Lighting control system: energy efficiency and users' behaviour in office buildings

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Abstract

Due to new European standards and requirements regarding energy performance in non-residential buildings, it is strategic to explore and quantify the benefits of typical energy saving design measures (automatic systems) compared with traditional operation systems (manual system) considering appropriate reference case studies so to benchmark the performance of automatic control systems. In order to set up design and intervention strategies towards energy saving and environmental protection, efficient daylight-responsive systems for illumination of buildings, including installation of automatic lighting control systems, can provide a significant contribution. Moreover, it is becoming increasingly important to establish a realistic baseline of the actual lighting energy consumption in buildings for the different scenarios nowadays used (both manually and automatically operated), which incorporates occupants' behaviour. The analysis of the energy-saving potential of automated lighting scenarios have been monitored in real use conditions and not in controlled laboratory environments, in order to prove the automation systems efficiency in operating time. The building analyzed is an office block of 6 floors, each with 35 units. Different automation scenarios (in number, typology and location of devices installed) were implemented during the renovation activity carried out in 2007. The building configuration, characterized by the same number and offices distribution for each floor, allows for the simultaneous comparison of the operation systems implemented. The monitoring activity was carried out for two years, starting from February 2008. Using standardisation techniques that consider differences in occupancy duration, as well as indoor and outdoor illuminance levels, it is possible to define the quantitative difference between energy performance of conventional and automatic control scenarios.

1. Introduction

As far as the importance of environmental issues is concerned, the built environment plays an important role: the residential and commercial sectors account for more than 40% of end energy consumption in the European Union and are thus responsible for an important part of carbon dioxide emissions systems (UNEP, 2007). According to an IEA (International Energy Agency) estimation, the lighting electricity use ranges from 5% to 15% of the total electrical energy use in industrialized countries. Approximately 50% of lighting energy (531 TWh) in IEA member countries evaluated is used within the service sector (Mills, 2002).

Considerable savings could be achieved even by application of intelligent control technologies in existing buildings, with acceptable economical parameters (Zalesk, 2006). New European regulations refer specifically to the use of occupancy and light sensors to control the artificial light and to improve the systems' efficiency (UNIEN 15913-2008).

Design software tools are intended to help designers with the elements of daylighting design (IEA, 2000) in order to preview the energy saving obtainable using automation lighting systems: specifically the dimming regulation of artificial light as a function of the natural light level detected in discrete points (Erhorn et al., 1994; Reinhart et al., 2001; Reinhart et al., 2001). These simulation tools require lengthy input processes and are too time consuming to be used by architects and designers. Therefore, simplified methods to estimate energy saving of artificial lighting use from daylighting have been developed. Among them the most important operate giving geometrical factor (windows area, windows type, perimeter area) and do not include automation control systems (Krarti et al., 2005).

Moreover, energy simulation tools for existing buildings do not adequately model the actual performance of daylighting systems: indeed it is possible to overestimate electrical lighting energy saving by 20.7% annually (Seo et al., 2011). The main causes are temporal problems, outdoor illuminance and sky luminance distribution simulation, fenestration features operation, indoor illuminance level expected, human factors and lighting control results.

The last two factors express a high variability and influence significantly the final result of the energy saving amount expected using automation systems. For this reason the international scientific community carried out several studies in order to monitor and analyze users' interactions with building control systems and devices (Hunt, 1979; Reinhart et al. 2002, Mahdavi et al., 2008).

The computational modelling of occupants' control-oriented actions in building performance simulation applications can be significantly improved based on such empirical information on user behaviour (Mahdavi et al., 2007) and on data monitored in real use condition. In this way, it is possible to collect data about both building users' interactions with building control systems and devices' efficiency in order to develop a stochastic model for predicting lighting energy consumption.

For this reason it is strategic to explore and quantify the benefits of typical energy-saving design measures (automated systems) compared with a traditional operation system (manual system), defining suitable reference cases for benchmarking the performance of automated lighting control. The analysis of the energy-saving potential of automated lighting scenarios should be monitored in real use conditions and not in controlled laboratory environment, in order to prove the automation systems efficiency in operating time (Mahdavi et al., 2008).

2. Case study

A specific case study has been analyzed: an office building in Trento (northern Italy) in which a total refurbishment of the electrical system and informatics net have been carried out recently. The building has 6 floors, each of 1200 m^2, with a similar indoor distribution. The two main expositions are north and south. The building is characterized by four different and modular office typologies, each with the same power density installed and with the same natural light condition, even if with different surface and occupant number (Table 1).

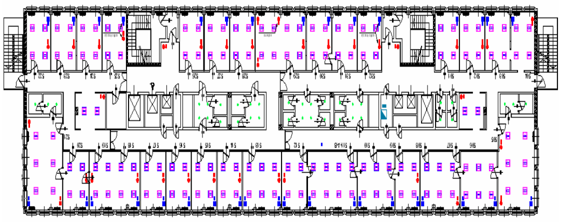

Fig. 1 – Floor type

There is the same windows typology (dimension 1.15m x 1.20m) with a constant inter-axis belong both the façades. The same shading system is present: internal venetian blind, manually operated.

The artificial light is provided by lamps (1/55 W each, tubes T5). They have been designed in order to maintain 500 lux at the end of the luminaires life, by night. In the first utilization period they produce an over-density of luminous flux.

In the central part of the building service spaces are positioned: corridors, bathrooms, stairs and elevators.

OFFICE TYPOLOGY	DEPTH (m)	WIDTH (m)	SURFACE (m^2)	WINDOW SURFACE (m^2)	ELECTRICAL POWER (W / m^2)
A	5	3,5	17,5	2,76	12,57
B	5	5,25	26,25	4,14	12,57
C	5	7	35	5,52	12,57
D			40-56	6,9	11,00-9,82

Table 1 – Office typology

The D type office represents a peculiar situation regarding:

- *utilisation modality*: not office but meeting room , with different occupancy level;
- *exposition:* not only one but two façade with South East/ South West windows;
- *surface*: the meeting rooms can be different floor by floor;
- *power density:* could by different in relation with the surface area.

Excepted from D type, the other office types can be homogeneously compared, distinguished only by

façade expositions. In this paper we will refer about S_xyy or N_xyy office where:
S = south façade
N = north façade
x = floor
yy = office progressive number
If there is no office number the code refers to the average data for a specific floor (e.g. S_1, N_1; etc.).

2.1 Technology applied

As reported in the introduction, it is strategic to prove the effectiveness of the automation system in real use condition in order to obtain a benchmarking of the correction factor to introduce in the software tool calculation. Simulation tools (Relux 2009, Adeline 3) have been used in this research just to estimate the indoor illuminance level available in the building monitored and the relative energy saving obtainable using dimming technology.
The research focus is not the simulation result but the real energy-saving data derived by the monitoring campaign.
The lighting system on the fifth floor is still manually operated, as required in the previous installation system (switching on/off the office luminaires by two channels: right table zone, left bookshelves zones).
In each of the other five floors a specific scenario has been applied using automation systems with different type and number of controlled parameters and increasing complexity level, as described in the following. With scenario is intended in this paper a real setting of controls, not a simulation result.

Scenario 1 (6th FLOOR): requires that the IR occupancy sensor installed (Figure2) switches off the light if nobody is detected in the office for more than 15 minutes.
The used devices also have the light level detection function, in order to turn off the light if unnecessary, but their sensitivity is not high enough (the illuminance threshold is manually selected) and it can suddenly and improperly control the lighting operation.
With this technology is not possible to monitor and record the value read by the devices; thus it is difficult to give a functionality diagnosis of these sensors. Asking the users, they have complained of errors in the presence detection.

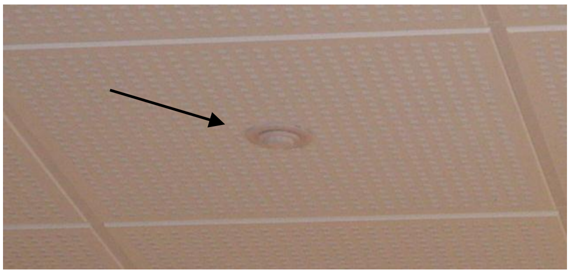

Fig. 2 – Presence sensor

Scenario 2 (4th FLOOR): implies in addition that lights are switched off, if the daylight-based task illuminance level exceeds 500 lx.
It is also possible to manually dim the luminaires. Technology by KNX (www.knx.org) has been used; digitally sends on the bus the communication telegrams, enabling the monitoring action.
These devices (Figure 3) give more accurate measures (higher number of switching segments), and moreover their application program allows the maintenance of a constant illuminance level, even not enabled in this application, in order to investigate this specific activation modality. In this application the user decision ability is higher, using a dimming regulation modality: the light intensity is manually selected and maintained until the absence is detected. Defects in brightness reading depend on the surface colour corresponding to the detection direction (vertical line) that could describe a different condition compared to that one on the working surface.
Because the KNX installation flexibility, in the future this configuration could be changed just downloading a new device parameterization.

Fig. 3 – Brightness and presence sensor

Scenario 3 (3rd FLOOR): the luminaires are switched on when occupancy is detected and dimmed (by two separately controlled circuits, depending on the windows distance) so as to provide predefined minimum illuminance levels (500 lux). It is moreover possible to force the automated regulation in compliance with users' preferences, maintaining this value until the absence is detected.

The smart devices applied in order to detect the presence are the same used for scenario 1. Two luminance sensors have been installed for each façade in order to detect the natural light level incoming from the windows. The two reference rooms have been chosen in order to avoid the use of shading system for the detected windows, and in this way to obtain the higher level of natural light contribution for the two expositions façades.

Obviously it is possible to have lower inside illuminance level and probably lower dimming value in offices where the venetian blinds are partially closed.

The installation position and direction of these devices is a crucial point in order to manage a correct measure. It is strictly related to its internal position in correspondence with the window. For the specific case study there is a homogeneous distribution in the façade of the transparent surfaces.

The dimming percentage required is selected by the electrical engineer during the commissioning process, operated directly by manual regulation, using the manual calibration of each dimming channel.

The installation in each office of both this specific light sensor and the presence detector was evaluated as being too expensive a solution. It is not possible to record the illuminance level detected by these sensors because it is an internal variable to the system's functionality.

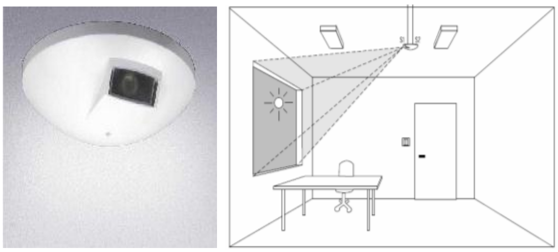

Fig. 4 – Light sensor and its installation modality

The communication protocol, applied to control this lighting control system, is the DSI. In the installed configuration it is not possible to record the dimming percentage as a digital value.

Scenario 4 (2nd FLOOR): the activation modalities are the same as scenario 3 (possibility to switch between the automatic and manual control of the artificial light). The procedure and the number of the inside illuminance measures are different. In this case there is one light/occupancy sensor for each office, with a specific artificial light level required. The detection point is positioned in the middle of the room, on the working desk.

The communication protocol is KNX, as for scenario 2. The regulation actions of the devices for this scenario can be recorded (occupancy, inside illuminance, dimming percentage, manually forced command).

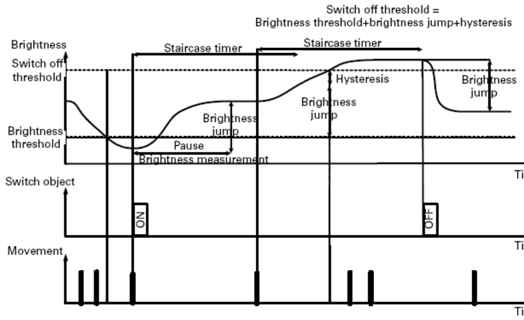

Fig. 5 – Functionality system for the presence/light sensor: constant illuminance level maintenance

Scenario 5 (1st FLOOR): requires the unlocking function of the occupancy sensors by switching in each office. This allows that when the occupancy detector is enabled, the light is automatically dimmed in order to maintain a minimum illuminance level of 500 lux.

The user can autonomously decide to have only the light turn on or off but with the dimming level directly calculated by the system, with any possibility to be manually changed.

The used technology is still the KNX protocol (gateway DALI), and all the parameters controlled by the bus system are simultaneously recorded. This was the last floor to be built, so an additional function for the installed devices was available, concerning the occupancy detection: the detection area can be divided in four sectors. With this application B sector could be excluded, preventing switching on the light in one office with the open door even if somebody walks in the corridor closed to the detected area.

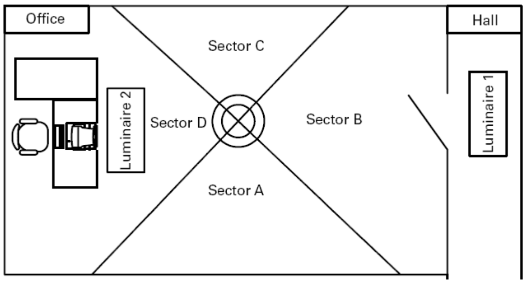

Fig. 6 – Detection area subdivision

3. Method

The research activity has the aim of setting up a new approach for the design of lighting systems in office buildings using smart devices in order to achieve:

- higher energy saving,
- better visual comfort conditions,
- user satisfaction for smart technology utilization modality.

The analysis of these three topics has been developed in real use conditions and not in controlled laboratory environments. In this way it is possible to test the potentialities and limits of technological solutions currently available on the market, the comfort perceived by humans and performed by the system, the interaction between users and partially/completely automated systems.

In order to quantify the difference between energy performance of conventional lighting systems and each automated control scenarios, the energy demand of each case has been considered separately and a pair wise comparison has been performed.

In this research the manual lighting system is assumed as operated by an on/off switch; the automated scenarios are defined above.

In order to test scenarios so as to reduce the energy demand and guarantee at the same time visual comfort improvement, the following factors have been considered:

- control of the user's presence in the office, as a necessary condition to turn on the light;
- regulation of the artificial light, in relation to the natural light level;
- possibility of a manual regulation of the light, forcing the automatic regulation, in order to better meet the user's needs.

The balance between manual and automatic regulation is a crucial point in order to evaluate the realistic usability to the analyzed technology.

To carry out this analysis it is necessary to compare homogeneous or normalized environments (by specific factors) simulating the same boundary conditions.

In order to understand and model users' behaviour in offices operated manually and to quantify the energy saving potentials of automation systems for lighting control, a typical day data analysis was carried out. In this way it is possible to perform an hourly data analysis, depicting typical patterns of presence, actions, and energy use over time instead of mere daily overviews (Mahdavi et al., 2006). All collected data are temporally expressed in terms of a sequence of three-minute intervals. In this way the data collection results are synchronized and it is possible to relate different events occurring at the same time interval in a specific room.

We compare the lighting energy use in the offices for the implemented scenarios using standardisation techniques. In particular the following normalisation factors have been considered:

- *Occupancy level*: energy consumption (Wh/m^2) is related to actual presence time in the classrooms resulting in occupancy-normalised values (W/m^2);
- *Outside illuminance*: For the scenarios implemented, the occupancy periods could differ from classroom to classroom. Thus, the corresponding outdoor illuminance levels (and thus the effectively available daylight) were compared to see if the boundary conditions could be assumed to be identical for the scenarios;
- *Indoor illuminance factor*: To compare manual and automated operation scenarios in terms of energy consumption, one should consider the visual performance requirements (in this case illuminance levels). The automated scenario guarantees that minimum illuminance levels are maintained, unlike in the manual operation. To

take this effect into consideration, a specific illuminance factors were formulated in relation with the indoor illuminance level requirements defined in compliance with the UNI EN 12464-2/2004 regulations.

The analytical definition of the normalisation factors expressed above are detailed, presented and justified in (Chiogna et al., 2011).

In order to quantify the difference between energy performance of conventional versus each automated control scenarios, we isolated the energy demand of each case and performed a pair-wise comparison.

4. Results and discussion

Monitoring results are stored in a databank and structured by the supervision software Gefasoft 7.1. For each day, a file is generated with temporally ordered data. Each single message is labelled with a distinctive number by means and the different data points have been synchronized using the Visual Basic program.

Figure 7 compares the mean presence value in the traditional floor with the presence levels for the 5 automated control scenarios.

As Figures 7 and 8 demonstrate, there is a difference between the monitored occupancy levels in each different floor of the building not only during typical day analysis (Figure 7) but also considering the monthly occupancy hours (Figure 8). Thus, it was necessary to normalise the energy use values based on the occupancy data so as to make a comparison between various scenarios possible.

A normalisation was also performed regarding the available outdoor illuminance levels, even though in this case the variations of illuminance levels for various scenarios was not so relevant throughout the observation period (Figure 9).

In winter months (Figure 10) as in summer months the correspondence between low illuminance level and high-energy demand is respected considering the mean value in the whole observation period.

The major consumption in winter months confirms the correlation between outside illuminance level and energy demand.

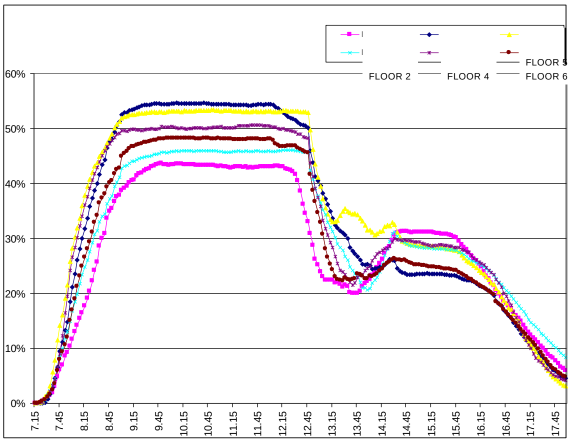

Fig. 7 – Presence levels in percentage each floor of the building in April

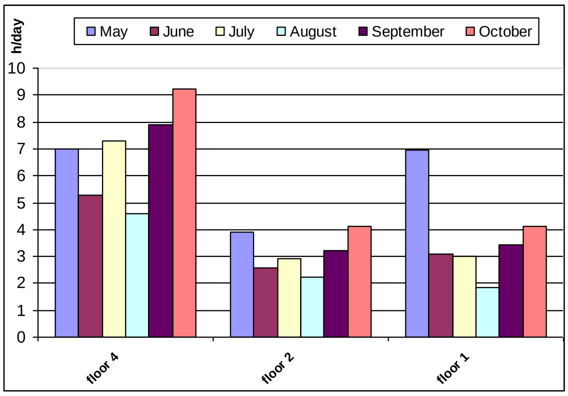

Fig. 8 – Mean presence daily hours from May to October level in floor 1,2 and 4

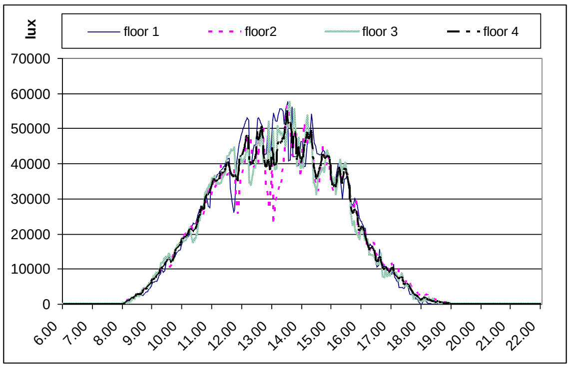

Fig. 9 – Outdoor illuminance levels for occupancy hours: floor 1,2,3,4 in September

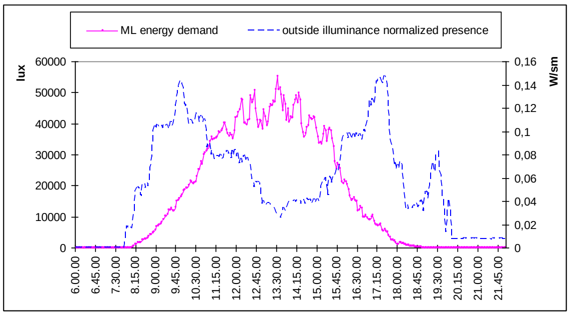

Fig. 10 – Correlation between outdoor illuminance and energy demand for floor 2 in winter time

Figures 11-14 show the energy saving respectively in summer and winter months for each floor calculated not just as absolute value but as value additionally normalized for the following factors: presence, outdoor illuminance and inside illuminace. Moreover, the percentage of energy saving has been converted in two values correlated to environmental and economic factors: CO_2/m^2 and €/m² (Fig 14 -16). The conversion factor in order to express kWh in grams of CO_2 equivalent is 580 (ISPRA, 2011); the price of electricity used for the calculation is 0,14588 €/kWh (mean price in 2009 for the private use of the electricity). The effect of normalisation factors is significant in the energy saving calculation.

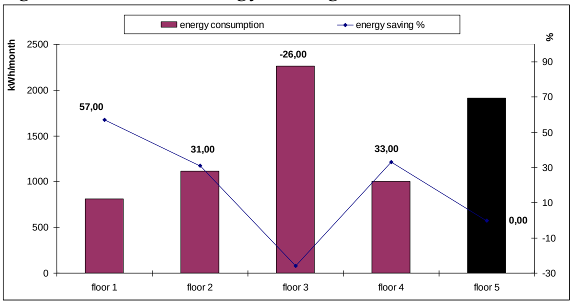

Fig. 11 – Energy saving of each scenario (normalized by presence, indoor and outdoor factor) in the summer' months

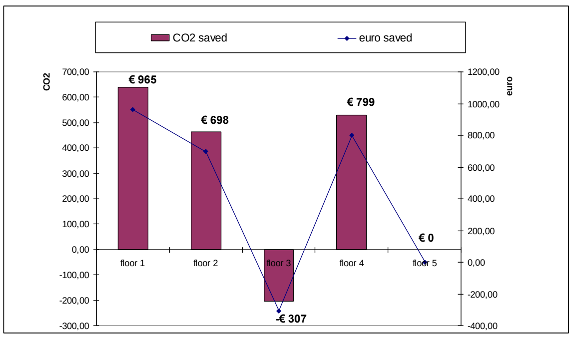

Fig. 12 – Energy saving of each scenario , in terms of CO2/month and €/month ,) in the summer months

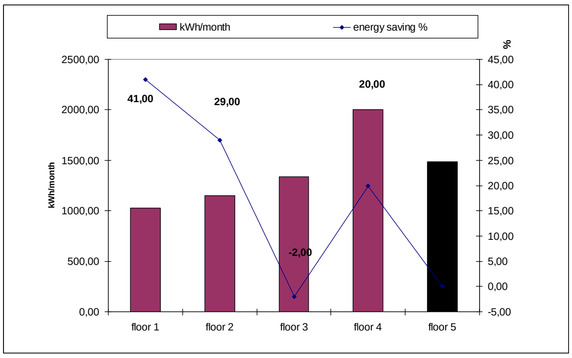

Fig. 13 – Energy saving of each scenario (normalized by presence, indoor and outdoor factor) in the winter months

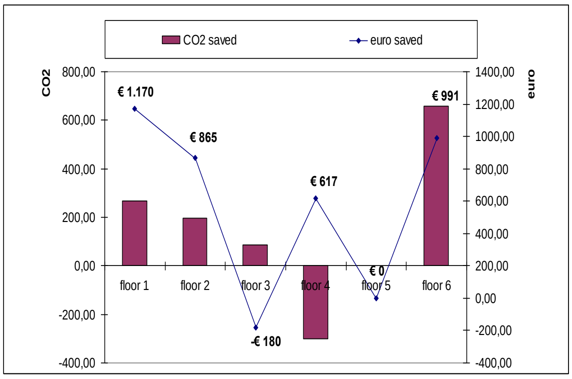

Fig. 14 – Energy saving of each scenario, in terms of CO2/month and €/month) in the winter months

The use of automation techniques allows to reach a significant energy saving amount (Figure 11-14).The overall energy use comparison between traditional and automated classrooms shows that, depending on the observation month,

a) floor 1 requires 41% to 51% less energy for electrical lighting;

b) floor 2 consumes monthly 30% to 31% less electrical energy for lighting;

c) floor 3 needs 2% to 26% more electrical energy for lighting;

d) floor 4 needs 20% to 33% less electrical energy for lighting;

For the scenario 1, applied at the sixth floor, it was not possible to normalize the energy consumption using the data monitored by the KNX systems. Using the presence schedule data of the worker, only a monthly presence normalisation factor has been calculated. In this case, it was not possible to evaluate the effective presence in the office or just in the building of the worker. For this reason, the results about this floor have been not included in this analysis. Only the qualitative impression of the users was investigated: the general impression was that the system does not perform because of the improper turning off of the lights even if people were in the office.

For the data detailed above, it is clear that an automated scenario not correctly implemented, such as the scenario 3 applied on the third floor, can produce increasing energy consumption also in comparison with offices operated manually.

Considering the trend of energy demand considering the use of the dimming regulation (floor 1 and 2) or not (floor 4) it is clear the different lighting energy use in relation with the outside illuminance level.

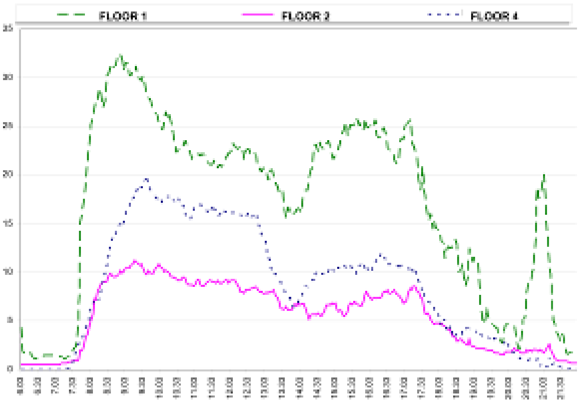

Fig. 15 – Lighting energy use percentage in June: typical day representation for the floors 1, 2 and 4

5. Conclusion

The research results demonstrate that the use of automated systems for the artificial light control can yield considerable energy savings (between 30% and 60% in the observed winter semester), depending on the complexity of the parameters controlled and on the number and of the devices installed.

The tested automated systems could be further improved using a shading control system.

The next research steps involve further data analysis of additional data (correlation between orientation and energy demand) and documentation of control-oriented user behaviour.

The behaviour model extracted from this data analysis could be incorporated in software tools for lighting performance simulation in buildings.

6. Acknowledgements

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