Lighting energy savings in offices using different control systems and their real consumption

B. Roisin \textsuperscript{a,*}, M. Bodart \textsuperscript{b}, A. Deneyer \textsuperscript{c}, P. D’Herdt \textsuperscript{c}

\textsuperscript{a} Université Catholique de Louvain (UCL), Unité Architecture, Place du Levant, 1, B-1348 Louvain-La-Neuve, Belgium
\textsuperscript{b} Fond National de la Recherche Scientifique (FNRS), Université Catholique de Louvain (UCL), Unité d’Architecture, Place du Levant, 1, B-1348 Louvain-La-Neuve, Belgium
\textsuperscript{c} Belgian Building Research Institute (BBRI), Division of Energy and Climate, Avenue Pierre Holoffe, 21, 1342 Limelette, Belgium

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Abstract

This paper compares the potential of lighting energy savings in office rooms by using different control systems, for three locations in Europe and the four main orientations. The method is based on DAYSIM simulations to perform daylight calculations, on laboratory measurement to evaluate precise system energy consumptions and on the implementation of a new algorithm to simulate a close-loop daylight dimming system. It appears that the control of the electrical power in function of daylight leads to very high savings; they slightly depend on the room orientation and the location. Savings vary from 45 to 61%. The performances of an occupancy sensor are also tested. Threshold values of occupancy rate for which daylight dimming leads to higher gains than an occupancy control system vary between 27 and 44% depending on location and orientation. The measurements of the energy consumption of the sensors and detectors also permit to conclude that systems with embedded DALI-compatible ballast controllers should be abandoned in favour of a centralized DALI-compatible ballast controller or embedded analogue systems.

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1. Introduction

Recently, many different lighting control systems have been developed. One of their first application field is the tertiary sector and, in particular, office buildings. Their aims are to reduce the lighting energy consumption while maintaining a high level of lighting comfort. While authors agree on the positive impact of these systems, there is a disagreement in quantifying their saving potential. This quantification can be based either on monitoring in existing buildings or by simulations.

Measured lighting energy savings show a very large range of variation. Jennings et al. have tried to identify the impact of different control systems on office lighting consumption \cite{1}. By measuring the consumption of retrofitted installations, they concluded that an occupancy sensor can save up to 20% and a daylight dimming control system up to 26% by comparison with manual switching. Knight measured gains from 44 to 76% using daylight control systems \cite{2}. Galasiu et al. have evaluated the impacts of window blinds control on two different daylight control systems \cite{3}. The savings using an open loop dimming control system and different controlled shading systems vary from 5 to 45%. In a Norwegian study, the saving potential due to daylight dimming systems is about 30–40% for south-facing rooms and 20–30% for north-facing \cite{4}. Li et al. evaluated the performances of daylight dimming and on/off control system \cite{5}. They concluded that the daylight dimming system reduces the energy consumption by 33%. The correlation curve between electric lighting load and vertical daylight illuminance which can be useful to determine energy savings is found in \cite{5,6}. A survey in Turkey evaluates the gains obtained with a daylight dimming system according to the type of sky. For clear days the gains are 35%, 33% for mixed days and 16% for overcast days, with a mean of 31% for the whole year \cite{7}.

Simulations can be very useful, especially during the design phase of a building. The simulation work can be divided into two parts. First, the evaluation of dynamic daylight availability of the room, in order to be able to calculate the needed...
complementary electric light, for the whole year, according to the chosen time step. Secondly, the implementation of lighting control systems.

1.1. Evaluation of the daylight availability

It can be very time consuming to calculate the daylight availability in a room, for a whole year. A solution to this problem is to use the daylight coefficient method (DC) developed by Trengenza and Waters [8], like proposed by Mardaljevic [9]. He used the software RADIANCE and found it accurate and faster than traditional methods. His conclusion was confirmed by Reinhart and Herkel who implemented the DC method, using RADIANCE, in a software called DAYSIM and compared it to five other dynamic methods based on RADIANCE daylight simulations [10,11]. The software DAYSIM was validated by Reinhart and Walkenhorst by comparing results with measurements. The conclusion is that indoor illuminances can be modelled with comparable accuracy for various blind settings under arbitrary sky conditions [12].

1.2. Implementation of lighting control systems

Some researcher have focused on the implementation of lighting control systems but made no link with the daylight modelling. Littlefair presents algorithms to quantify the savings for various types of photoelectric and manual controls [13]. Ehrlich et al. focused on the accurate simulation of photosensor-based lighting controls in order to improve the comparison between such systems, their selection, placement and commissioning [14]. Choi et al. developed a detailed computer analysis model in order to investigate the performance of daylight responsive dimming systems [15].

1.3. Link between daylight availability and lighting control systems

Some authors worked on the link between daylight simulations and algorithms modelling lighting control systems. Li and Tsang did simulations based on a DC method using RADIANCE and implemented a unique closed loop sensor. They compared results with measurements in a corridor and concluded that results of their method are in good agreement with measurements, but they did not give any quantitative energy lighting savings [16]. Clarke and Janak developed a method based on the conflation of the ESP-r and RADIANCE systems [17]. They concluded that optimized daylighting control system could save between 40 and 70% of the energy consumption of artificial lighting [18]. Beside the simulations of gains using daylight control systems, Mahdavi et al. focused on the implementation of control strategies to achieve some objective functions taking into account visual comfort and energetic considerations [19,20,21]. Reinhart proposed the modelling of several lighting control systems (program lightswitch) and implemented those algorithms in the DAYSIM software [22]. By simulations, he concluded that a switch-off occupancy control system can save up to 20% of lighting energy consumption and that a daylight control system can save up to 60%.

2. Objectives and methodology

The main objective of this study was to predict, by simulation, the energy consumptions of lighting in offices according to different control systems. Therefore, we used the simulation program DAYSIM to calculate the daylight availability in an office room during the whole year [10]. Although DAYSIM is able to model several lighting control systems, we did not use it for that part of the calculation. We wanted to test an individual daylight dimming control system that could not be modelled in DAYSIM at that moment. We developed thus an algorithm for simulating individual daylight dimming control systems according to a close-loop system. We calculated then the necessary complementary artificial lighting by implementing real consumption values of ballasts and control systems we measured in laboratory.

The second objective of this study was to measure the digital controller energy consumption and to compare it with simple analog system. Indeed, nowadays, the digital addressable lighting interface (DALI) is spreading. While its main advantages are the flexibility, the independence between the luminaire control system and the electric wiring and the possibility of pre-programming lighting scenes, some manufacturers have the tendency to provide one controller per luminaire, in order to have the possibility of a standalone use and to facilitate the luminaire installation [23]. However, this is not essential and it could induce (useless) extra energy consumption. With the measurements of the consumption of the auxiliaries, we can determine the minimum number of luminaires that should be linked with one controller for the same energy consumption as an analog system.

This paper compares three different lighting control systems installed in a single office, taking into account the real energy consumption of auxiliary systems (electronic ballast and management system), the daylight availability over the year, the orientation of the room and its location, in Europe. The lighting controls are an individual daylight dimming system and an occupancy control system which can either switch off or dim the light. The impact of each of these systems was calculated by comparison with a simple scheduled automatic switch off system. The combination of these systems was also evaluated.

The energy consumption of the lighting systems (including ballast, tube and control device) was accurately measured in laboratory. The equipment, the methodology and the results are described in the first part of this paper.

The second part of this paper describes how accurate dynamic daylight simulations, obtained from real climatic data’s and taking into account the position of the blinds, were used to predict the daylight penetration and the complementary electric lighting necessary to reach the set point illuminance level.

Additionally, the influence of the relative room occupancy (in function of the working hours) on the savings was analysed.
3. Equipment

The measured equipment consists of an ETAP luminaire R2600/158 Isolum (60°) equipped with tubes Philips Master TLD super 840 58W [24]. Two different electronic dimmable ballasts were chosen: the first having an analogue (1–10 VDC) command (Philips HF-R 158 TLD) and the other having a digital (DALI) command (Philips HF-R DALI 158 TLD). In the later case (DALI ballast), a controller is required to transfer the information from the detectors to the ballasts.

The photometric curve of the luminaire is shown in Fig. 1. The different control systems considered here are:

- **IDDS**: Individual Daylight Dimming System. The lamp light flux is controlled according to the daylight availability. The sensors (one per luminaire working in close-loop) are fixed on the luminaires and measure the reflected illuminance of the plane located under them (this product is known as ELS-ETAP Lighting System).
- **MDS**: Movement Detection Switching. This system, based on an infrared occupancy sensor, switches the light on and off, according to movement detection. The length of the delay can be chosen in order to limit the number of switch on and switch off cycles.
- **MDD**: Movement Detection Dimming. This system, as the MDS, is based on an infrared occupancy sensor, but dims the light to a chosen flux in case of absence. This flux can be chosen by a set of dip switches located on the sensor. In our case, we choose the minimum output flux (3% of the nominal flux) to maximize the gains.

As already mentioned in Section 2, these control systems can be combined and we tested the combination of an individual daylight dimming system with a movement detection switching and with a movement detection dimming. In these cases, the lights are dimmed according to the daylight availability when there is someone in the room and are either switched off or dimmed to 3% when there is nobody in the room.

4. Methodology

The methodology developed in this work combines electrical and photometric measurements and computer simulations. The first step was to analyse the system “ballast-tube-detector” in order to evaluate the real energy consumption of the different combinations.

4.1. Electric and photometric measurements

4.1.1. Total power measurement on an electronic ballast

This measurement was simply done by connecting the wattmeter to the ballast. By varying (using a voltage source) the control signal (1–10 VDC) of the analog ballast we obtained the power of the whole system for different output fluxes. For the digital ballast, we used the controller to control the output flux of the ballast. By modifying a set of dip switches on the controller the flux of the lamp could be controlled. But with this method, only five different output fluxes can be measured. Having measurements for more output fluxes would have required sending a digital signal (DALI protocol) to the ballast.

4.1.2. Detector power

The power of the detectors was also measured. The IDDS sensors power is negligible whereas the presence detectors have a constant power of 0.5 W. For the DALI-compatible systems, the power of the controller has to be added. That leads to a power of 2–2.5 W depending on the state of the luminaire (On or Standby position).

4.1.3. Relative photometric measurement

The luminous flux of the lamp was measured in order to compare it with the manufacturer data’s. A photosensor (TAOS TSL250R) was clipped at a random place of the tube and pointed to it. We obtained the luminous flux in dimming mode compared with full flux. A calibration in an Ulbricht sphere allowed us to calculate the absolute nominal luminous flux. Fig. 2 shows the relationship between the source electrical power and the relative lamp luminous flux, for the chosen ballasts.

Fig. 2 clearly shows a linear relationship between the source electrical power and the lamp relative flux. The linear regression line, which is quite the same for the two types of ballasts, has the following expression:

\[
P = 0.46\phi_{\text{relat.}} + \begin{cases} 
9.02 \quad \text{(Analog)} \\
9.34 \quad \text{(DALI-compatible)} 
\end{cases}
\]

(1)

The constant term of this expression shows that the ballast consumption is not nil even with the tube in turn-off state. Note
that we can get the overall electrical power of the system by adding the detector power to these values (0.5 W for an analog ballast, 2–2.5 W for a digital (DALI-compatible) ballast).

4.2. Simulation method

The objective of this work was to evaluate the lighting energy consumption of a typical office in different situations. We create thus a theoretical office (width 3.05 m, length 6.55 m and height 3.05 m (see Fig. 3)). A window of 3.05 m /C2 1.01 m is located in one of the surfaces of the room and its sill is placed at 1.01 m above the ground. This window is fitted with a double glazing of 77% visible transmittance. The room was arbitrarily oriented according to the four main orientations (north, south, west and east) and placed in three different locations (Brussels—50.9°N; 4.53°E, Athens—37.9°N; 23.73°E and Stockholm—59.65°N; 17.95°E) in order to test the influence of the latitude on the light energy savings possibilities. The location of Brussels was of first importance for us and the two other locations were chosen in order to test two extreme locations in Europe.

4.2.1. Daylight

Precise dynamic daylight simulations were made using the software DAYSIM in order to calculate the daylight illuminance for each daylight sensor location in the room, every 5 min, over the whole year. DAYSIM, which uses the RADIANCE algorithm, uses hourly climatic data files in order to calculate the illuminance according to a precise sky modelling taking into account the sun position and the real sky distribution [12]. Moreover, this software includes the possibility to consider the use of shadings. Two modes to simulate shading devices such as blinds are proposed by the software: the simple dynamic device model or the advanced dynamic device model. We used the simple model who models a generic blind system that transmits 25% of diffuse daylight and no direct sunlight compared to the case when the blinds are retracted. This is a basic blind model that is sufficient for initial design consideration when the type of shading control device is still unspecified. According to this model, the blinds are lowered when the workplane irradiance is over 50 W/m² [22]. This value was chosen following the results of a monitoring conducted by Reinhart and Voss [25].

4.2.2. Artificial light

The number of luminaires and their position was calculated with DIALux. The best solution was to place four luminaires in two rows as shown in Fig. 4.

With this configuration, the average artificial illuminance is equal to 615 lx and the uniformity on the working plane is equal to 0.73. The lighting system is not too oversized, which is important in order to compare the savings with realistic values.

4.2.3. IDDS modelling

The IDDS system regulates the lamp flux in function of the daylight availability. At each time step t, as it works in close-loop, the simulation of its comportment requires an iterative process. The goal of this modelling is to dim all the lamps adequately to obtain the set-point illuminance (500 lx) under each sensor.

Under each sensor i, we can say that the sum of the artificial light and the daylight must be equal to the set-point:

\[
E_{dl,i}(t) + \sum_{j=1}^{n} \tau_j(t)E_{ji} = SP
\]

With t is the time step under consideration, n the number of luminaires and thus of sensors (four in our case), \(E_{dl,i}(t)\) the daylight illuminance at time t under the sensor associated to the luminaire i (calculated with DAYSIM), \(\tau_j(t)\) the dimming rate of luminaire j at time t (the dimming rate of a luminaire is the flux given by the luminaire at time t divided by the nominal flux of

Fig. 2. Electrical power as a function of relative luminous flux: (a) analog ballast; (b) DALI-compatible ballast.

Fig. 3. Representation of the office.
this luminaire), \(E_{ij}(t)\) the illuminance due to the luminaire \(j\) at full flux under the sensor associated to the luminaire \(i\) (this value was calculated with DIALux), and SP is the set-point illuminance.

The artificial light can be separated in two: the contribution of the luminaire associated to the sensor and the contributions of the others luminaires. We can thus rewrite Eq. (2), assuming \(\delta_{ij}\) a term to make this separation:

\[
E_{dl,i}(t) + \sum_{j=1}^{n} \delta_{ij} \tau_{j}(t)E_{ji} + \tau_{i}(t)E_{ii} = SP \quad \text{with} \quad \delta_{ij}
\]

We can now isolate the dimming rate of the luminaire \(i:\)

\[
\tau_{i}(t) = \frac{SP - E_{dl,i}(t) - \sum_{j=1}^{n} \delta_{ij} \tau_{j}(t)E_{ji}}{E_{ii}}
\]  

We see in Eq. (4) that the dimming rate of the luminaire \(i\) depends on the dimming rate of the others luminaires. Thus to calculate it, we need the following iterative process. If we note \(k\) the number of iterations, for each time step \(t\), we have \(\tau_{ik}\) the rate \(\tau\) of the \(k\)th iteration:

\[
\tau_{ik}(t) = \frac{SP - E_{dl,i}(t) - \sum_{j=1}^{n} \delta_{ij} \tau_{jk-1}(t)E_{ji}}{E_{ii}}
\]

At each time step \(t\), the iteration requires an initial value of \(\tau_{ij}(t)\) chosen arbitrary between 0 and 1. In order to speed up the process, the calculation takes the dimming rate of the precedent time step as initial value. This leads to a higher convergence speed than if the initial value was chosen randomly.

The algorithm will converge to the set-point for each sensor, only if the full fluxes of the luminaires allow it. The dimming rate values higher than 1 are indeed forbidden. It is also impossible to have values lower than the full dimming rate (typically 3%). The possibility of convergence and the speed depend thus on the size of the installation and on the number of sensors. For our research, we decided to stop the iteration when the difference \((1 - (\tau_{j}/\tau_{i-1}))\) was less than \(10^{-6}\). Usually, this required 10–15 iterations.

4.2.4. Occupancy modelling (MDS/MDD)

To model occupancy, a 5 min time step occupancy profile was generated automatically.

The dimming rate of each luminaire, taking into account the occupancy, is calculated by Eq. (6):

\[
\tau_{i}(t) = P(t)\tau_{on,i}(t) + (1 - P(t))\tau_{off,i}(t)
\]

With \(P(t)\) equal to 1 in case of presence and to 0 in case of absence, \(\tau_{on,i}(t)\) the dimming rate of the luminaire \(i\) when there is somebody in the room (1 for MDD/MDS, the value calculated by Eq. (5) for IDDS + MDD or IDDS + MDS) and \(\tau_{off,i}(t)\), the dimming rate of the luminaire \(i\) when there is nobody in the room (0 for MDS, 0.03 for MDD).

The delay between the departure of the room occupant and the light switch off or dimming was set to 10 min.

Beside the three tested control systems, we considered that the lights are managed by a scheduled automatic shut off system that switches off all lamps and sensors from 6 p.m. to 8 a.m. The positive impact of this scheduled shut off system is easily understandable for IDDS and MDD. It has also a positive impact on energy saving with the MDS control system as it switches off the light sensors preventing their parasitic consumption during the night.

The results presented at Section 5.1 are based on presence in the room from 8 a.m. to 12 a.m. and from 1 p.m. to 6 p.m. In Section 5.2 we analyse the influence of the occupancy profile on energy savings with MDD and MDS systems.

4.2.5. Computing the energy consumption

The year overall energy consumption can be estimated with the results of previous parts. The relative flux \(\Phi_{rel,\%}\) in Eq. (1) can be replaced by the dimming rate of luminaires calculate with the IDDS and/or presence modelling. Multiplying this equation by the time step of the simulation and making the sum over the
whole year would lead to the yearly energy consumption. Note that if the dimming rate of luminaires is null (in case of absence with an MDS), the consumption is null and not equal to the value given by Eq. (1).

5. Results and analysis

5.1. Analysis of the different systems

The calculations were made for each orientation and location.

For the reference situation, we considered that the lamps and sensors are only managed by a scheduled automatic shut off system.

An inefficient situation without night-time shut off would lead to an over-consumption of 235% by comparison with the reference case. Figs. 5–7 present the annual gains obtained for each system and combinations, for the four tested orientations and for the three locations. The values above each bar are the relative difference between the considered case and the reference case calculated by the following equation:

\[
\text{difference} = 1 - \frac{C_{\text{considered}}}{C_{\text{reference}}}
\]

With \(C_{\text{considered}}\) the annual consumption of the considered case and \(C_{\text{reference}}\) the annual consumption of the reference case.

We observe that the only system whose gains are influenced by the orientation and the location is the IDDS. That is easy to understand as the savings obtained with the MDS and the MDD control systems depend only on occupancy, which is not affected by the location and the orientation. The advantage of the south orientation is observed in each location and leads to a gain of 7–12% (depending on the location) compared to a north orientation. West and east lead to similar savings of 4.5–10%. We can also observe that, even in the worst situation, the IDDS control is efficient and leads to a minimum gain of 45% by comparison with the reference case. Figs. 5–7 show that, when there is an IDDS, the annual lighting energy consumption is linked to the annual daylight availability (higher for Athens...
than for Stockholm); the savings are higher for a low latitude location (Athens) but remain very high (around 50%) for a high latitude location, regardless of the window orientation.

Comparing the different control systems, the IDDS system is the most interesting and leads to the highest gains in case of a single office with 90% occupancy. We can possibly consider installing presence detector in combination with the IDDS system (IDDS + MDD or IDDS + MDS) but the additional gains are not really significant in this case. The influence of the occupancy rate is discussed later in the paper.

If we analyse the monthly energy consumption for the three locations (Figs. 8–10), we can observe the difference between summer and winter.

We observe that, even in a north orientated office in winter, the impact of an IDDS system is quite important (about 30% of gains). The difference in consumption between a north and a south-orientated room is quite small compared to the consumption without IDDS. This results from the fact that in a south-orientated office, the blinds are closed more often than in a north orientated office (about 20% of the working hours for the south and 0% for the north). During some months (autumn and winter), east and west orientations could be better than south but north is always the worst. Over the whole year, the south orientation leads to highest energy gains. Note that the difference between the monthly energy consumptions without IDDS system is due to the variation in the number of working hours.

![Fig. 9. Monthly consumption with and without IDDS in Brussels.](image)

![Fig. 10. Monthly consumption with and without IDDS in Stockholm.](image)

![Fig. 11. Values of presence and probability to have presence for typical workdays with a presence rate of 100, 80, 60 and 20%.](image)
days in each month (in our study the offices are empty on Saturday and Sunday). For instance there are 23 working days in January (resulting in a consumption of 50.67 kWh) and 20 days in February (resulting in a consumption of 44.63 kWh).

The energy gains by using an occupancy sensor are not as high as those reported in literature [1,26,27]. First, this is due to the fact that we consider a timer that shuts off the lights during nights and weekends, in our reference case. Secondly, in this study we consider a room occupied the whole day except during the lunch time. Many offices have a more variable presence resulting in higher gains using presence detection.

5.2. Impact of the presence on the MDD and MDS system

In this section, we analyse the annual energy consumption using a MDD or MDS system with a variable presence schedule. The presence schedule, during working hours, was automatically and randomly generated by steps of 10% from 0 to 100%. For each time step, the value 0 or 1 of the presence (\(P(t)\)—see Eq. (6)) is generated following a probabilistic reasoning. If there is presence at a time step \(t\), the probability to have presence at a time step \(t + 1\) is high and decrease with the time; if there is absence a time \(t\), the probability to have presence at time \(t + 1\) is low and increase with the time. The values of high and low probabilities as well as the speed of the increasing/decreasing depend on the presence rate. Fig. 11 shows some examples of presence schedules with their respective probability for 20, 60, 80 and 100% of presence rate.

Fig. 12 presents the energy gains, for MDD and MDS systems as a function of the presence rate, regardless of the location. Firstly, we observe that the curves are not linear. This is due to the fact that the time delay of the control system before extinction has a greater influence for shorter presence time. Secondly, we see that the gains are not equal to 100% when the presence is null. The consumption of the detectors (for the MDS) and the remaining flux (for the MDD) are responsible for this fact. The advantage of using MDS compared to MDD is clear; with the MDD system, for each luminaire, the tube is lit at 3% (of full flux) and then presents a power of 11 W (10.4 W from remaining flux (see Fig. 2(a) or Eq. (1)) and 0.5 W from the detector) when there is nobody in the room. With the MDS system, when nobody is present, the only consumption is the consumption of the detector, which has a power of 0.5 W.

However, the MDD system is interesting for landscape offices as it prevents people to be placed in a bright spot, compared to the average room illuminance, when working alone in the office room. It keeps a low general room illuminance, to prevent too high contrasts between the occupant’s working plane and the rest of the room. In single offices the MDS control system is preferred.

The curves allow us to evaluate the occupancy rates threshold for which an occupancy sensor is more interesting than a daylight dimming sensor, for each location and orientation. These results are presented in Table 1. For example in a south oriented building in Brussels, we observe that the MDS system is more interesting than the IDDS system when occupation drops below 35%. With these values, we can say that when occupancy rate in a single office is less than 27%, MDS is always preferable to IDDS and when occupancy rate is greater than 44% the best solution is to use IDDS. For occupancy rates between these two extremes, the best system depends on the location and the orientation.

5.3. Using DALI-compatible control systems

Results presented in Sections 5.1 and 5.2 are valid for the analogue ballasts. Using luminaires with a digital (DALI-compatible) ballast and an embedded controller would decrease the performance of the systems. For a 2310 working hours year, the energy consumption of the controllers of the four luminaires (18.5 kWh) should be added to the lighting consumption. It represents only 3% of the consumption obtained with the
reference system but reaches nearly 9% of the consumption of the best system (IDDS + MDS in a south-orientated office in Athens). So the current trend to install DALI-compatible systems with one controller per luminaire can be practical for their standalone use (e.g., if the DALI line is not yet installed) but reduces the energetic gains. Furthermore, if embedded controllers are installed in each luminaire without a night time cut off, the yearly parasitic consumptions of the controllers would reach nearly 70 kWh, a third of the consumption of the best system! A DALI-compatible controller begins to be energetically profitable in an MDS/MDS installation where one controller (and its associated detector) can replace the analogue detectors of at least four luminaires. At this moment, the consumption of one DALI-compatible controller and its detector (2 W) equals the consumption of four analogue detectors (0.5 W each).

6. Discussion

All along this study, we have considered a passive occupant who does not care about switching on or off the lights in function of available daylight. As presented by Reinhart, the results presented here could be better with a user who cares about daylight [22]. Moreover, in this study, we do not consider wall switches. The light is either always turned on during the days when there is no presence detector or automatically switched on when an occupant enters the room when there are presence detectors. Some researches have shown a relation between workplane illuminance and the switch-on probability [28]. The study with an absence detector (manual on/automatic off) instead of an MDS/MDD detector would have surely shown better gains because the occupant would not turn on the light every time he enters his office. Even in an office with daylight control systems, sometimes the users do not turn on the light even if the 500 lx are not reached. This would save even more energy but could have an impact on comfort, profitability and eyestrain. A second impact on the electric consumption of the use of an absence detector is due to the fact that the sensors are switched off when the lights are off. In this case, the parasitic consumption of the sensors (0.5 W each) is null whenever nobody is present in the room [29].

In our study, the chosen simulation time step was 5 min. This is very short and is justified by results of research by Walkenhorst et al. [30]. By comparing lighting electric consumption of simulations using irradiances from 1 h and 1 min data sets, they found that the consumptions are underestimated by 6–18% when using 1 h irradiances. Because 1 min data sets are not easily available, they have implemented a modified Skartveit–Olseth method to make 1 min data sets from 1 h data sets [31]. During our study, we did the same comparison between results based on 1 h irradiance step data files and 1 min irradiance time step data files, made following their modified Skartveit–Olseth method. Contrary to Walkenhorst et al., we found less than 1% of differences between 1 h and 1 min simulations for simulation for a whole year. The difference between these two studies could be further investigated.

7. Conclusion

This paper tried to analyse the performance of different lighting control systems for a single office. The first part treats the power measurement of the different parts in a lighting installation, including detectors and control systems. The relationship between the lamp power (including ballast) and its relative light output was measured. This relation is very useful to calculate the energy consumption of a system when it is dimmed. We also measured the power of different detectors and found that an IDDS sensor has a negligible power, a MDS/MDD detector has a power of 0.5 W and a DALI-compatible controller and its detector have a power of 2 W. Evaluating these values, we can say that a DALI-compatible system can be profitable only when one controller and detector manages at least four luminaires.

The control systems are adjusting the electric light according to available daylight or presence. Combinations of these two types of control systems were also considered. The study shows that electric lighting savings are high when regulating the light according to daylight availability and slightly depend on the orientation and location. The best configuration we simulated is the south-orientated office in Athens. In this case, the saving potential is equal to 61% of the annual power consumption. The worst case is a north-orientated office in Stockholm for which the potential gain is nearly 45%. Addition of a presence detector offers supplementary gains of 1–4% when the office is occupied during the whole day except the lunch time.

When adjusting the light in function of occupation, energy savings are higher if the lights are switched off than if they are simply dimmed in case of absence. A shut off system is preferable for single offices or meeting rooms whereas a dimming system is interesting for large landscape offices, for visual comfort reasons.

When an occupancy sensor is used, lighting energy savings increase when the occupation rate decreases, but the relationship between the occupation rate and the energy consumption is not linear as the time delay (time before switch off or dimming after the occupant leave the room) has a greater influence as the occupation rate decreases. This study permits also to determine when a daylight dimming regulation is preferable to an occupancy sensor switching. If the occupancy rate is higher than 44%, the IDDS is always better and if it is less than 27%, an occupancy sensor is preferable.

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