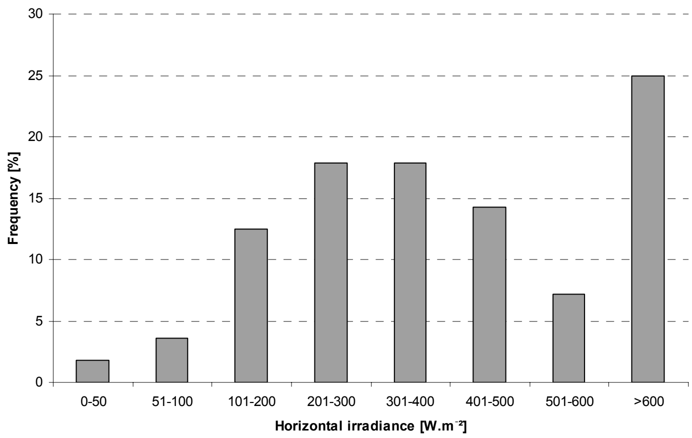


Figure 48: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in room 225 over a period of one year

Figure 49 illustrates the relationship between frequency distribution of opening shades and time over a period of one year. Between 8 and 12 o'clock, occupants of room 225 tend to open shades. They tend to open shades also between 15 and 18 o'clock more frequently, so most of the opening actions are registered during morning hours and early evening hours.

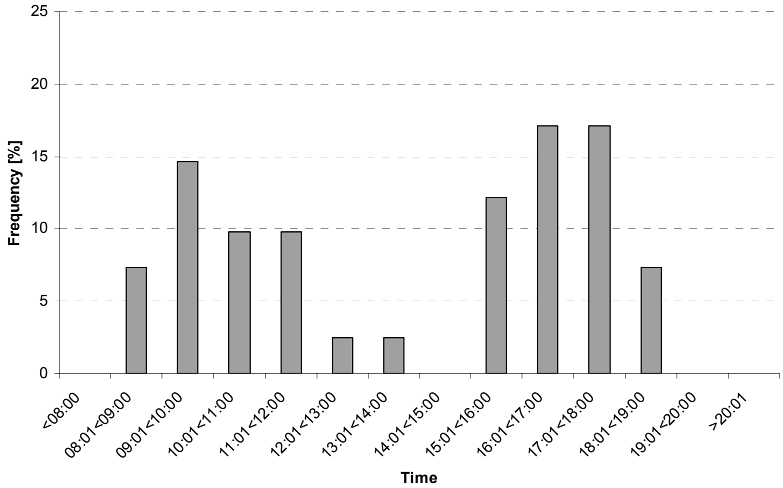


Figure 49: Frequency distribution of the event "opening shades" grouped in terms of one hour periods of the day for room 225 over a period of one year

In Figure 50, frequency of closing shades rises from 10 to 13 o'clock. At 13 o'clock, the frequency reaches 30%. Between 14 and 17 o'clock, the frequency of closing shades begins falling. After 18 o'clock, no closing action was registered.

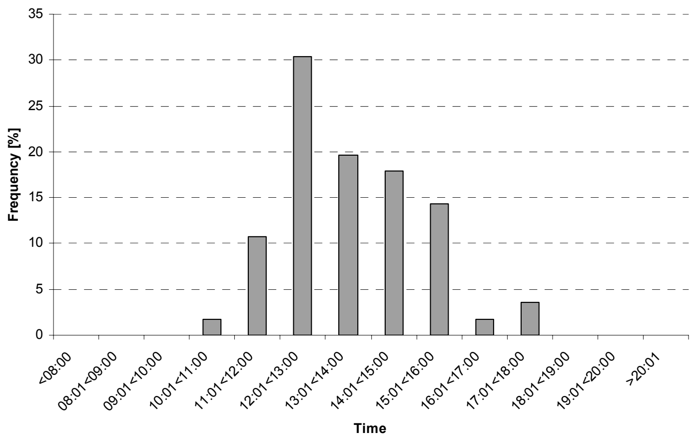


Figure 50: Frequency distribution of the event "closing shades" grouped in terms of one hour periods of the day for room 225 over a period of one year

The following four figures illustrate shades deployment results for room 226. Figure 51 illustrates the frequency distribution of opening shades in terms of horizontal irradiance over a period of one year. By irradiance classes between 50 and 100 W.m^{-2}; between 200 and 300 W.m^{-2}, frequency is higher than the frequency registered by other irradiance classes.

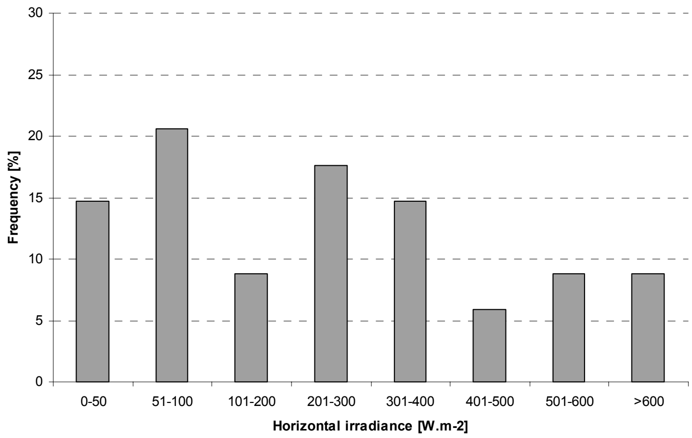


Figure 51: Frequency distribution of the event "opening shades" grouped in terms of horizontal irradiance classes in room 226 over a period of one year

In Figure 52 illustrates the relationship between frequency distribution of closing shades versus irradiance. Between 50 and 100 W.m^{-2} and between 300-400 W.m^{-2}, frequency is very low. However, there is a remarkable relationship because of the increasing number of closing actions by higher irradiance classes.

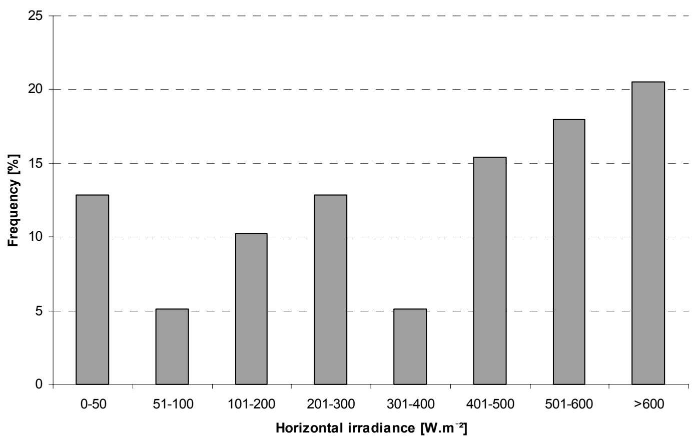


Figure 52: Frequency distribution of the event "closing shades" grouped in terms of horizontal irradiance classes in room 226 over a period of one year

Figure 53 presents the relationship of frequency distribution of opening shades versus time of the day. Number of opening actions increases beginning from morning hours up to early evening hours. Between 18 o'clock and 19 o'clock, frequency of opening actions is about 23%.

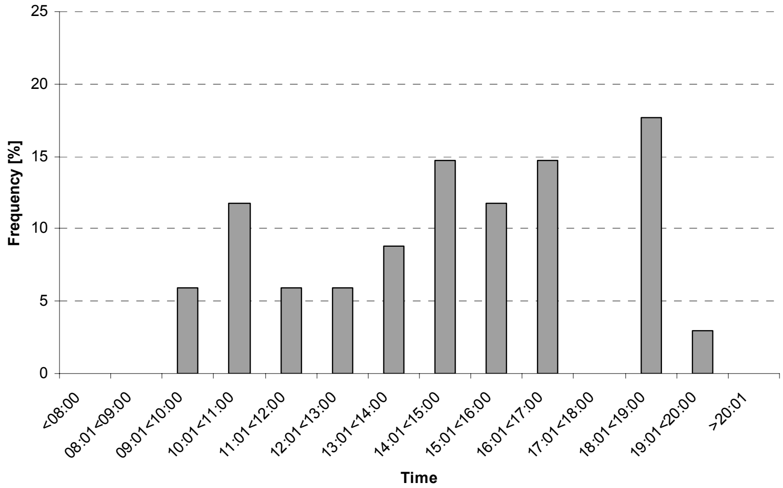


Figure 53: Frequency distribution of the event "opening shades" grouped in terms of one hour periods of the day for room 226 over a period of one year

Figure 54 presents the relationship of frequency distribution of closing shades versus time of the day. Most of the opening actions were registered between 10 and 12 o'clock. Also between 13 and 16 o'clock, occupants of room 226 tend to close shades frequently.

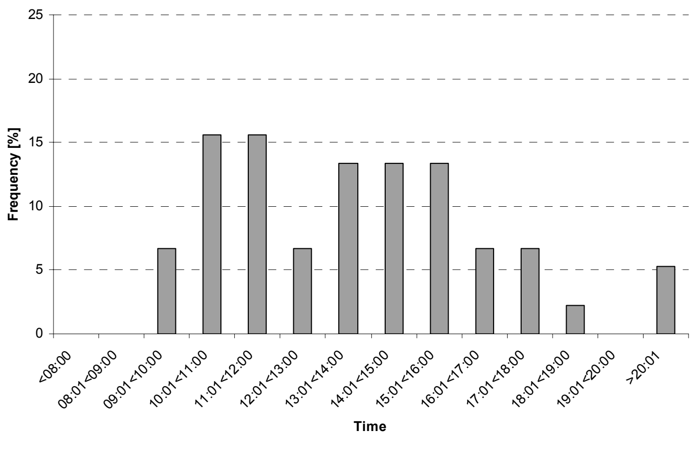


Figure 54: Frequency distribution of the event "closing shades" grouped in terms of one hour periods of the day for room 226 over a period of one year

3.2 Lighting

Data taken from occupancy and light status logger was analyzed for finding the amount of wasted energy caused by the absences of occupants. For this study, total time of absences of occupants and total time of lighting was compared.

Time gaps when the light is on and the occupant is absent were measured. For example, in room 111, light was on for 163 hours during the absences of the occupant. Room 111 is lit by 9 fixtures of 43W (36W + 7W) and energy price per kWh is app €0.06. The room are is 13,34 m². Following calculations may be done for energy saving:

1) **9 fixtures x 0.043 kW/ fixture x 163 hours/year = 63 kWh/year**

2) **63 kWh/year x €0,06/kWh = €3.78/year**

3) **€3.78 / 13,34 m² = €0.28/m²**

The first result shows the amount of wasted energy over a period of one year for the analyzed room. The second result refers to the cost of wasted energy. The third result refers to the cost per m² of the room.

Rooms are listed with the given number (see Table 3). Information for the room includes number of light sources, wattage of the source, cost per kWh and area of the room. In the next column, "Hours" belong to the time of occupancy, absence and sum of them. "Work days" shows for how many days the room might be extra lit with the wasted energy. Definitions of energy, cost and cost per m² are explained by the calculation above.

The following three tables present lighting results for rooms on the North façade:

Table 1: Lighting results for rooms 111-115 over a period of one year

		Occupancy	Absences	Total
Room 111	Hours	535	163	698
9 Light Sources	Work days	67	20	87
9 x 43 = 387 W	Percentage	77	23	100
kWh ~ € 0,06	Energy (kWh)	207	63	270
13,34 m²	Cost (Euro)	12,42	3,78	16,21
	Cost/m²	0,93	0,28	1,21
Room 112	Hours	1725	328	2053
12 Light Sources	Work days	216	41	257
12 x 43 = 516 W	Percentage	84	16	100
kWh ~ € 0,06	Energy (kWh)	890	169	1059
19,02 m²	Cost (Euro)	53,41	10,15	63,56
	Cost/m²	2,81	0,53	3,34
Room 113	Hours	1162	188	1350
9 Light Sources	Work days	145	24	169
9 x 43 = 387 W	Percentage	86	14	100
kWh ~ € 0,06	Energy (kWh)	450	73	522
13,34 m²	Cost (Euro)	26,98	4,37	31,35
	Cost/m²	2,02	0,33	2,35
Room 114	Hours	2182	228	2410
12 Light Sources	Work days	273	29	301
12 x 43 = 516 W	Percentage	91	9	100
kWh ~ € 0,06	Energy (kWh)	1126	118	1244
18,87 m²	Cost (Euro)	67,55	7,06	74,61
	Cost/m²	3,58	0,37	3,95
Room 115	Hours	319	128	447
9 Light Sources	Work days	40	16	56
9 x 43 = 387 W	Percentage	71	29	100
kWh ~ € 0,06	Energy (kWh)	123	50	173
14,25 m²	Cost (Euro)	7,41	2,97	10,38
	Cost/m²	0,52	0,21	0,73

Table 2: Lighting results for rooms 116-122 over a period of one year

		Occupancy	Absences	Total
Room 116	Hours	502	394	896
9 Light Sources	Work days	63	49	112
9 x 43 = 387 W	Percentage	56	44	100
kWh ~ € 0,06	Energy (kWh)	194	152	347
14,14 m²	Cost (Euro)	11,66	9,15	20,81
	Cost/m²	0,82	0,65	1,47
Room 117	Hours	814	200	1014
9 Light Sources	Work days	102	25	127
9 x 43 = 387 W	Percentage	80	20	100
kWh ~ € 0,06	Energy (kWh)	315	77	392
14,15 m²	Cost (Euro)	18,90	4,64	23,55
	Cost/m²	1,34	0,33	1,66
Room 118	Hours	636	189	825
9 Light Sources	Work days	80	24	103
9 x 43 = 387 W	Percentage	77	23	100
kWh ~ € 0,06	Energy (kWh)	246	73	319
14,15 m²	Cost (Euro)	14,77	4,39	19,16
	Cost/m²	1,04	0,31	1,35
Room 121	Hours	1356	404	1760
9 Light Sources	Work days	170	51	220
9 x 43 = 387 W	Percentage	77	23	100
kWh ~ € 0,06	Energy (kWh)	525	156	681
13,44 m²	Cost (Euro)	31,49	9,38	40,87
	Cost/m²	2,34	0,70	3,04
Room 122	Hours	758	201	959
9 Light Sources	Work days	95	25	120
9 x 43 = 387 W	Percentage	79	21	100
kWh ~ € 0,06	Energy (kWh)	293	78	371
13,44 m²	Cost (Euro)	17,60	4,67	22,27
	Cost/m²	1,31	0,35	1,66

Table 3: Lighting results for rooms 123-126 over a period of one year

		Occupancy	Absences	Total
Room 123	Hours	188	164	352
9 Light Sources	Work days	24	21	44
9 x 43 = 387 W	Percentage	53	47	100
kWh ~ € 0,06	Energy (kWh)	73	63	136
14,24 m²	Cost (Euro)	4,37	3,81	8,17
	Cost/m²	0,31	0,27	0,57
Room 124	Hours	207	208	415
12 Light Sources	Work days	26	26	52
12 x 43 = 516 W	Percentage	50	50	100
kWh ~ € 0,06	Energy (kWh)	107	107	214
18,87 m²	Cost (Euro)	6,41	6,44	12,85
	Cost/m²	0,34	0,34	0,68
Room 125	Hours	481	192	673
9 Light Sources	Work days	60	24	84
9 x 43 = 387 W	Percentage	71	29	100
kWh ~ € 0,06	Energy (kWh)	186	74	260
14,14 m²	Cost (Euro)	11,17	4,46	15,63
	Cost/m²	0,79	0,32	1,11
Room 126	Hours	1101	252	1353
9 Light Sources	Work days	138	32	169
9 x 43 = 387 W	Percentage	81	19	100
kWh ~ € 0,06	Energy (kWh)	426	98	524
13,2 m²	Cost (Euro)	25,57	5,85	31,42
	Cost/m²	1,94	0,44	2,38

The following three tables present lighting results for rooms on the Southwest façade:

Table 4: Lighting results for rooms 211-215 over a period of one year

		Occupancy	Absences	Total
Room 211	Hours	818	212	1030
12 Light Sources	Work days	102	27	129
12 x 43 = 516 W	Percentage	79	21	100
kWh ~ € 0,06	Energy (kWh)	422	109	531
17,54 m²	Cost (Euro)	25,33	6,56	31,89
	Cost/m²	1,44	0,37	1,82
Room 212	Hours	1112	371	1483
9 Light Sources	Work days	139	46	185
9 x 43 = 387 W	Percentage	75	25	100
kWh ~ € 0,06	Energy (kWh)	430	144	574
13,44 m²	Cost (Euro)	25,82	8,61	34,44
	Cost/m²	1,92	0,64	2,56
Room 213	Hours	757	230	987
12 Light Sources	Work days	95	29	123
12 x 43 = 516 W	Percentage	77	23	100
kWh ~ € 0,06	Energy (kWh)	391	119	509
18,88 m²	Cost (Euro)	23,44	7,12	30,56
	Cost/m²	1,24	0,38	1,62
Room 214	Hours	1366	238	1604
12 Light Sources	Work days	171	30	201
12 x 43 = 516 W	Percentage	85	15	100
kWh ~ € 0,06	Energy (kWh)	705	123	828
19,02 m²	Cost (Euro)	42,29	7,37	49,66
	Cost/m²	2,22	0,39	2,61
Room 215	Hours	1174	190	1364
9 Light Sources	Work days	147	24	171
9 x 43 = 387 W	Percentage	86	14	100
kWh ~ € 0,06	Energy (kWh)	454	74	528
13,34 m²	Cost (Euro)	27,26	4,41	31,67
	Cost/m²	2,04	0,33	2,37

Table 5: Lighting results for rooms 216-221 over a period of one year

		Occupancy	Absences	Total
Room 216	Hours	978	463	1441
9 Light Sources	Work days	122	58	180
9 x 43 = 387 W	Percentage	68	32	100
kWh ~ € 0,06	Energy (kWh)	378	179	558
14,24 m²	Cost (Euro)	22,71	10,75	33,46
	Cost/m²	1,59	0,75	2,35
Room 217	Hours	1308	734	2042
9 Light Sources	Work days	164	92	255
9 x 43 = 387 W	Percentage	64	36	100
kWh ~ € 0,06	Energy (kWh)	506	284	790
14,14 m²	Cost (Euro)	30,37	17,04	47,42
	Cost/m²	2,15	1,21	3,35
Room 218	Hours	1039	561	1600
9 Light Sources	Work days	130	70	200
9 x 43 = 387 W	Percentage	65	35	100
kWh ~ € 0,06	Energy (kWh)	402	217	619
14,34 m²	Cost (Euro)	24,13	13,03	37,15
	Cost/m²	1,68	0,91	2,59
Room 219	Hours	291	136	427
9 Light Sources	Work days	36	17	53
9 x 43 = 387 W	Percentage	68	32	100
kWh ~ € 0,06	Energy (kWh)	113	53	165
14,25 m²	Cost (Euro)	6,76	3,16	9,91
	Cost/m²	0,47	0,22	0,70
Room 221	Hours	676	374	1050
12 Light Sources	Work days	85	47	131
12 x 43 = 516 W	Percentage	64	36	100
kWh ~ € 0,06	Energy (kWh)	349	193	542
17,94 m²	Cost (Euro)	20,93	11,58	32,51
	Cost/m²	1,17	0,65	1,81

Table 6: Lighting results for rooms 222-226 over a period of one year

		Occupancy	Absences	Total
Room 222	Hours	1020	224	1244
12 Light Sources	Work days	128	28	156
12 x 43 = 516 W	Percentage	82	18	100
kWh ~ € 0,06	Energy (kWh)	526	116	642
18,34 m²	Cost (Euro)	31,58	6,94	38,51
	Cost/m²	1,72	0,38	2,10
Room 223	Hours	229	128	357
9 Light Sources	Work days	29	16	45
9 x 43 = 387 W	Percentage	64	36	100
kWh ~ € 0,06	Energy (kWh)	89	50	138
14,25 m²	Cost (Euro)	5,32	2,97	8,29
	Cost/m²	0,37	0,21	0,58
Room 224	Hours	1104	492	1596
9 Light Sources	Work days	138	62	200
9 x 43 = 387 W	Percentage	69	31	100
kWh ~ € 0,06	Energy (kWh)	427	190	618
14,15 m²	Cost (Euro)	25,63	11,42	37,06
	Cost/m²	1,81	0,81	2,62
Room 225	Hours	779	160	939
9 Light Sources	Work days	97	20	117
9 x 43 = 387 W	Percentage	83	17	100
kWh ~ € 0,06	Energy (kWh)	301	62	363
14,15 m²	Cost (Euro)	18,09	3,72	21,80
	Cost/m²	1,28	0,26	1,54
Room 226	Hours	364	182	546
9 Light Sources	Work days	46	23	68
9 x 43 = 387 W	Percentage	67	33	100
kWh ~ € 0,06	Energy (kWh)	141	70	211
14,15 m²	Cost (Euro)	8,45	4,23	12,68
	Cost/m²	0,60	0,30	0,90

Status of lighting devices was on for 7934 hours during absences of occupants. That results in an energy waste of 3334 kWh. If considered that 3334 kWh has to be added to lighting costs, efficiency of installing occupancy sensors becomes remarkable. This waste of energy causes €200 loss annually for the total of analyzed office rooms.

Table 7: Lighting results for total of all rooms over a period of one year

		Occupancy	Absences	Total
All rooms	Hours	24980	7934	32914
All Light Sources	Work days	3123	992	4114
	Percentage	76	24	100
kWh ~ € 0,06	Energy (kWh)	10185	3334	13519
440,76 m²	Cost (Euro)	611,09	200,03	811,12
	Cost/m²	1,39	0,45	1,84

After calculation of annually wasted energy, a scenario of installing infrared occupancy sensors with switch on-off function is presented (UD 2003). €200 is 26% of the annually lighting costs. To find out how many years it takes to pay back the cost of installing occupancy sensors, the following calculation is done:

According to the Conrad Catalog 2006, a wall-switch occupancy sensor for max 1000W (Wattage of 12 light sources draws about 516W totally) costs about €35, the material cost for 29 rooms would be:

€35/sensor x 29 sensors = €1015

It takes about one hour to install one sensor and the labor cost draws about €15 per hour, so the installation costs would be:

€15/hour x 29 hours = €435

Total cost would be about €1450.

€1450 / €200 / year = 7 years

If sensors are installed in these 29 rooms, the payback for the sensors and maintenance will take 7 - 8 years. This result matches with the expectation of the hypothesis, so that energy saving is possible in long term by using of occupancy sensors.

4. CONCLUSION

In this thesis, an analysis of user control actions in an office building was presented. The relationship between control actions and environmental parameters were illustrated with graphs and tables.

Results for shades deployment show that occupants in most of the rooms tend to close the shades more often by irradiance classes of 300-400 Wm^{-2}. By low irradiance values, user's tendency of opening shades is more pronounced. There is significant variation in shading behavior for analyzed 29 rooms. The distance of the work plane from the window may effect the adjustments of shades. Glare and overheating in the room lead also occupants to change the position of blinds.

An analysis of the occupancy patterns and light use showed a significant potential for the reduction of electrical energy consumption. Roughly 25% of the electrical energy used for lighting could be used through the integration of occupancy sensors in the building's system.

In this research, the relationship between the degree of shades deployment and environmental parameters such as global horizontal irradiance is analyzed. Future research should explore the possible effects of other indoor and outdoor environmental conditions (specifically air temperature) on people's shading behavior.

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