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# Monitoring of Daylight Controlled Dimming Systems and Occupancy in Three Equivalent Classrooms

R. Delvaeye[1,2,*], L. Stroobant[1,3], R. Klein[1], P. Hanselaer[1], P. D'Herdt[2], H. Breesch[1], W. Ryckaert[1]

[1] KU Leuven, ESAT/Light&Lighting Laboratory, Technology Campus Ghent, Gebroeders De Smetstraat 1, 9000 Ghent, Belgium.

[2] Belgian Building Research Institute (BBRI), Division of Energy and Climate, Avenue Pierre Holoffe 21, 1342 Limelette, Belgium.

[3] Ghent University, Department of Information Technology – IBCN, Gaston Crommenlaan 8 (Bus 201), 9050 Ghent, Belgium.

[*] Corresponding author at: Belgian Building Research Institute (BBRI), Division of Energy and Climate, Avenue Pierre Holoffe 21, B-1342 Limelette, Belgium.

Tel.: +32 2 655 79 52 ; E-mail address: ruben.delvaeye@bbri.be

**Abstract**

*Providing a daylight controlled dimming system in a building design can reduce the lighting energy consumption significantly. However, while both the lighting energy savings and the light-on time have a major impact on the payback period of the daylight controlled dimming system, it's quite difficult to make a true estimation of these parameters. Anyway, it has to be made sure that the energy savings are not at the expense of the visual comfort. This paper presents the results of a 1-year monitoring campaign in 3 classrooms of a school in Belgium in which a daylight controlled dimming system was installed. Aspects regarding both energy savings and visual comfort are examined. Also the results of the monitoring of the occupancy in the classrooms are discussed. The research shows that the occupancy, and thus the light-on time, tends to be low in classrooms. The annual light-on time varied from 567 to 603 hours. The energy savings of the daylight controlled dimming systems in the 3 equivalent classrooms varied significantly, from 18% to 46%. Beside the energetic aspect, the visual comfort due to the lighting systems is even more important. All too often, bad commissioning and a lack of following up the functioning of systems lead to poor performance of the systems.*

***Keywords – daylight controlled dimming system; energy savings; commissioning; occupancy; school buildings; monitoring***

## 1. Introduction

Although the installation of light controls can reduce the lighting energy consumption significantly while preserving the visual comfort, it is difficult to quantify their actual energy saving potential. This is particularly the case for Daylight Controlled Dimming systems (hereafter called "DCD systems"), which automatically dim the artificial lighting as a function of the daylight availability. Widely divergent results for the energy saving potential of DCD systems are obtained: Jennings et al. [1] speak about 21% of lighting energy savings over a 7-month monitoring period with automatic daylight dimming controls. In 2 different research projects of Li about daylight control in office buildings, energy savings of 50% and 33% respectively are obtained [2], [3].

To examine the energy saving potential of DCD systems in educational buildings in temperate maritime climates, a research project called "Impact of DCD systems on design and renovation of school buildings" took place in the period 2013-2014. The main focus was a long-term monitoring campaign in several classrooms in 6 secondary schools in Flanders (Belgium). Each classroom was equipped with a DCD system. The installed type of DCD system varied from case to case.

In this paper, the general results of a 1-year monitoring campaign in 3 equivalent neighbouring classrooms of the same secondary school are discussed. The monitoring has been carried out simultaneously in the 3 rooms, all equipped with a different type of DCD system. Firstly, attention is paid to the occupancy of the classrooms and the light-on time of the lighting systems. Furthermore, an overview of the total annual energy savings of the DCD system per classroom is given. The classroom in which the highest energy savings were obtained, is further examined. The analysis comprehends an energy component as well as a component regarding the visual comfort.

## 2. Description of the Case Study

### 1. Building and Environment

The 3 classrooms are located at the 1st floor of a building of the secondary school Don Bosco in Haacht (Belgium). All 3 classrooms have the same room geometry. The classrooms have a width along the window side of 9.2m and have a depth of 7.8m. The height of all classrooms is 2.8m. The reflection coefficients for ceiling/walls/floor are 79%/37%/12% respectively.

The window configuration in the exterior wall is equal for each of the side-lit classrooms. The windows are oriented between North and North-West and the daylight penetration in the classrooms is not hampered by external obstructions. The Window-To-Wall-Ratio amounts to 43% and the Window-To-Floor-Ratio to 16%. Obscuration is carried out using curtains.

### 2. Artificial Lighting and Light Control Systems

In favour of the research project, new, dimmable, fluorescent lighting was installed in the classrooms. The luminaire configuration is shown in Fig. 1. The control of the artificial lighting is split up into 2 groups, both individually controllable by a push button: group "general lighting", and group "board lighting". The general lighting in the 3 classrooms consists of a configuration of 3 rows of 3 luminaires. All luminaires are dimmable. The installed board lighting includes an asymmetrical reflector in any case.

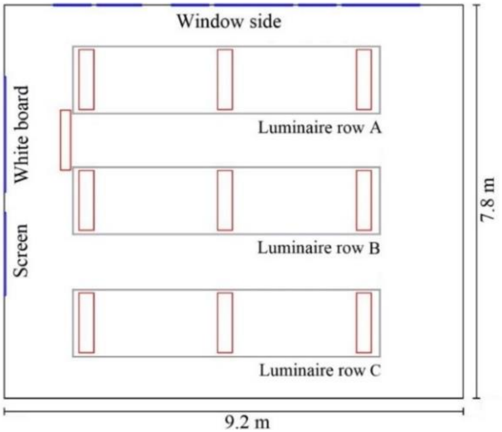


Fig. 1: Floor plan classroom

The lighting systems of the classrooms are designed to have a maintained mean illuminance value $\bar{E}_{fin}$ at the horizontal working plane of about 500lx. Further details on the general lighting in the 3 classrooms are summarized in Table 1.

Table 1: Characteristics of general lighting and daylight control system per classroom

| | **Classroom 1** | **Classroom 2** | **Classroom 3** |
|---|---|---|---|
| **Maximum measured power per luminaire** | 54W | 59W | 60W |
| **Number of luminaires** | 9 | 9 | 9 |
| **$\bar{E}_{fin}$** | 572lx | 572lx | 478lx |
| **Normalized power density [4]** | 1.19 W/(m².100lx) | 1.30 W/(m².100lx) | 1.58 W/(m².100lx) |
| **Type of DCD system** | Individual daylight sensor per luminaire (closed loop) | Centrally positioned daylight sensor (closed loop) | Outward facing daylight sensor (open loop) |

In addition to the installation of dimmable, fluorescent lighting in the 3 classrooms, also light control systems were implemented. At first, all classrooms are equipped with an absence detector. The switch off delay of all detectors is set to 10 minutes. Besides, a different type of DCD system has been implemented in the 3 classrooms. The DCD system controls all 3 luminaire rows of the general lighting in any case.

In classroom 1, each luminaire is equipped with an individual daylight sensor. As each of the 9 luminaires for general lighting has its own daylight sensor, each luminaire is dimmed separately. A centrally positioned daylight sensor was implemented in classroom 2. The daylight sensor provides only 2 dimming levels, while the general lighting consists of 3 luminaire rows. Therefore, the row of luminaires at the window side is dimmed at a 1st level and the rows in the middle and at the corridor side are dimmed together at a 2nd level. Centrally positioned daylight sensors are generally combined with a presence or absence detector in the same casing. In classroom 3, an open loop system using an outward facing daylight sensor is installed. The daylight sensor only measures daylight and provides a separate dimming level for each row of luminaires parallel to the window side.

The commissioning of the DCD systems is carried out by a representative of the manufacturer of the systems. It was asked to commission the systems in such a way that the mean illuminance at the horizontal working plane would approach 500lx in all circumstances.

## 3. Occupancy Schedule of the Classrooms

The common schedule of the school is shown in Table 2.

Table 2: Schedule school

| **Time period** | **Activity** |
|---|---|
| *8h35* | *Start of school day* |
| 8h35 – 12h05 | Lessons 1-2 + 10 min break + Lessons 3-4 |
| *12h05* | *End of school day at Wednesday* |
| 12h05 – 13h05 | Lunch break |
| 13h05 – 15h45 | Lesson 5-6 + 10 min break + Lesson 7 |
| *15h45* | *End of school day in case of a 7-lessons day* |
| 15h45 – 16h35 | Lesson 8 |
| *16h35* | *End of school day in case of a 8-lessons day* |

The duration of a lesson is 50 minutes. In a normal school week, lessons take place from Monday to Friday. On Wednesday, the schedule from Table 2 is shortened to only the first 4 lessons. All lessons take place between 8h35 and 16h35. There are no evening classes organized in the classrooms. During the weekend, the school is closed, so no occupancy is expected. Based on the schedule in Table 2, a maximal occupancy of the classrooms of 30 hours (36 lessons of 50 minutes) per week can be expected.

The major holidays at Belgian secondary schools are Christmas holidays, spring half-term, Easter holidays, summer holidays and autumn half-term. The total duration of the holidays per year is approximately 14 weeks. Altogether, the theoretical maximal occupancy per year of a classroom of a secondary school where only daytime lessons take place, is 1140 hours.

# 3. Description of the Monitoring System

The long-term monitoring in the classrooms is carried out by means of a central PLC system, using a Beckhoff CX9020 [5]. Several types of terminals are connected via EtherCAT to the PLC and data are gathered from each classroom by 3 monitoring applications.

The main monitoring parameters which are utilized, are the quantities connected with electric energy consumption and the occupancy data of the classrooms. Also the results of the global irradiance measurements under an unobstructed horizon and momentary illuminace measurements are used.

## 1. Energy Consumption and Energy Savings

The measurement of the electrical quantities is carried out for each individual row of luminaires parallel to the window side. The active power and the energy consumption are measured by electronic single-phase energy meters (type Eltako WSZ12DE-32A) [6].

The energy savings obtained by implementation of a DCD system are calculated as:

$$W_{\%} = (W_{L,\text{without DCS}} - W_{L,\text{with DCS}})/(W_{L,\text{without DCS}}) * 100 \qquad (1)$$

With:

- $W_{\%}$: relative lighting energy savings due to the implementation of a DCD system (%)
- $W_{L,\text{with DCS}}$ : lighting energy consumption with DCD system during light-on time (kWh) (= the energy consumption monitored by the electronic single-phase energy meters.)
- $W_{L,\text{without DCS}}$ : lighting energy consumption without DCD system during light-on time (kWh) (= the theoretical energy consumption of the artificial lighting during light-on time if no DCD system would have been installed. It is calculated as the product of the maximum measured active power and the light-on time.)

The light-on time is defined as the time that the users of the classrooms want the artificial lighting to be turned on during their presence.

The energy consumption of the light control systems is usually not taken into account. As the daylight sensors are found in the luminaires in classroom 1, the energy consumption of these sensors is inevitably counted. However, according to Roisin et al. [7], their energy consumption is negligible.

## 2. Presence Detection and Occupancy

The monitoring of the occupancy is carried out by means of a presence detector (type Esylux PD-C360i/24 DC24Vplus) [8]. The detector is installed in the middle of the classroom at ceiling height (2.8 m) and the switch off delay is set to 1 minute. It comprises an event based monitoring, which allows us to determine the state of the occupancy at each moment.

It is likely that the detector will falsely report absence of people on occasion. To discard this inaccuracy of the detector, a filter is applied to the raw occupancy monitoring data. On the one hand, the filter fills up gaps of absence of less than 2 minutes between short periods of occupancy. On the other hand, the last minute of each period is deleted by the filter as this occupancy is the result of the switch off delay and is thus apparent.

### 3. Global Irradiance

The monitoring of the global horizontal irradiance is carried out using a silicon pyranometer (type Kipp & Zonen SP Lite2) [9], positioned outdoors under an unobstructed horizon.

### 4. Illuminance

Temporary measurements of the illuminance at the horizontal working plane of the classrooms are carried out, as this parameter has a major impact on the visual comfort of the occupants. The measurements of the interior horizontal illuminance are performed on a working plane height of 0.8m above finished floor by means of photometric sensors (Gigahertz-Optik ; type detector head: VL-3701-2 ; type measuring instrument: P9710-1) [10].

## 4. Results and Discussion

### 1. Occupancy and Light-On Time of the Classrooms

Table 3 gives an overview of the monthly occupancy and the light-on time in the 3 classrooms (monitoring period: 01/12/2013 – 30/11/2014).

Table 3: Monthly occupancy and light-on time of the 3 classrooms in Haacht

| | **Occupancy (h)** | | | **Light-on time (h)** | | |
|---|---|---|---|---|---|---|
| | Class 1 | Class 2 | Class 3 | Class 1 | Class 2 | Class 3 |
| Dec '13 | 45.7 | 57.0 | 51.2 | 41.7 | 50.6 | 43.7 |
| Jan '14 | 95.2 | 103.5 | 87.1 | 86.0 | 79.2 | 68.7 |
| Feb '14 | 101.7 | 108.0 | 96.1 | 88.5 | 77.8 | 79.7 |
| Mar '14 | 72.0 | 65.2 | 71.6 | 57.2 | 39.0 | 49.6 |
| Apr '14 | 36.2 | 30.8 | 35.9 | 28.9 | 19.8 | 13.3 |
| May '14 | 98.1 | 96.0 | 76.7 | 66.3 | 55.5 | 50.2 |
| Jun '14 | 57.7 | 49.7 | 49.7 | 32.8 | 27.3 | 15.7 |
| Jul '14 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 |
| Aug '14 | 1.1 | 1.5 | 0.8 | 1.6 | 0.7 | 0.5 |
| Sep '14 | 109.6 | 114.5 | 113.0 | 71.7 | 73.1 | 90.4 |
| Oct '14 | 81.5 | 81.4 | 80.3 | 55.1 | 68.6 | 72.6 |
| Nov '14 | 94.3 | 98.6 | 93.1 | 72.8 | 88.7 | 82.2 |
| **Total** | **793.1** | **806.1** | **755.4** | **602.9** | **580.2** | **566.6** |

It is notable that the occupancy of the classrooms is considerably lower than expected. While the theoretical maximal occupancy per year is 1140 hours, the actual occupancy per year of the 3 classrooms varies from 755 to 806 hours. The main reason for this is the incomplete usage in time of the classrooms: it turns out to be impossible to fill up every unit in the classrooms' schedule. There are inevitably a few lessons per week in which no classes need the monitored classrooms (e.g. because of practical lessons or physical training). Besides, having an $8^{th}$ lesson (15h45 – 16h35) is the exception rather than the rule. Moreover, the occupancy in December and June is much lower than the initially estimated occupancy: the exams take place in these periods and students have to be at school for only half a day to take the examination.

The light-on time is even lower than the occupancy as it was not always necessary to have the artificial lighting turned on. The lighting system of the classrooms is switched off during 24% to 28% of the yearly occupancy. Ignoring the summer holidays (July & August) and the months with reduced activity due to exams (December & June), the ratio between the average light-on time and the occupancy over the 3 classrooms can be considered per month. This ratio is at its maximum in November: the artificial lighting was turned on during 85% of the occupancy. The lowest value is assessed in April. In this period, the lighting was only turned on during 60% of the occupancy. Overall, the maximum light-on time in the classrooms ran up to 602.9 h per year.

The obtained results for occupancy contrast rather sharply with the default value for annual operating hours for educational buildings of 2000 hours (1800 hours during daylight time, 200 hours during non-daylight time), proposed in EN 15193 [11], while the assessment of usage of lighting during occupancy is good in the norm (lighting switched off during 24% to 28% of yearly occupancy time, compared to 25% proposed in EN 15193). Taking both conclusions into account, it is expected that calculating the payback period of the DCD systems with the monitoring results or with the standard values given in the norm EN 15193 will make a significant difference.

## 2. Lighting Energy Savings of the DCD Systems

Fig. 2 gives an overview of the relative yearly lighting energy savings in the 3 classrooms due to implementation of a DCD system.

Although the 3 monitored classrooms are located at the same site and have the same geometry, orientation and interior finish, the differences in lighting energy savings are substantial. The energy savings achieved in classroom 1, in which an individual daylight sensor per luminaire is installed, came to 34%. The energy savings in classroom 3, which is equipped with an open loop DCD system, amounts to 46%. This is 2.6 times higher than the energy savings in classroom 2. The contrast also becomes noticeable by comparing the total energy consumption and the total light-on time of the 2 classrooms: while the light-on time of classroom 2 is only 3% higher than the light-on time of classroom 3, the energy consumption is 52% higher.

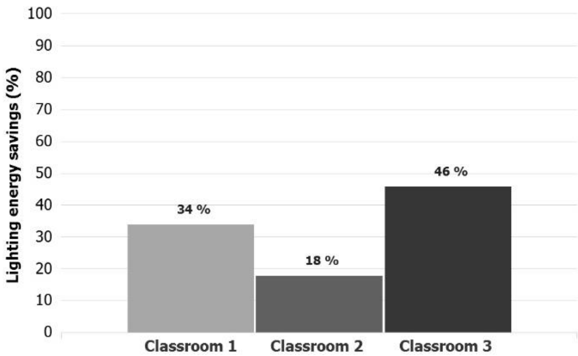


Fig. 2: Yearly lighting energy savings in the 3 classrooms in Haacht

This substantial difference can be the result of 2 problems:

- The DCD system in classroom 2 doesn't dim enough. This leads to illuminance levels on the working plane which are much higher than necessary and to low energy savings.
- The DCD system in classroom 3 dims too much. This leads to illuminance levels on the working plane which are too low (bad visual comfort), but very high energy savings.

It is also possible that the difference is the result of a combination of these 2 problems. Hereafter, the incidence of the 2nd potential problem is verified.

## 3. Energetic and Visual Comfort Analysis of Classroom 3

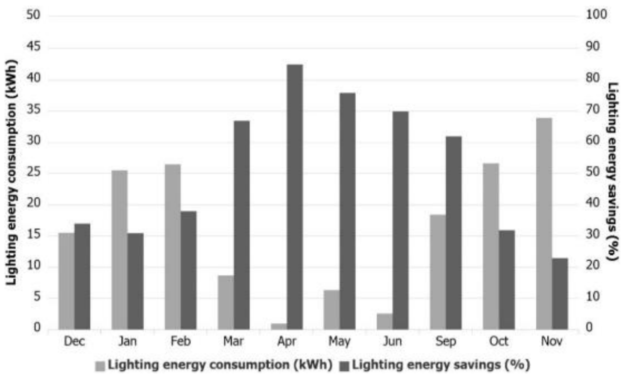


Fig. 3: Monthly lighting energy consumption and energy savings in classroom 3 in Haacht

Fig. 3 shows the energy consumption and the energy savings in classroom 3 for each month of the monitoring period with the exception of July and August as these results are irrelevant because of extremely low light-on times.

Even though the annual lighting energy savings in classroom 3 amount to 46%, there is a large variation on the lighting energy savings per month. While the minimum monthly energy savings in classroom 3 were found to be 23% (November), a maximum value of 85% was noticed in April. Overall, most additional artificial lighting seems to be needed during the meteorological autumn and winter (September until February).

A serious problem with the functioning of the DCD system in the classroom was detected half October 2014: the occupants sabotaged the sensor of the DCD system by covering it with a sticky note. Based on the monitoring results, it is suspected that the act of sabotage is committed in the beginning of October 2014. Interviews showed that occupants did this because they considered the total illuminance level in the classroom to be too low.

The suspicion of the occurrence of insufficient total illuminance levels in the classroom was examined by setting up a monitoring of the illuminance level on to the working plane during the weekend 11/10/2014 – 12/10/2014. The photometric sensors 1, 2 and 3 were positioned at 4.75 m of the front of the classroom and at 1.5 m, 3.5 m, 5.5 m of the wall at the window side respectively. The presence detector was disengaged during the monitoring to avoid that the artificial lighting would turn automatically off when the switch off delay would have expired. The results of the illuminance measurements in time (daylight + artificial light) are combined with the monitoring data of the active power of the different luminaire rows and the global horizontal irradiance under an unobstructed horizon and are shown in Fig. 4.

As seen in Fig. 4, the illuminance levels in the 3 points and the active power of the 3 luminaire rows stayed at a constant value during the night. The illuminance level in points 1, 2 and 3 measured 598, 575 and 525 lx, slightly more than the requested 500 lx.

As the daylight level was rising in the morning of 11/10/2014, all 3 luminaire rows started dimming. It is noticeable that the luminaire row A dimmed back to its minimum level (approximately 55 W) and then automatically switched off already 1h55min after having started to dim at 8:00 AM. This didn't cause any problems at that moment as the amount of incident daylight was rising fast enough at the same time: the total illuminance in point 1 rose from 614 lx at 8:00 AM to 1049 lx at 9:55 AM. However, when the global irradiance level reverted at noon, the luminaire row A didn't turn back on, which resulted in a lowered total illuminance in point 1 of 223 lx. Overall, the illuminance in point 1 was due to the dip of the daylight level lower than 500 lx and 400 lx for 20 and 10 minutes respectively. A similar problem in illuminance point 1 occurred between 3:00 PM and 3:10 PM. Because of the relatively low daylight levels, luminaire rows B and C didn't turn off and they kept on adjusting their dimming level as a function of the incident daylight. Yet, both rows B and C didn't succeed in maintaining 500 lx in the points 2 and 3. The minimal illuminance level in point 2 and point 3 during daylight availability was 436 lx (2:59 PM) and 359 lx (4:35 PM) respectively.

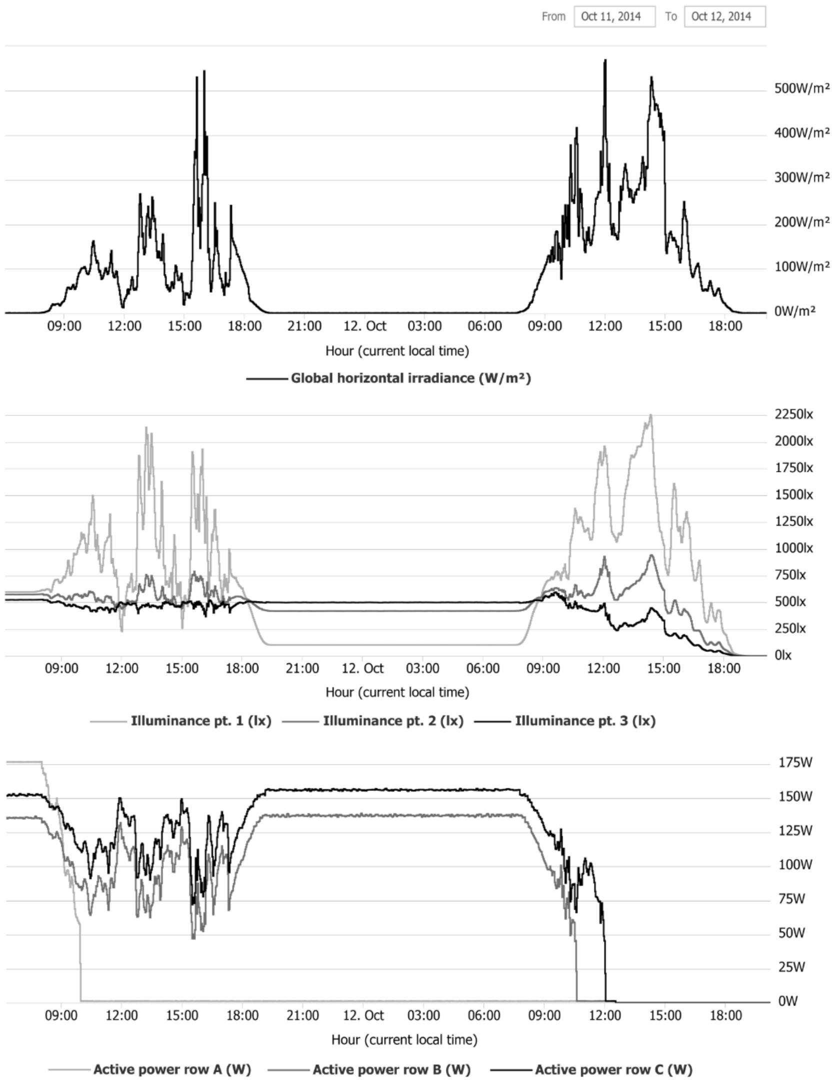


Fig. 4: Inspection of the visual comfort in classroom 3

At sundown, the active power of the luminaire rows B and C got back to approximately the same constant value as the night before. The luminaire row A still didn’t switch back on, despite the lack of daylight. This resulted in a constant illuminance level of 103 lx in point 1 during the night. Because of the state of luminaire row A, the illuminance level in point 1 was 5 times smaller than the desired illuminance level. Also the illuminance in points 2 and 3 was negatively influenced by the off status of luminaire row A. The illuminance level during the night in points 2 and 3 amounted to 421 lx and 501 lx, compared to 575 lx and 525 lx the night before.

At sunrise on 12/10/2014, about 8:00 AM, the illuminance level in point 1 started to increase and already reached the minimum threshold of 500 lux at 8:42 AM and didn't underspend this threshold until 5:00 PM, although luminaire row A was turned off all day long. Comparing the course of the global horizontal irradiance of 11/10/2014 and 12/10/2014, it is notable that higher global horizontal irradiances appeared on 12/10/2014 and they lasted longer than on 11/10/2014. This seemed to have a serious impact on the dimming course of luminaire rows B and C: while the luminaire rows B and C didn't turn off during the first monitoring day, row B turned off already at 10:35 AM and row C turned off at noon on 12/10/2014. This didn't cause any problems in illuminance point 2 at the moment of dimming as the required value of 500 lx was obtained at each moment. But this wasn't the case in illuminance point 3: the illuminance level varied between 600 lx and 409 lx during dimming of luminaire row 3. After luminaire row 3 was turned off, the illuminance level in point 3 never got back to required 500 lx on 12/10/2014.

All luminaire rows have automatically turned off as a function of the incident daylight, but they didn't switch back on when the evening falls. This results in illuminance levels of 0 lx in the 3 points during the night, although it was desired that the 500 lx threshold would be achieved.

In spite of the fact that the DCD system in classroom 3 saved the highest amount of energy of the 3 classrooms (46% energy savings, compared to 34% in classroom 1 and 18% in classroom 2), the results of the monitoring of the illuminance show that the DCD system didn't operate as it should have. The luminaire rows dim too fast when a certain amount of daylight comes in and the luminaires don't switch back on after they turned off due to bright weather conditions. These problems resulted in too low total illuminance levels on the working plane during the monitoring period. It is very likely that these problems incited the occupants to cover the daylight sensor with a sticky note.

It should be emphasized that by covering the daylight sensor, the occupant mortgages the energy profit of the DCD system in the short as well as in the long run. During periods in which high daylight levels appear, occupants often experience less problems about the fact that the DCD system is dimming to fast as the incident amount of daylight is high enough. No actions are performed by the occupants. Once the meteorological autumn and winter sets in, daylight levels start to decrease. During the transitional period, problems may occur. This can trigger the occupants to cover the daylight sensor, as it is an easy solution to solve their problem. However, when daylight levels start rising again, occupants don't receive a new impulse to uncover the daylight sensor. Due to this, the potential energy savings of the DCD system are nullified.

## 5. Conclusions

This paper presents the results of a 1-year monitoring campaign in 3 classrooms of a school in Belgium in which a DCD system has been installed.

Firstly, this paper indicates that the occupancy of secondary schools in Belgium in which full-time education takes place, is low. The occupancy ranges from 755 to 806 hours. This contrasts sharply with the default value for annual operating hours for educational buildings of 2000 hours, proposed in EN 15193 [11]. Moreover, the lighting system of the classrooms was switched off during 24% to 28% of the yearly occupancy.

This study showed that, apart from the building characteristics, the energy savings achieved by the DCD systems can vary strongly with the type of DCD system and its commissioning. Although all classrooms were located at the same site and have the same geometry, orientation and interior finish, the energy savings varied from 18% to 46%.

Anyway, it has to be made sure that energy savings are not at the expense of the visual comfort. Problems regarding the visual comfort occurred in the classroom in which the highest energy savings were achieved. The occupants sabotaged the daylight sensor by covering it with a sticky note. This indicates the importance of commissioning DCD systems with care. Moreover, good functioning of the system has to be verified regularly to obtain the estimated energy savings, but also to guarantee the good visual comfort at any time.


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