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Automated daylight-linked control systems performance with illuminance sensors for side-lit offices in the Mediterranean area

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ABSTRACT

Daylight-linked control systems (DLCSs) installation guarantees noticeable benefits, optimizing both energy saving and occupants' visual comfort. These systems performances are influenced by different factors, above all daylight availability. To deepen this issue, daylight illuminance measurements were performed at the work-plane and at the ceiling (corresponding to the position of a typical closed-loop photosensor) in a side-lit office during summer and winter. The office was equipped with two windows: one facing South and the other facing West. For each orientation, starting from measurements, the functioning of different closed-loop DLCSs was modelled. Results underlined that proportional dimming systems guarantee the best performances for each analyzed case, however they demonstrated that, for specific indoor daylight levels and task illuminances, switching systems can be profitable as well. It was underlined that, for specific daylight conditions, integral reset control guarantees performances comparable with those of proportional dimming. However, it was observed that for integral reset and multi-levels stepped systems, the risk that total illuminances (daylight plus electric light) are lower than the prescribed ones is higher than the other analyzed control strategies.

1. Introduction

Daylight-linked control systems (DLCSs) are commonly known as an effective tool to save energy by optimizing daylighting. Regulations themselves suggest using such systems, for example [1] reports: "*Energy savings can be made by harvesting daylight, (…) and making full use of controls*". However, DLCSs benefits effectiveness is a very debated research topic, since researches [2–7] demonstrated that correlated energy savings can be very different depending on the specific application. In a recently published review paper Ul Haq et al. [8], starting from previous studies results, underlined that savings can vary from about 9% to about 20% in offices, from about 20% to about 66% in classrooms and from about 11% to about 46% in indoor open spaces and atria.

These great differences are fundamentally ascribable to two issues: 1) DLCSs performances primarily depend on indoor daylight availability, so the same system installed in two different spaces can provide different savings; 2) given a specific space, the same control can differently operate depending on its setting and on its components characteristics. Controls performances are indeed influenced by the adopted control strategy [3–5], photosensors characteristics [9,10] and locations [11], calibration setting [9,12], ballast typology [11,13], luminaires zoning [2].

Consequently, the DLCSs operating conditions modelling can be very difficult during design process and the evaluation of energy savings and of the installation economic convenience can be problematic. Obviously, all these issues constitute a solid barrier to the common spread of such systems [14,15] and often, when DLCSs are installed, achieved benefits are lower than expectations. This is particularly true considering that, final performances of DLCSs depend not only on the way they are designed, installed and calibrated, but, first and foremost, on users' degree of acceptance. If people do not enjoy the way DLCSs operate, disable them and personally control lighting setting. Previous studies highlighted that people prefer to have a direct and manual control on the environment they use and that, when automated controls are installed they are more satisfied when they have the possibility to partially manage the lighting system [16–18].

Even though the amount of parameters to set when designing DLCSs is huge, previous researches demonstrated that the very analysis of daylight availability is a fundamental tool to guide technical choices. Indeed, results of the analysis can provide useful information about the quantity of daylight entering the space to control and about its environmental distribution and this information has a key role in the definition of DLCSs setting. For example, Li et al. [19] underlined that the choice of the control strategy can be based on a comparison between the typical indoor daylight illuminances characterizing the

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Nomenclature

A	reference area corresponding to the work-plane [m^2]
DIA	Daylight Integration Adequacy [%]
$\overline{E}_{A,dl}(t)$	average daylight illuminance referred to the area A [lx]
$\overline{E}_{A,dl,tc}$	average daylight illuminance at the area A at the calibration time [lx]
$\overline{E}_{A,el}(t)$	average electric light illuminance provided by the lighting system to the area A [lx]
$\overline{E}_{A,el,id}(t)$	average electric light illuminance a system should ideally provide to the area A, in order to perfectly integrate daylight and achieve $\overline{E}_m$ [lx]
$\overline{E}_{el,ref}(t)$	average electric light illuminance of the reference system [lx]
$\overline{E}_{A,el,tc}$	average electric light illuminance at the area A when luminaires are turned on at δ_{tc} [lx]
$\overline{E}_{A,el,100\%}$	average electric light illuminance when luminaires are on at 100% [lx]
$\overline{E}_m$	average maintained illuminance at the area A according to standard prescriptions [lx]
ILE	Intrinsic Light Excess [lx·h]
$ILE_{\%}$	Percentage Intrinsic Light Excess [%]
LD	Light Deficit [lx·h]
$LD_{\%}$	Percentage Light Deficit [%]
LR	Light Requirement [lx·h]
$LR_{el,id}$	ideal electric light requirement [lx·h]
LR_{dl}	light requirement fulfilled by daylight equal to LR-$LR_{el,id}$ [lx·h]
LW	Light Waste [lx·h]
$LW_{\%}$	Percentage Light Waste [%]
$S_{dl}(t)$	daylight component of the photosensor signal [lx]
$S_{dl,tc}$	daylight component of the photosensor signal at the calibration time [lx]
$S_{el}(t)$	electric light component of the photosensor signal [lx]
$S_{el,100\%}$	electric light component of the photosensor signal when luminaires are on at 100% [lx]
$S_{el,tc}$	electric light component of the photosensor signal at the calibration time [lx]
$S_{el,\delta max}$	electric light component of the photosensor signal when luminaires are turned on at δ_{max} [lx]
S(t)	photosensor signal, sum of $S_{dl}(t)$ and $S_{el}(t)$ [lx]
S_{down}	photosensor signal corresponding to switch-off action in stepped systems [lx]
S_{lim}	signal corresponding to δ_{min} according to the slope of the algorithm curve in dimming systems [lx]
S_{off}	photosensor signal corresponding to switch-off action in switching systems [lx]
S_{on}	photosensor signal corresponding to switch-on action in switching systems [lx]
S_{tc}	photosensor signal during calibration, sum of $S_{dl,tc}$ and $S_{el,tc}$ [lx]
S_{up}	photosensor signal corresponding to switch-on action in stepped systems [lx]
T	defined time period [h]
$\Delta E(t)$	$\overline{E}_{A,el}(t) - \overline{E}_{A,el,id}(t)$ [lx]
$\delta(t)$	luminaires light output set by the control system [%]
δ_{max}	luminaires maximum light output [%]
δ_{min}	luminaires minimum light output [%]
$\delta_{ref}(t)$	luminaires light output of the reference system [%]
δ_{tc}	luminaires light output necessary to integrate $\overline{E}_{A,dl,tc}$ [%]

considered environment and the required task illuminance. For example, they suggested that when the required task illuminance is low and daylight levels are generally high, an on-off switching system could be more appropriate than a dimming one. On the contrary, when daylight levels are generally low, dimming systems determine higher savings. Other studies [2,3] underlined the possibility to increase energy savings grouping luminaires in different control zones depending on their distance from the window, i.e. depending on the daylight availability characteristic of a specific part of the room. [12] demonstrated how seasonal weather changes affect the relationship between the daylight photosensor signal and the work-plane illuminance. The study highlighted that an in-depth daylight analysis is useful to identify the correct way to calibrate DLCSs and that varying calibration algorithms according to seasonal rhythms improves DLCSs performances.

In this context, on field studies, aiming at monitoring daylight in real indoor environments, are fundamental to increase knowledge about DLCSs and to understand the influence that daylight availability has in affecting these systems performances. They are particularly useful when measurements are performed with a small time step, since the short time daylight fluctuations can strongly affect control systems functioning [20].

The evaluation of the way DLCSs integrate daylight should be performed by means of proper indices. In this respect, recent studies [21–23] underlined the necessity to introduce a new methodology to assess DLCSs performances, based on the analysis of the very capability of DLCSs in integrating daylight, by overcoming the usual approach based exclusively on energy savings calculation. High energy savings achievement does not assure that the control system provides an adequate light amount, but only that it provides a lower light amount compared to a reference system (that generally is a system always switched-on at 100%).

DLCSs functioning is based on the assumption that, at each time t, the daylight photosensor signal, $S_{dl}(t)$, is always representative of the average daylight work-plane illuminance $\overline{E}_{A,dl}(t)$ and that the ratio $\overline{E}_{A,dl}(t)/S_{dl}(t)$ can be assumed constant on time varying and equal to that measured during calibration phase ($\overline{E}_{A,dl,tc}/S_{dl,tc}$). Actually, considering that indoor daylight distribution continuously changes according to time of day, weather conditions and shading devices configurations, the $\overline{E}_{A,dl}(t)/S_{dl}(t)$ ratio continuously varies and deviates from $\overline{E}_{A,dl,tc}/S_{dl,tc}$ [9,10]. This determines that, during the operating life of a control system, the sum of electric light and daylight illuminances at the work-plane can be higher or lower than the average illuminance required by regulations, $\overline{E}_m$. Consequently, if total illuminances are often lower than the task one, energy savings could be ascribable to unappropriated lighting conditions.

To account for this aspect, Doulos et al. [21] introduced a new performance parameter, the lighting adequacy, that is "the percentage for occupied time with total illuminance exceeding design illuminance" [21]. Similarly, Bonomolo et al. [22] proposed two indices: Over-illuminance Avoidance Ratio (OAR) and Under-illuminance Avoidance Ratio (UAR). They describe the capability of the system in avoiding over-illuminance and under-illuminance conditions, i.e. in avoiding that the sum of electric light and daylight illuminances at the work-plane is higher or lower than the target. In this regard, Bellia and Fragliasso [23] introduced a new concept: the Intrinsic Light Excess. The authors underlined that when the sum of electric light and daylight illuminances at the work-plane is higher than $\overline{E}_m$, the causes can be different. They can be due not only to the deviations of the $\overline{E}_{A,dl}(t)/S_{dl}(t)$ ratio from the $\overline{E}_{A,dl,tc}/S_{dl,tc}$ one, but also to the control strategy characteristics. For example, sometimes dimming systems are set to regulate luminaires luminous flux from a maximum to a minimum level, without completely turning lights off. In these cases, each time daylight is alone sufficient to fulfil light requirements, a light excess occurs as well, because luminaires always emit a minimum luminous flux. This excess cannot be avoided unless changing the control strategy. Therefore, the light excess is defined Intrinsic Light Excess if it is due to the system typology characteristics and Light Waste if it is due to the deviations of the $\overline{E}_{A,dl}(t)/S_{dl}(t)$ ratio from the $\overline{E}_{A,dl,tc}/S_{dl,tc}$. Based on this idea the authors proposed the following parameters: Daylight Integration Adequacy (DIA), Percentage Light Deficit ($LD_{\%}$), Percentage Intrinsic Light Excess ($ILE_{\%}$) and Percentage Light Waste ($LW_{\%}$). The DIA is defined as the percentage of the lighting system operating hours for which it is verified that the sum of daylight and electric light illuminances is equal or higher than $\overline{E}_m$, but, when higher, the excess is intrinsic. DIA^+ and DIA^- are associated to DIA as well: DIA^+ is the percentage of lighting system operating hours for which Light Waste occurs; DIA^- is the percentage of lighting system operating hours for which a Light Deficit occurs. Finally, $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$ quantify the deficit light, the intrinsic excess and the waste.

The goal of the paper is to investigate the relationship between daylight availability and DLCSs performances.

For this purpose, daylight illuminance measurements were performed in a side-lit office characterized by a double exposure (South and West). Measurements were repeated during summer and winter by shading one window in turn, in order to obtain seasonal data related to two different case studies (the former south-oriented and the latter west-oriented). Illuminances were measured at the work-plane and at the location of a typical ceiling-mounted photosensor, with one-minute time-step. Starting from obtained data, the functioning of different control systems was evaluated by applying the specific control equations and considering real calibration conditions. Finally, DIA, $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$ were used to evaluate the capability of the control systems in integrating daylight, in order to underline how the suitability of a control strategy actually depends on the daylight availability. Moreover, a new formulation of $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$ was proposed in order to make easier results interpretation.

2. Method

As it was anticipated in the Introduction, the work is divided in three parts: daylight measurements in a side-lit office; modelling of the functioning of different closed-loop DLCSs based on daylight measured data; DLCSs performances evaluation by means of DIA, $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$.

The case study is a square office located at the seventh floor of one of the University of Naples buildings (Latitude 40° 51′ 22 N, Longitude 14° 14′ 47 E). It is side-lit by two balcony windows, one facing South and the other facing West. Both windows are equipped with a roller

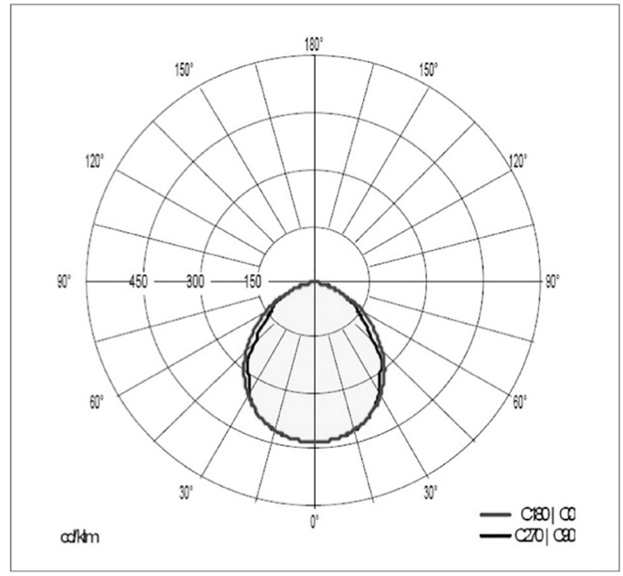

Fig. 2. Luminaire photometry.
(Source: luminaire manufacturer)

blind and a 1.6 m overhang shades the west one. Once closed, the roller-blinds completely exclude the daylight penetration. An L-shaped desk is located in an office corner and a bookcase is positioned along one of the walls. Room dimensions are reported in Fig. 1.

A proper lighting system was designed for the test-room by using DIALux software [24]. Recessed LED luminaires characterized by crystal optic for glare control optimization were chosen. According to the technical sheet, they were characterized by a 4280 lm luminous flux, a 51 W power, a 4000 K Correlated Colour Temperature and Colour Rendering Index higher than 80. Their photometry is reported in Fig. 2.

The office is generally used for architecture students tutoring. Considering the prescriptions reported in [1], the corresponding visual task is "technical drawing" and 750 lx work-plane illuminance and 0.7 uniformity values are needed to perform it. To achieve these requirements, four luminaires were necessary. They were located in two rows. The system so designed, considering a 0.8 maintenance factor, determined an average work-plane illuminance at the desk equal to 778 lx and a uniformity value equal to 0.85.

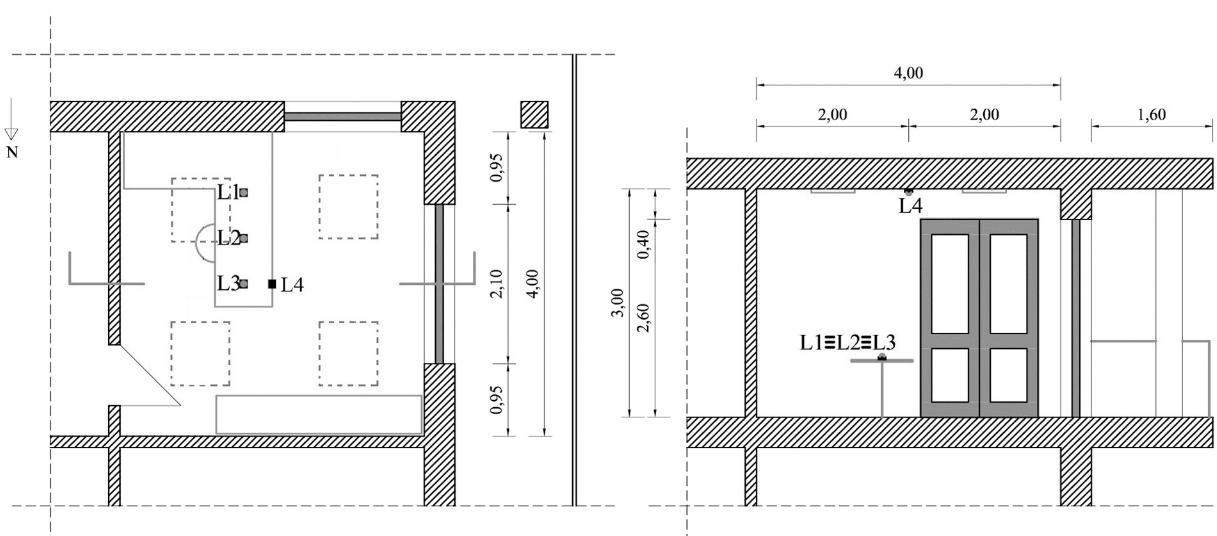

Fig. 1. Measured plan and section of the office.

2.1. Daylight measurements

Daylight measurements were performed during June 2017 and December 2017. Four Nesa illuminance-meters [25] were located in the room: three of them (L1, L2 and L3) were positioned along the desk longitudinal axis, at a 0.5 m distance one from each other, and the last one (L4) was located at the ceiling to simulate the positioning of a closed-loop photosensor (see Fig. 1). The illuminance-meters were all characterized by a 0–20,000 lx measurement range. Illuminances were stored by a datalogger with a 1-min time step, in order to obtain high frequency data, useful to accurately evaluate control systems functioning and their capability in integrating daylight considering the short time fluctuations. The acquisition time ranged from 9:00 to 19:00. Measurements were performed by alternatively considering one of the two orientations: to obtain data referred to south orientation, the west roller blind was completely closed and, to obtain data referred to west orientation, the south roller blind was completely closed. Totally, data referred to 24 days were obtained: 6 for each orientation and each season. Based on measured data, Daylight Autonomy (DA) [26] was calculated to characterize the environment. This metrics was used to account for time variations of daylight, not considered in other calculation procedures, which are based on a static daylight availability approach (for example that proposed by [27]).

2.2. DLCSs modelling

Five different closed-loop control strategies were chosen: switching, three levels and two levels stepped, proportional dimming and integral reset.

The calculation procedure used to model the functioning of the considered DLCSs was schematized in Fig. 3.

As it can be noticed in the scheme, the procedure puts together measured and calculated data. Specifically, daylight was measured, whereas electric light was simulated. Moreover, the relationship between the light output level and the corresponding absorbed power related to the selected luminaire and its controller was on-field measured.

The first phase of the calculation procedure was the evaluation of the photosensor signal. It must be underlined that for this application, the illuminances at the photosensor were assumed to be representative of the signals and, for this reason, the signal unit of measurements is lx (see the Nomenclature). Specifically, it was assumed that daylight illuminance at L4 coincides with the daylight component of the photosensor signal, $S_{dl}(t)$. On the other hand, the electric light component of the photosensor signal was evaluated at each time t as the product of the light output to the electric light component of the photosensor signal when luminaires are 100% on, $S_{el,\ 100\%}$. This value was calculated by using DIALux, setting a calculation point corresponding to the L4

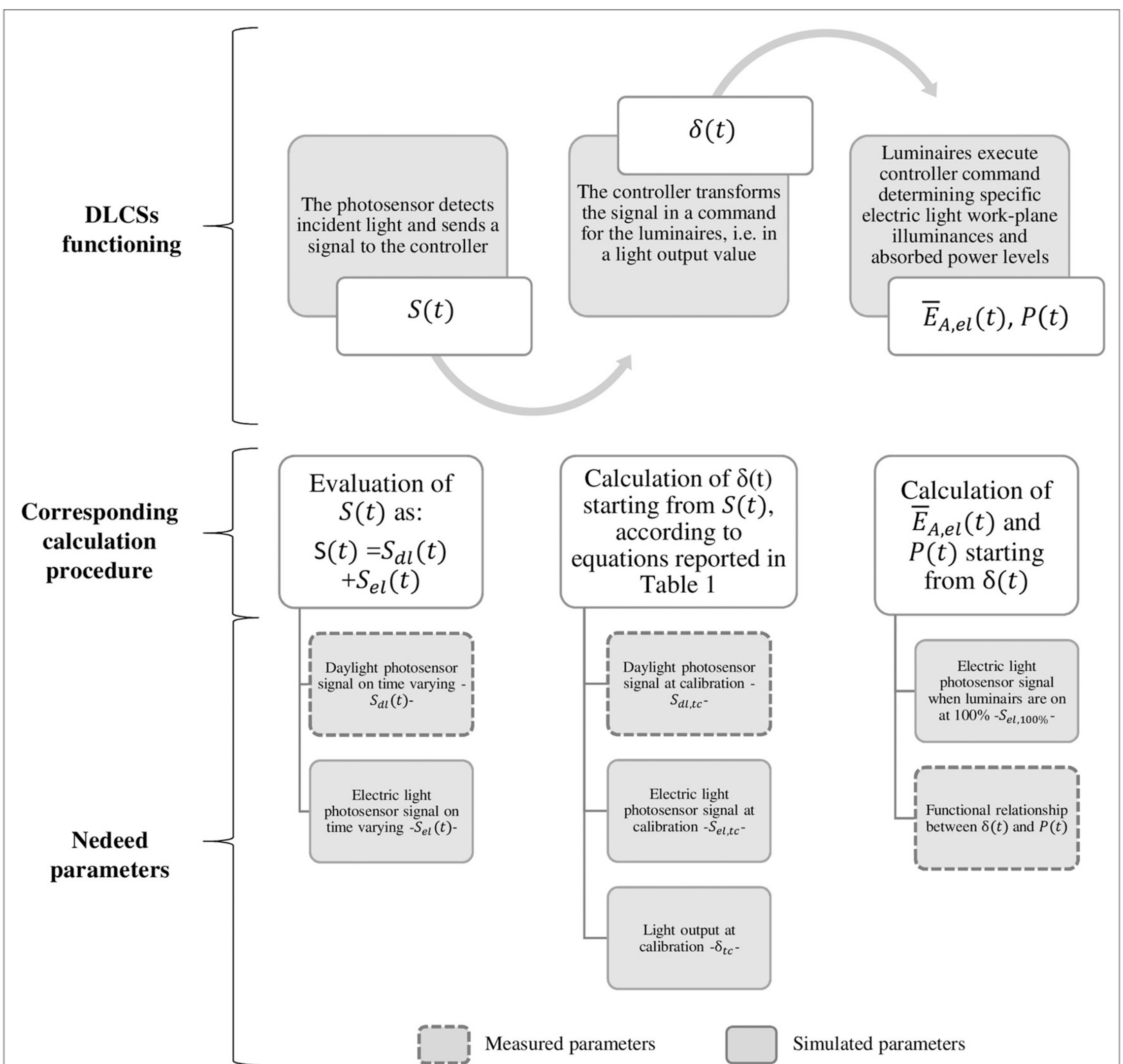

Fig. 3. Scheme of the calculation procedure.

position. Considering the 0.8 maintenance factor, it is equal to 284 lx.

Starting from the photosensor signal, for each considered DLCS, it was possible to calculate the light output on time varying $\delta(t)$ by using the control equations reported in Table 1 (for symbols see the Nomenclature), describing the control algorithms represented in Fig. 4.

According to the equations reported in Table 1, for each control algorithm, it is necessary to set specific calibration parameters. They are listed in Table 2 (for the symbols see the Nomenclature). In Table 2, the last column reports the value attributed to each parameter or the equation used to calculate it.

For switching and stepped systems the dead-band extent was evaluated according to the suggestions reported in [29]. As regards δ_{min}, as it will be in-depth explained soon, it was on-field measured and it was equal to 34%. δ_{max} was 100% for switching systems and 80% for dimmable ones (stepped and dimming). Indeed, the control systems simulation was performed considering that the lighting system was at the beginning of its operating life. Considering that the system was designed applying a maintenance factor equal to 0.8, i.e. it was oversized to account for the luminous flux decay over time, it was possible to reduce δ_{max} to 80%. In three-levels stepped system, δ_{max} was equal to 100%, since the minimum light output is 34%. So, in this case, the three light output levels were: 34%, 67% and 100%. The electric light component of the photosensor signal corresponding both to 100% and 80% light output values ($S_{el,\ 100\%}$ and $S_{\delta max}$) were calculated by means of the DIALux software. δ_{tc} was chosen according to the indications in [30], i.e. it is slightly higher than the minimum one. Finally, as for $S_{dl,\ tc}$ values, they were evaluated in the following way. $S_{dl,\ tc}$ corresponds to the daylight photosensor signal registered at the calibration time. According to [24] it must be measured, for switching systems, when the daylight illuminance at the work-plane is slightly higher than the task illuminance. For dimming systems, $S_{dl,\ tc}$ must be measured when daylight illuminance is such that the electric light output necessary to integrate daylight is slightly higher than δ_{min}. To obtain $S_{dl,tc}$ values, the daylight illuminance at calibration was determined (800 lx for switching systems and 300 lx for dimming ones). Then, for each orientation, measured work-plane illuminances around 800 lx (between 790 lx and 810 lx) and around 300 lx (between 290 lx and 310 lx) were selected. The corresponding L4 illuminances were taken from the database and the related average value was calculated and assumed to be $S_{dl,\ tc}$. Previous works [5,7,12] underlined that weather conditions and seasonal variations affect the ratio of the work-plane illuminance to the photosensor signal. So, differently calibrating control systems over time improve their performances. For this reason, the calibration procedure was repeated for winter and for summer. $S_{dl,\ tc}$ values were reported in Table 3 related to switching and dimming systems and referred to each season and orientation.

Once $\delta(t)$ values over time were obtained, it was possible to calculate $\overline{E}_{A,el}(t)$ and $P(t)$. $\overline{E}_{A,el}(t)$ is calculated as the product of $\delta(t)$ and $\overline{E}_{A,el,100\%}$, i.e. the work-plane illuminance when luminaires are on at 100%. This value was calculated by means of DIALux, without considering the maintenance factor (973 lx).

To evaluate the absorbed power, the functional relationship between $\delta(t)$ and $P(t)$ was on field assessed. Indeed, the luminaire selected for the application is installed in another room of the University: the Photometry and Lighting Laboratory of the Department of Industrial Engineering. The laboratory is a 2.80 m·3.50 m wide and 2.70 m high. It is equipped with a false ceiling containing different light sources all managed by a DALI control unit. One of these sources is the above-

Table 1
Control equations [23,28].

Control typology	Control equation
Switching	$\delta(t)=\begin{cases}\delta_{max} & \text{if } S(t)\le S_{on}\\ 0 & \text{if } S(t)\ge S_{off}\\ \delta_{t-1} & \text{if } S_{on}<S(t)<S_{off}\end{cases}$
Two-levels stepped switching system	$\delta(t)=\begin{cases}\frac{1}{2}\delta_{max} & \text{if } S(t)\le S_{up} \text{ and } \left[\delta_{t-1}+\left(1-\frac{S(t)}{S_{up}}\right)\cdot\delta_{max}\right]\le\frac{1}{2}\delta_{max}\\ \delta_{max} & \text{if } S(t)\le S_{up} \text{ and } \left[\delta_{t-1}\left(1-\frac{S(t)}{S_{up}}\right)\cdot\delta_{max}\right]>\frac{1}{2}\delta_{max}\\ 0 & \text{if } S(t)\ge S_{off}\\ \delta_{t-1} & \text{if } S_{up}<S(t)<S_{down}\end{cases}$
Three-levels stepped switching system	$\delta(t)=\begin{cases}\frac{1}{3}\delta_{max} & \text{if } S(t)\le S_{up} \text{ and } \left[\delta_{t-1}+\left(1-\frac{S(t)}{S_{up}}\right)\cdot\delta_{max}\right]\le\frac{1}{3}\delta_{max}\\ \frac{2}{3}\delta_{max} & \text{if } S(t)\le S_{up} \text{ and } \frac{1}{3}\delta_{max}<\left[\delta_{t-1}+\left(1-\frac{S(t)}{S_{up}}\right)\cdot\delta_{max}\right]\le\frac{2}{3}\delta_{max}\\ \delta_{max} & \text{if } S(t)\le S_{up} \text{ and } \left[\delta_{t-1}\left(1-\frac{S(t)}{S_{up}}\right)\cdot\delta_{max}\right]>\frac{2}{3}\delta_{max}\\ 0 & \text{if } S(t)\ge S_{off}\\ \delta_{t-1} & \text{if } S_{up}<S(t)<S_{down}\end{cases}$
Proportional dimming system	$\delta(t)=\begin{cases}\frac{m\bullet S_{dl}(t)+q}{1-m\bullet S_{el,100\%}} & \text{if } S_{dl}(t)\le S_{dl,lim}\\ \delta_{min} & \text{if } S_{dl}(t)>S_{\mathrm{dl,lim}}\end{cases}$ Where: $m=\frac{\delta_{tc}-\delta_{max}}{S_{tc}-S_{el,\delta max}}$ $q=\frac{S_{tc}\bullet\delta_{max}-S_{el,\delta max}\bullet\delta_{tc}}{S_{tc}-S_{el,\delta max}}$ $S_{dl,lim}=\frac{\delta_{min}(1-m\bullet S_{el,100\%})-q}{m}$
Integral reset system	$\delta(t)=\begin{cases}1-\frac{S_{dl}(t)}{S_{el,\delta 100\%}} & \text{if } S_{dl}(t)\le S_{dl,lim}\\ \delta_{min} & \text{if } S_{dl}(t)>S_{dl,lim}\end{cases}$ Where: $S_{dl,\ lim}=S_{el,\ \delta max}-\delta_{\min}\cdot S_{el,\ \delta 100\%}$

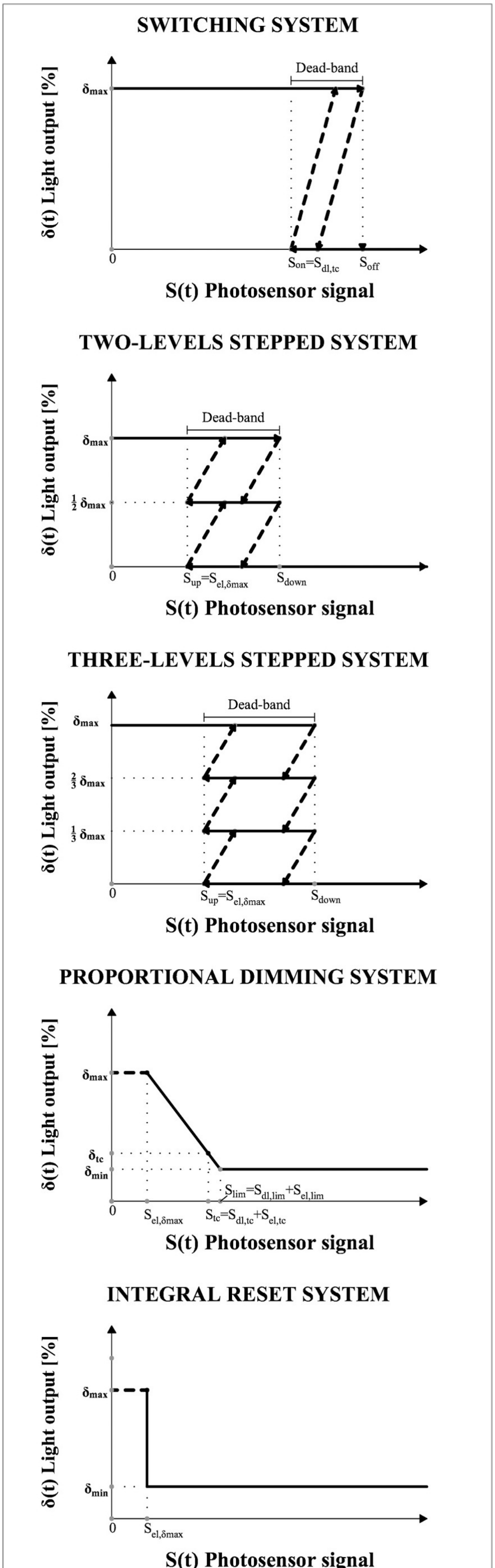

Fig. 4. Chosen control algorithms.

mentioned luminaire. Luminaire light output was varied from the maximum luminous flux and the minimum one. An illuminance meter Konica Minolta T-10A was positioned at a distance from the floor equal to 0.75 m and corresponding to the luminaire barycenter projection. It was observed that the illuminance varied from 338 lx to 115 lx. So, the minimum light output is 34%. Then, the absorbed power was measured by means of an electronic power meter connected to the laboratory fuse box, while varying the light output from the maximum to the minimum. Twenty light output steps were considered and results are reported in Fig. 5.

The relationship between $\delta(t)$ and $P(t)$ is linear. When the light output is 100% the absorbed power is equal to 47.1 W, when the light output is equal to 34% the absorbed power is 16.9 W, i.e. the 36% of the maximum value. Based on these observations, starting from $\delta(t)$ the absorbed power was evaluated according to the equation reported on the graph.

2.3. DLCSs performance evaluation

Once the electric light illuminances at the work-plane were defined, DIA, $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$ were calculated.

DIA, DIA^+ and DIA^- were evaluated according to the definitions proposed in [23] and reported in the introduction. On the contrary, for this application a new formulation of $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$ was applied. Specifically, the parameters were calculated as:

$$\text{Percentage Light Deficit} = LD_{\%} = \frac{LD}{LR} \bullet 100\ [\%] \tag{1}$$

$$\text{Percentage Intrinsic Light Excess} = ILE_{\%} = \frac{ILE}{LR} \bullet 100\ [\%] \tag{2}$$

$$\text{Percentage Light Waste} = LW_{\%} = \frac{LW}{LR} \bullet 100\ [\%] \tag{3}$$

LD, ILE and LW are the Light Deficit, the Intrinsic Light Excess and the Light Waste, expressed in lx·h and evaluated according to [31], whereas LR is:

$$LR = \text{Light Requirement} = \overline{E}_m \cdot \text{system operating hours}\ [lx \cdot h] \tag{4}$$

where $\overline{E}_m$ is the average illuminance prescribed by regulations.

In the previous formulation of $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$, the denominator was $LR_{el,id}$, instead of LR. $LR_{el,id}$ is the ideal electric light requirement evaluated as:

$$LR_{el,id} = \text{ideal electric Light Requirement} = \int_T \overline{E}_m - \overline{E}^*_{A,dl}(t)dt\ [lx \cdot h] \tag{4}$$

where:

$$\overline{E}^*_{A,dl}(t) = \begin{cases} \overline{E}_m(t) \text{ if } \overline{E}_{A,dl}(t) \geq \overline{E}_m \\ \overline{E}_{A,dl}(t) \text{ if } \overline{E}_{A,dl}(t) < \overline{E}_m \end{cases} [lx] \tag{5}$$

and $\overline{E}_{A,dl}(t)$ is the average daylight illuminance at the work-plane.

$LR_{el,id}$ depends on both the required task illuminance and the daylight availability. Consequently, the previous formulation of the parameters determined two problems: 1) it is not immediate to compare the performances of equal systems installed in spaces characterized by different daylight availability; 2) LD, ILE and LW can be higher than $LR_{el,id}$, so $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$ can assume values higher than 100%. The new formulation allows to solve these problems and makes the use of the parameters friendlier. Indeed, LR depends only on task illuminance. Moreover, LD, ILE and LW cannot be higher than LR, so $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$ values are always comprised between 0% and 100%.

The Appendix A reports the complete procedure to calculate the $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$.

Table 2
Control systems calibration parameters.

Control typology	Calibration parameter	Calculation procedure/ corresponding value
Switching system	$S_{dl,\ tc}$	See Table 3
	Dead-band	$S_{el,\ \delta max} + 0.2 \cdot S_{dl,\ tc}$
	$S_{el,\ \delta max} \equiv S_{el,\ 100\%}$	355 lx
	S_{off}	$S_{dl,\ tc}$ + Dead − band
	δ_{max}	100%
Two levels-stepped system	$S_{el,\ \delta max}$	284 lx
	Dead-band	$1.2 \cdot S_{el,\ \delta max}$
	S_{down}	$S_{el,\ \delta max}$ + Dead − band
	δ_{max}	80%
Three levels-stepped system	$S_{el,\ \delta max} \equiv S_{el,\ 100\%}$	355 lx
	Dead-band	$1.2 \cdot S_{el,\ \delta max}$
	S_{down}	$S_{el,\ \delta max}$ + Dead − band
	δ_{max}	100%
Proportional dimming system	$S_{el,\ \delta max}$	284 lx
	$S_{dl,\ tc}$	See Table 3
	$S_{el,\ tc}$	$\delta_{tc} \cdot S_{el,\ 100\%}$
	$S_{el.\ 100\%}$	355 lx
	δ_{max}	80%
	δ_{tc}	48%
	δ_{min}	34%
Integral reset system	$S_{el,\ \delta max}$	284 lx
	δ_{max}	80%
	δ_{min}	34%

Table 3
$S_{dl,\ tc}$ values for switching ad dimming systems [lx].

	Switching systems		Dimming systems	
	Summer	Winter	Summer	Winter
South orientation	1116	656	293	304
West orientation	997	818	353	338

3. Results and discussion

3.1. Daylight analysis

Figs. 6 and 7 report measured illuminances from 9:00 to 19:00 related to the two orientations during summer and winter. Data are referred to L1, L2 and L3 average illuminance.

As regards summer - south orientation (Fig. 6.a), measurements days were all characterized by very variable weather conditions, except for Jun/3/2017, for which a stable illuminance trend can be observed: illuminances increase until 13:00, when the maximum value is registered, and then gradually decrease until sunset.

For summer - west orientation (Fig. 6.b), work-plane illuminances are generally characterized by an almost constant trend during the first part of the day and start to strongly increase from 13:00 on, with a brusque peak at about 16:30 when direct radiation falls on the desk. The daylight fluctuations observed after 16:30 demonstrate that sky conditions were not steady when west orientation measurements were performed as well. Illuminance trend of Jun/17/2017 proves the occurrence of an overcast day.

As for winter measurements, indoor illuminance trends are completely different. Considering south orientation (Fig. 7.a), due to lower sun height, direct radiation hits the work-plane at around 14:00, determining very high illuminance levels. On the contrary, as for west orientation (Fig. 7.b), since sun sets early, direct radiation cannot reach the desk and illuminances are always lower than 800 lx.

According to results of a previous research [32], daylight illuminances higher than 3000 lx can determine visual or thermal discomfort (overheating). For this reason, illuminances higher than 3000 lx were identified. It was found that the critical time slot ranges from 16:45 to 18:15 for west orientation during summer and from 12:45 to 15:15 for south orientation during winter. During these time ranges, a shading device should be used, in order to avoid direct radiation penetration. This would change the ratio of the work-plane illuminance to the photosensor signal, affecting the performances of the control systems. This issue would deserve a deepened study. For this application, data useful to reliably evaluate the indoor daylight levels reduction due to the presence of a shading device were not available. Indeed, the south roller blind was always completely rolled up during south orientation measurements and the west roller blind was always completely rolled up during west orientation measurements. So, a simplified simulation method was used. It was considered that, when shading device use is necessary (i.e. when daylight illuminances are higher than 3000 lx), DLCSs were temporarily disabled. In that time range the lighting system worked at full capacity, to compensate for the indoor daylight reduction that a shading device would determine.

Fig. 8 reports DA values related to the four analyzed daylight conditions. DA was referred to the average illuminance of the three work-plane points and considering that the daylight contribution in the critical time slots was equal to 0, to account for the presence of the shading devices.

In Fig. 8 the ratio of LR_{dl} to LR (LR_{dl}/LR) is also reported. LR_{dl} is the

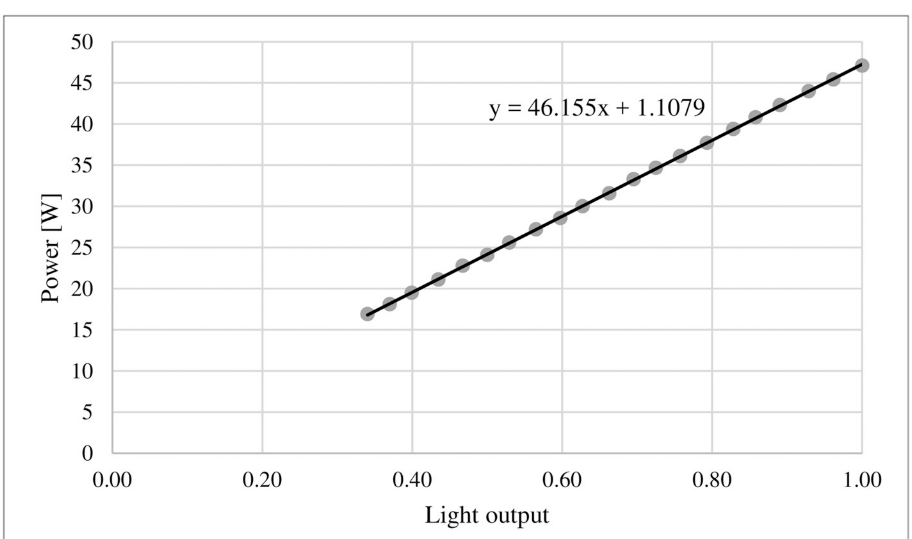

Fig. 5. Relationship between Light output and Power.

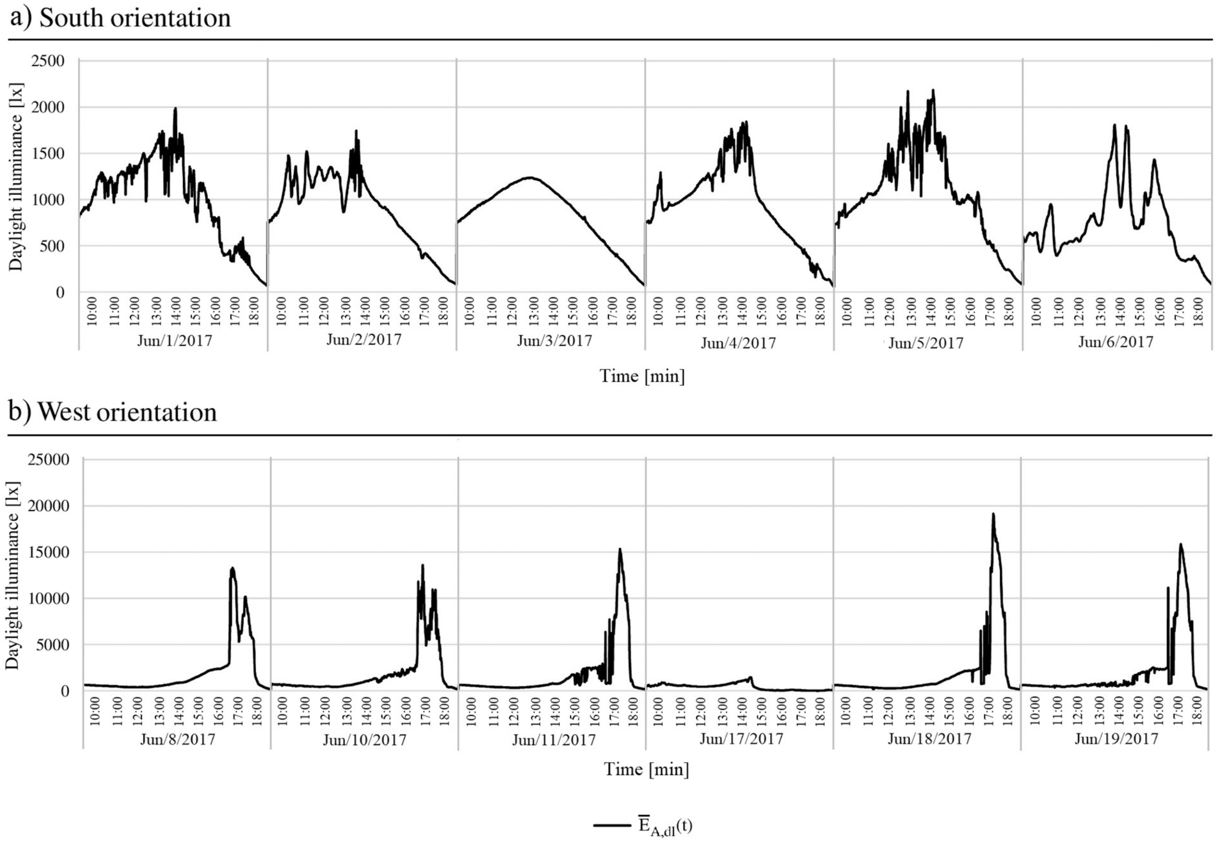

Fig. 6. Average daylight illuminances at the work-plane: summer measurements.

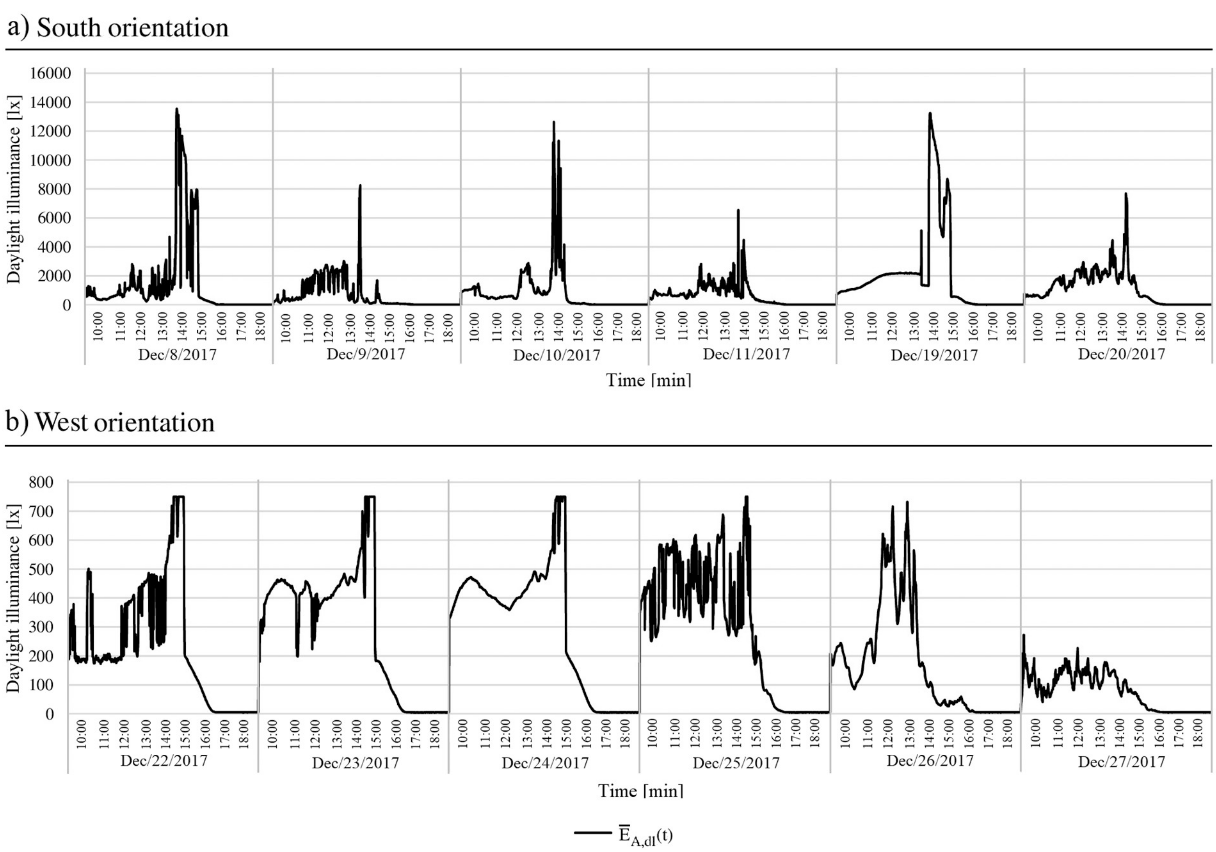

Fig. 7. Average daylight illuminances at the work-plane: winter measurements.

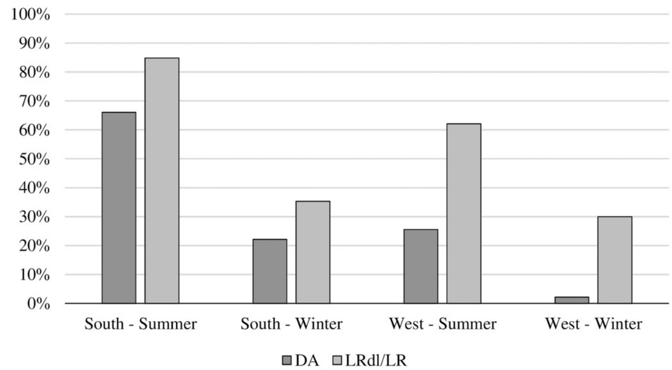

Fig. 8. DA and LR_{dl}/LR referred to south and west orientations.

Light Requirement fulfilled by daylight and it is equal to the difference between LR and $LR_{el,id}$. Consequently, the ratio LR_{dl}/LR can be considered a good indicator of the daylight potential of an indoor environment.

South orientation DA is much higher than the west orientation one during both summer and winter. During summer this is due to the necessity to shade direct solar radiation when the window is west-oriented. Conversely, during winter, even though the shaded window is the south one, 2 h west indoor daylight availability is so low, that illuminances rarely achieve the task illuminance.

LR_{dl}/LR informs about the percentage of the light requirement that daylight fulfils and the comparison between DA and LR_{dl}/LR is useful to make an early evaluation of control systems achievable benefits. For example, considering winter measurements, even though west DA value is lower than the south one, LR_{dl}/LR is comparable. Specifically, daylight alone could fulfil about 35% of the light requirement for south orientation and about 30% for west one. However, in south orientation case, the lighting system could be completely off for about 21% of the time, whereas for west orientation electric light integration is almost always needed.

3.2. Control systems functioning with south orientation

Figs. 9 and 10 represent luminaires light output as a function of the time for each control typology for south orientation during summer and winter. Moreover, on the secondary vertical axis, the corresponding total illuminance $\overline{E}_{A,tot}(t)$, sum of daylight and the electric light illuminances is reported. The dashed line identifies the task illuminance equal to 750 lx. Fig. 11 reports performance parameters values and energy savings. The reference system used to evaluate energy savings is a lighting system equipped with the same luminaires, but always on at 100%.

Considering the switching system (Fig. 9.a), during summer generally luminaires are switched on and stay continuously on from about 15:30 on. During the first part of the day, switching on and off actions depend on weather conditions and electric light fluctuations can be more or less sudden depending on daylight oscillations. Only on Jun/06/2017, luminaires are turned on for most of the day. The total illuminance is almost always higher than the task illuminance, so the system never works in deficit conditions. Moreover, when the system is turned on, total illuminance is much higher than the task illuminance.

As it can be observed in Fig. 11, the reported total illuminances trend corresponds to an 85.39% DIA value and a 14.14% DIA^+. DIA^- is almost null and equal to 0.47%. As it was easily predictable, $ILE_{\%}$ assumes a noticeable value (33.26%), whereas the $LW_{\%}$ is not very high and it is about 18.34%. The reported control operating conditions correspond to energy savings equal to about 48.32%.

During winter (Fig. 10.a) the switching lighting system is turned on from more than half day. This is due to the use of the shading device from 12:45 to 15:15 and to daylight illuminance reduction from 15:15 on. Even though during winter the obtained energy savings are lower than during summer, the way the system operates is comparable with that observed during summer. Indeed, $ILE_{\%}$ value is equal to 38.38%. LW% is almost 0, meaning that the obtained excess is exclusively due to the control strategy.

Considering summer, the use of multi-level stepped switching determines a significant energy saving increase: about 44.25% with the two-levels stepped switching and about 41.41% with the three-levels stepped switching (Fig. 11.c). This increase is due to the reduction both of $ILE_{\%}$ and $LW_{\%}$. However, for these two systems DIA^- and $LD_{\%}$ are not null. Specifically, they are equal to 27.94% and 7.20% for two-levels stepped systems and to 23.46% and 5.12% for three-levels ones. The functioning of the two-levels stepped and of the three-levels stepped systems is pretty similar. The fact that energy savings are almost equal (slightly lower for three-levels ones) depend on the fact that δ_{max} is higher for three-levels system. If the two-levels stepped could reach a light output value equal to 100% the energy savings would decrease and would be equal to 87.88%, slightly lower than those achieved by setting three steps (89.73%). Differences between the performances of the two systems typologies are more significant considering winter. This is due to the fact that luminaires are turned on at the maximum light output for more than half day. This determines that for three-levels stepped systems the $ILE_{\%}$ is much higher than two-levels ones. Considering a 100% maximum light output for two-levels stepped system the difference between the two systems would decrease as well. The ILE% would be 22.28% and the energy savings 34.78%.

During summer, the proportional dimming system (Fig. 9.d) generally works in intrinsic light excess conditions. The $ILE_{\%}$ value is significant (33.15%) and almost equal to that characterizing the switching system. This is due to the fact that the system cannot turn off luminaires, but it can at most dim them until δ_{min}. Looking at Fig. 9.d, it can be noticed that generally the system works at the minimum capacity (δ_{min} = 34%) until about 16:30, then daylight must be integrated and $\delta(t)$ increases. Light Deficit and Light Waste are not really significant. DIA^- is equal to 3.89%, but $LD_{\%}$ is equal to 0.16%. This means that when $\overline{E}_{A,el}(t)$ is lower than $\overline{E}_{A,el,id}(t)$, the difference between them is small (at most 76 lx and 30 lx on the average). As for the waste, a similar observation can be done: DIA^+ is equal to 14.11% and $LW_{\%}$ to 0.77%. This means that $\overline{E}_{A,el}(t)$ is generally very similar to $\overline{E}_{A,el,id}(t)$. During winter the performances of the dimming system are similar to summer, but the $ILE_{\%}$ is lower since, given the scarcer daylight availability, the system works at minimum light output for a smaller time period (see Fig. 10.d). During winter the use of the proportional dimming system does not determine consistent benefits in terms of energy savings (see Fig. 11.c). This is due to the fact that for most of the day the luminaires are on at the full capacity. Savings are likely to increase, considering a different functioning of the lighting system when the shading is needed, for example, admitting that luminaires can emit a luminous flux lower than the maximum one. However this would be verified in a specific study, since the presence of a shading system can consistently modify the $\overline{E}_{A,dl,tc}/S_{dl,tc}$ ratio [33].

Moreover, it is interesting to underline that the difference between energy saving obtained by means of simple switching systems and that obtained by means of proportional dimming ones is not so high: 12.21% in summer and 16.90% in winter. Considering that the initial cost of dimming system installation is important, switching strategy could be a valuable option. This is in accordance with [2], who underlined that dimming systems are not always the most advantageous choice and that, when daylight levels are generally higher than the task illuminance, switching systems can be more beneficial. On the contrary, when daylight availability decreases, high frequency dimming provides greater savings.

The prescribed task illuminance influences the control system functioning as well. For example, if the considered task illuminance were 500 lx, the $ILE_{\%}$ would decrease for switching systems due to the reduction of the time period during which luminaires are on, whereas it

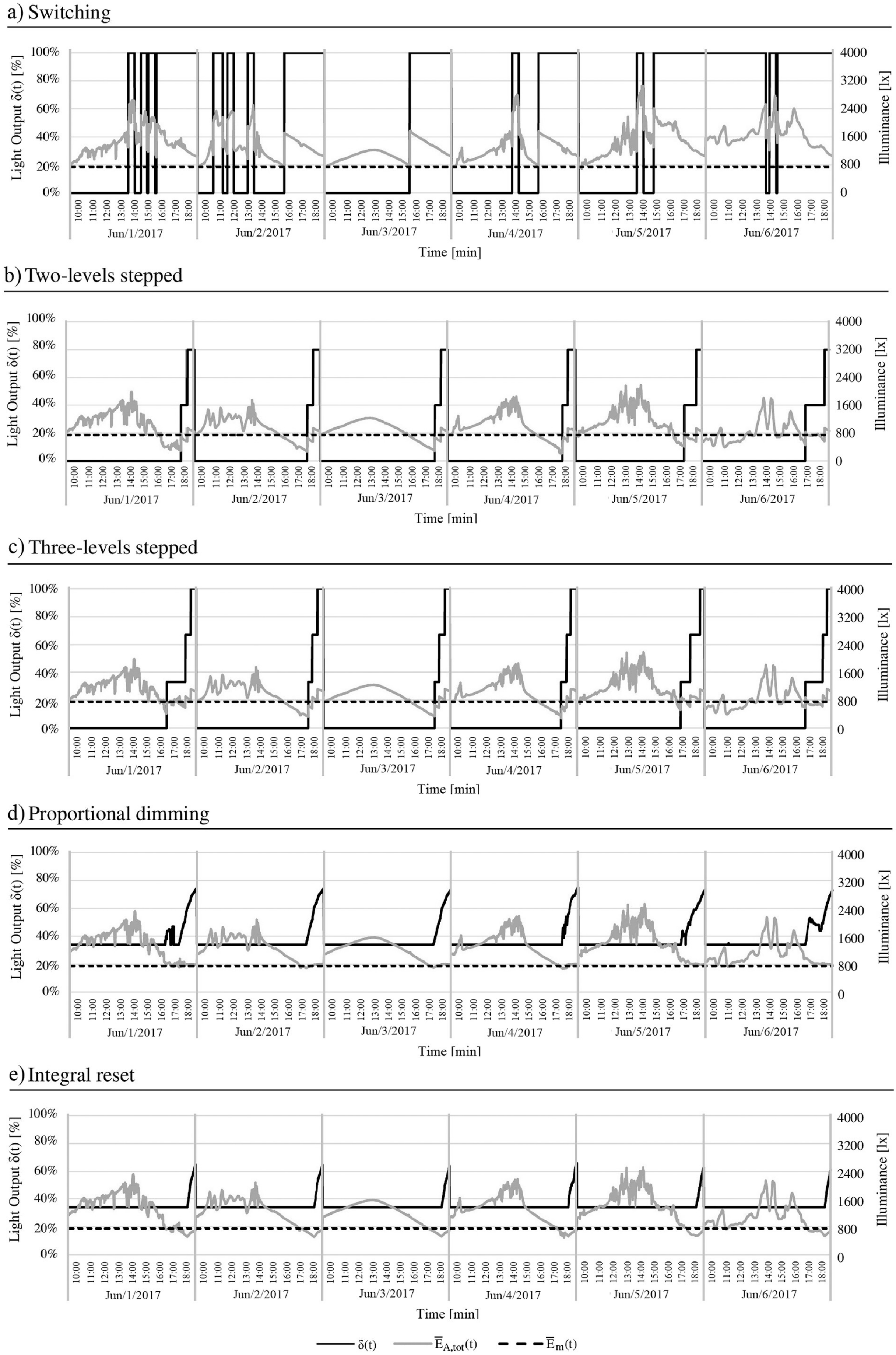

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Fig. 9. Control systems summer functioning – south orientation.

would grow for dimming systems due to the increase of the time period during which luminaires are on at δ_{min}. Specifically, for switching systems $ILE_{\%}$ would be equal to 23.24% and 31.44% in summer and winter respectively, whereas it would be 37.55% and 18.05% for dimming systems. This would determine that the difference between energy savings achievable with the two system typologies would be lower than considering a task illuminance equal to 750 lx. In detail, the savings would be 28.4% for the switching system and 37.78% in the dimming one in winter. During summer the use of the switching system would be preferable, guaranteeing energy savings equal to 72.98%, compared to the 61.69% achieved by means of the dimming system.

The integral reset (Figs. 9.e and 10.e) guarantees savings slightly higher than the proportional dimming ones. According to what reported in [6,13] this system typology determines total illuminance levels lower than the task one more frequently than the proportional dimming. However, it must be underlined that $LW_{\%}$ values are really low and slightly higher in summer. This is due to the fact that the daylight photosensor signal at calibration for dimming system is close to the maximum electric light signal (see Tables 2 and 3). So, the slope of the control algorithm is high and the proportional dimming system functioning is similar to that of the integral reset system.

It is interesting to compare the trend of work-plane total illuminances obtained by means of the switching system with that obtained by means of the proportional dimming one. For example, during summer, considering the Jun/03/2017 from about 15:30 on (see Fig. 9.a), the switching system turns on luminaires, consequently there is a brusque illuminance level increase, but the daylight trend is recognizable because electric light is steady. Whereas, with the proportional dimming (see Fig. 9.d), the total illuminance tends towards $\overline{E}_m$ and the daylight trend is not recognizable. On the other hand, when the weather is not steady (see for example Jun/02/2017 morning) and illuminance oscillations are high, the dimming system maintains electric light levels constant (see Fig. 9.d), allowing to appreciate daylight variations, whereas the switching system determines continuous and probably annoying electric light oscillations (see Fig. 9.a). Further studies would be necessary to investigate which lighting condition is preferred by occupants.

3.3. Control systems functioning with west orientation

Results related to the west orientation are reported in Figs. 12, 13 and 14.

Comparing Fig. 14.a and b to Fig. 11.a and b the following observations can be done. Both in summer and in winter switching systems are characterized by high $ILE_{\%}$ values. This determines energy savings to be lower and even null in winter case, since the luminaires must be always on to guarantee that task illuminance is achieved. Multi-levels systems perform slightly worse compared to the south orientation case, especially considering summer, characterized by $LD_{\%}$ values equal to 13.98% and 11.20% for two-levels and three-levels systems respectively. The same occurs for the integral reset system in winter, for which a $LD_{\%}$ value equal to 7.57% is observed. For this orientation, basing the calibration exclusively on the electric light conditions is more inappropriate, since there is a greater difference between the daylight signal registered at the calibration of the proportional dimming system and the electric light signal corresponding to δ_{max} (see Tables 2 and 3). The proportional dimming turns out to be the most suitable strategy guaranteeing significant savings in both seasons (52.65% in summer and 38.85% in winter) and being characterized by negligible light deficit values.

It is evident that in this case, contrarily to the south orientation, differences in energy savings are really relevant comparing switching and proportional dimming systems. This was predictable from the analysis of DA and LR_{dl}/LR demonstrating that with the west orientation, even if the DA was lower than the south one, LR_{dl}/LR was comparable. Considering that daylight contribution is high, but often not sufficient to allow lights to be turned off, the dimming system is more suitable than the switching one.

However, as it was mentioned in the previous paragraph, the required task illuminance plays a fundamental role in defining the control system performance. If the task illuminance was lower, also for west orientation, the switching system would allow to obtain significant energy savings. For example, considering the switching system during summer, with a task illuminance equal to 500 lx, $ILE_{\%}$ decreases to 50.84% determining energy savings to increase to 36.20%. If the task illuminance is 300 lx, the corresponding $ILE_{\%}$ is 30.87% and the savings are equal to 68.88%.

Finally, as it was previously reported, the simulated calibration conditions are different not only depending on the window orientation, but also depending on the season. This is useful to improve system performance and to account for seasonal variation of $\overline{E}_{A,dl}(t)/S_{dl}(t)$ ratio that, as reported in [12], can strongly affect control systems functioning. If, for example, the summer calibration conditions were used for winter as well, considering the south orientation and the switching system, energy savings would be reduced from 20,00% to 11.24%, due to $LW_{\%}$ increasing from 0.77% to 6.13%.

4. Conclusions

This paper presents the results obtained from an analysis aimed at evaluating the relationship between the indoor daylight availability and discusses the suitability of some closed-loop daylight-linked control systems (DLCSs).

To do that, illuminances at the work-plane and at the ceiling (corresponding to the location of a typical photosensor) were measured with a 1-minute time step in an office located in Naples during summer and winter. The office was equipped with two windows: one south-oriented and the other west-oriented. Measurements were repeated shading each window in turn, in order to obtain data referred to two different daylighting conditions. For each orientation, starting from illuminances at the photosensor location, the functioning of five different DLCSs was simulated: a switching, a two-levels stepped switching, a three-levels stepped switching, a proportional dimming and an integral reset.

Specifically, the simulations were performed associating measured and simulated data: daylight data (daylight photosensor signals, daylight work-plane illuminances, daylight components of calibration parameters) were all measured, whereas electric light ones (electric light photosensor signals, electric light work-plane illuminances, electric light components of calibration parameters) were simulated by the use of DIALux software. To calculate DLCSs light output as a function of the time, proper control equations were used. Then, to obtain the related absorbed power, the functional relationship between light output and absorbed power was on-field assessed, by testing a luminaire of the same typology used in DIALux simulations.

Finally, DLCSs performances were analyzed by means of the calculation of Daylight Integration Adequacy (DIA), Percentage Intrinsic Light Excess ($ILE_{\%}$), Percentage Light Waste ($LW_{\%}$), Percentage Light Deficit ($LD_{\%}$) and energy savings.

Results demonstrated that, depending on the daylight availability, the control systems functioning can be very different and determines diverse indoor light conditions.

The following observations can be done:

1. Considering south orientation, the differences between energy savings achievable by means of a switching system and of a

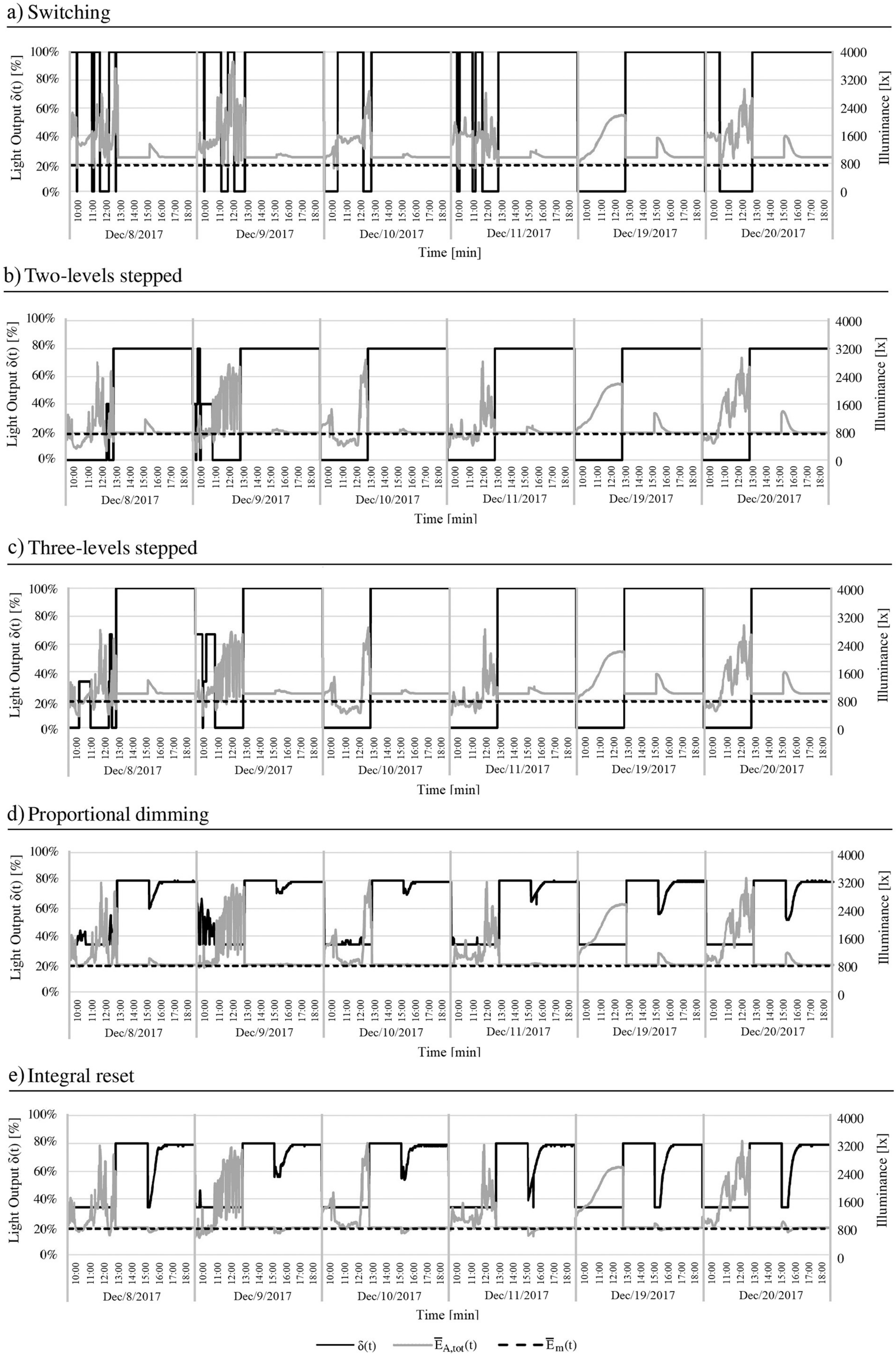

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Fig. 10. Control systems winter functioning – south orientation.

proportional dimming one are not really high (about 12.21% in summer and 16.90% in winter). This is due to the fact that the dimming one is characterized by a very high $ILE_{\%}$ value. The office orientation determines that daylight alone is sufficient to fulfil regulation requirements during most of the day. When this condition occurs, the dimming system, not able to completely switch off luminaires, turns them on at the minimum light output, with a consequent intrinsic excess. So, with work-plane daylight illuminances generally higher than the task illuminance, $ILE_{\%}$ values of dimming and switching systems can be similar for the effect of the minimum light output setting.

2. For west orientation the difference among the selected control systems are more significant. This is due to the fact that daylight illuminances are generally lower than the task illuminance, consequently the possibility to regulate light output instead of simply switching it on and off, determines an effective reduction of $ILE_{\%}$ values and, consequently, of the energy consumptions.
3. For both orientations and seasons, it was observed that proportional dimming guarantees good performances and that $LD_{\%}$ is generally low.
4. Despite results of previous researches, integral reset turned out to be not always inappropriate to control side-lit offices. In south orientation case, it guaranteed performances comparable with those of the proportional dimming.
5. Irrespective of the orientation, the task illuminance is fundamental in determining systems performances: the lower is the task illuminance the lower is the gap between the benefits due to dimming systems installation compared to switching ones.
6. The importance of varying calibration setting seasonally, in order to account for the variation of the ratio of the daylight work-plane illuminance to the photosensor signal, was highlighted by means of the simulations.

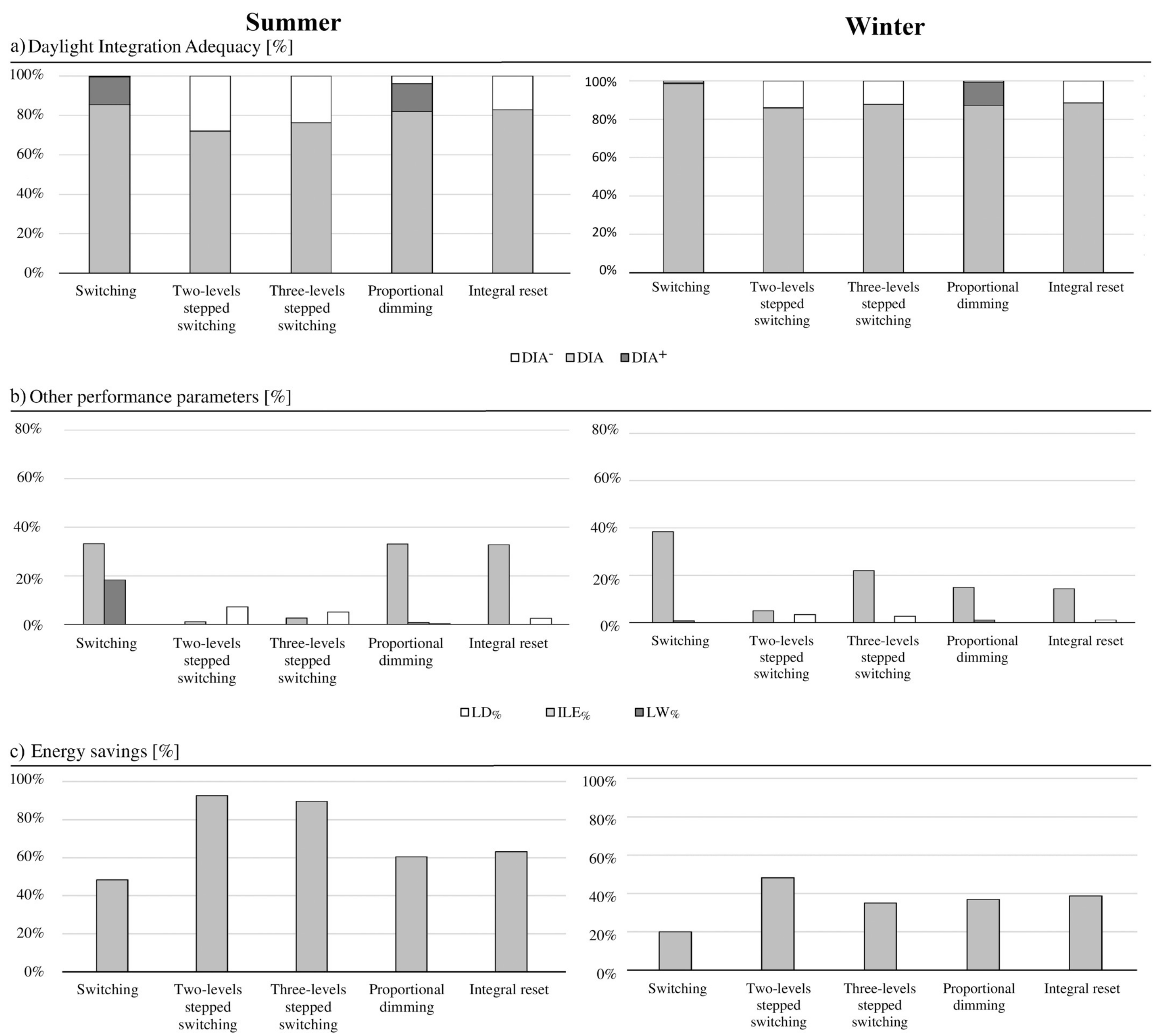

Fig. 11. Control systems performances evaluation – south orientation.

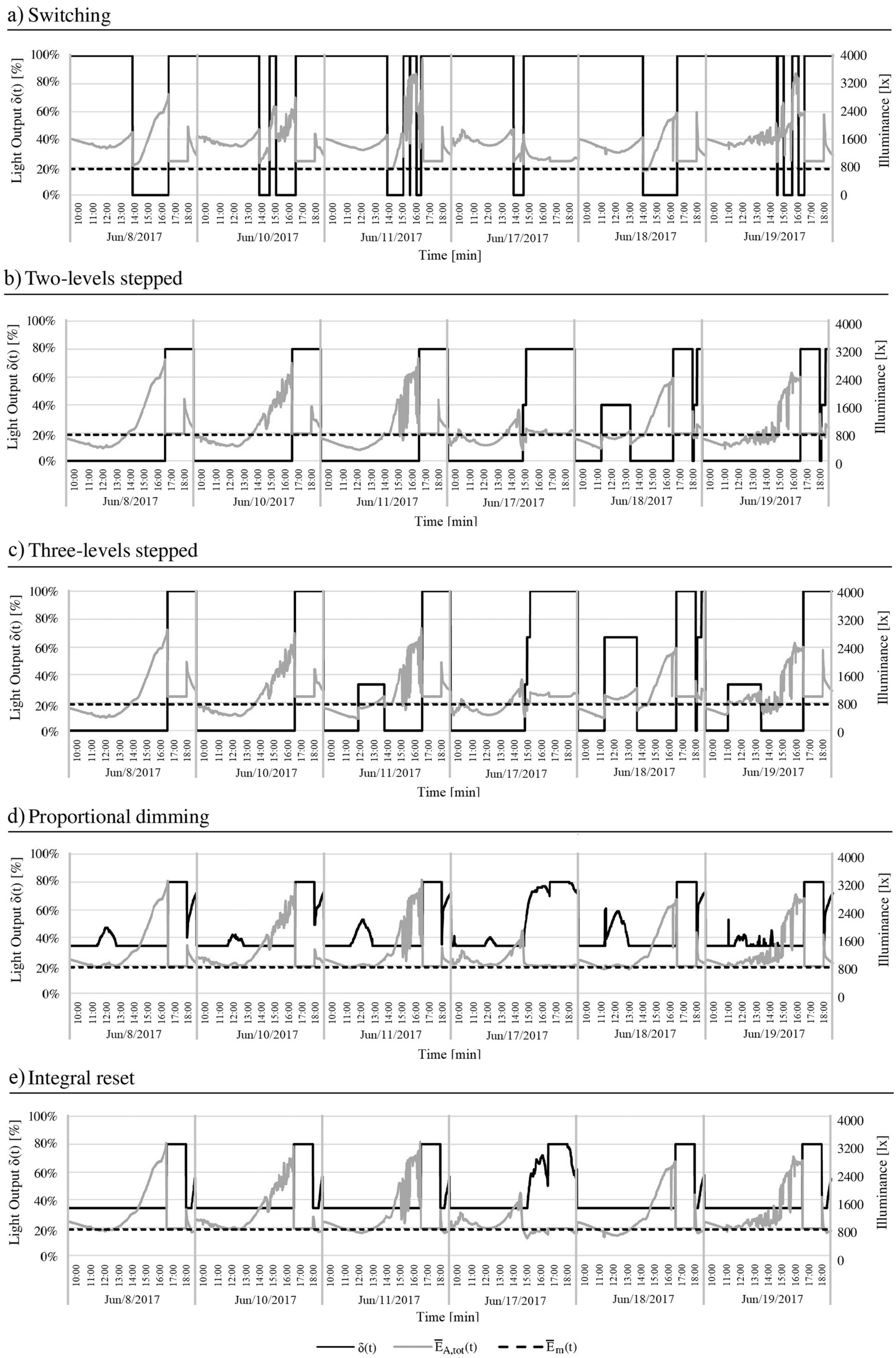

Fig. 12. Control systems summer functioning – west orientation.

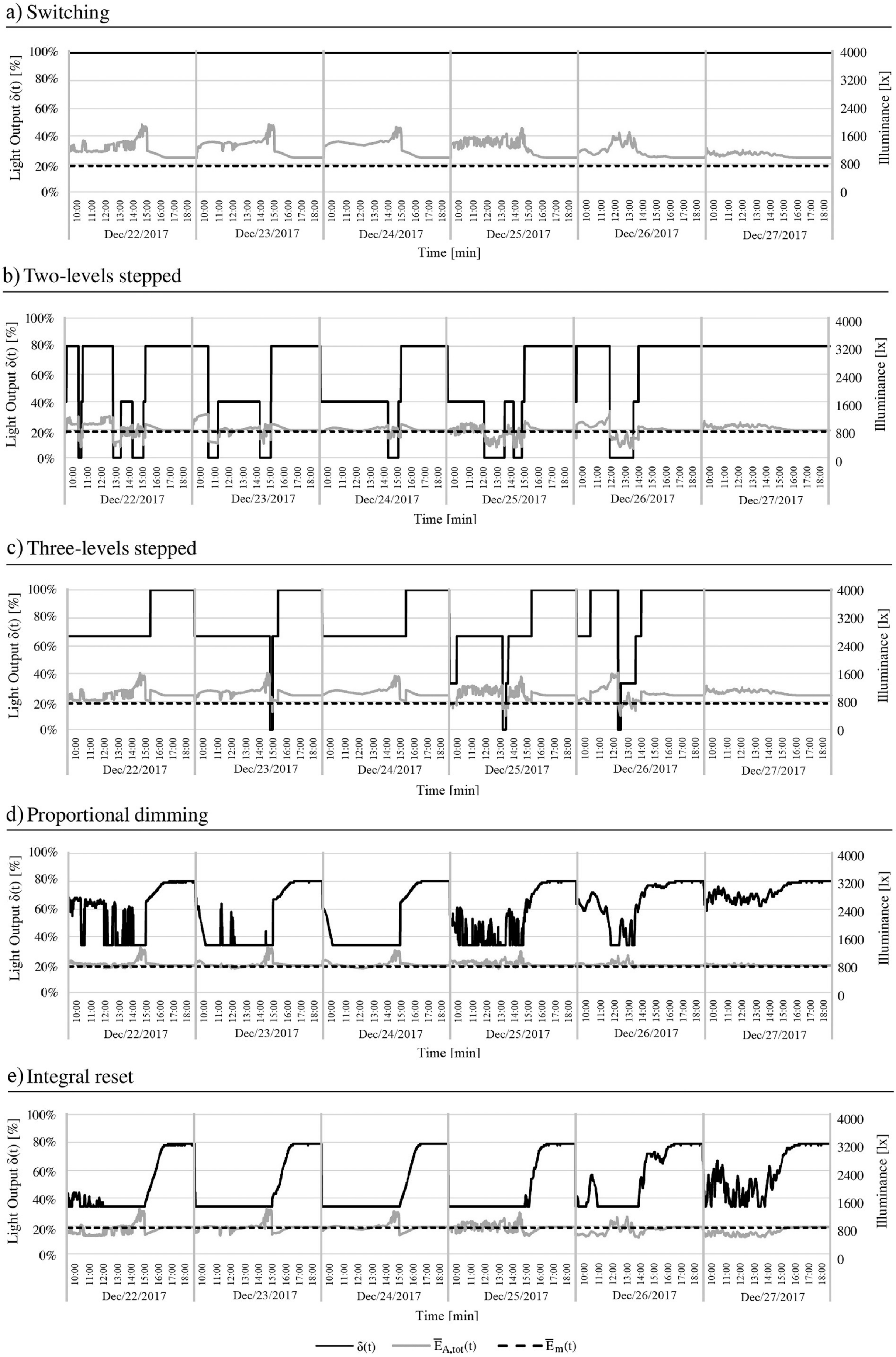

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Fig. 13. Control systems winter functioning – west orientation.

Despite the results are referred to a limited period (one summer and one winter week for orientation) they are useful to underline DLCSs performances dependency on daylight availability and to highlight how the control systems functioning can vary depending on daylight conditions. They suggest that it is not possible to identify control strategies proper for each case, that the evaluation of the best suitable control strategy must be performed case by case and that it must be strictly based on an in-depth analysis of the daylight trends in the analyzed indoor environment. As it was demonstrated, systems can perform really differently even if installed in the same room, by changing calibration conditions or the task illuminance. Consequently, irrespective of the reported observations related to the specific case, that could not be valid for other applications, the most important outcome of the paper is the presented methodology.

In this application, the performance parameters were obtained starting from measured data. However, they can be calculated starting from dynamic daylight simulations results. In this case, their use can be useful during early design phases to identify the most suitable control strategy referred to the specific daylighting characteristics of a space.

The proposed performance parameters can be used also after the installation. The monitoring and the evaluation in progress is fundamental to improve the operating conditions. If the system functioning turns out to be inappropriate, the performance parameters analysis allows to easily identify the most suitable and efficient setting.

It must be underlined that two aspects of the methodology should be improved. It was considered that the photosensor is a typical illuminance-meter with a spectral response matching the V(λ). However, commercially available sensors are generally characterized by spectral and spatial responses different from those of an illuminance-meter and this influences the global performances of control systems. Moreover, the shading systems effect is almost neglected, considering that, when indoor daylight levels potentially create discomfort, the DLCSs is

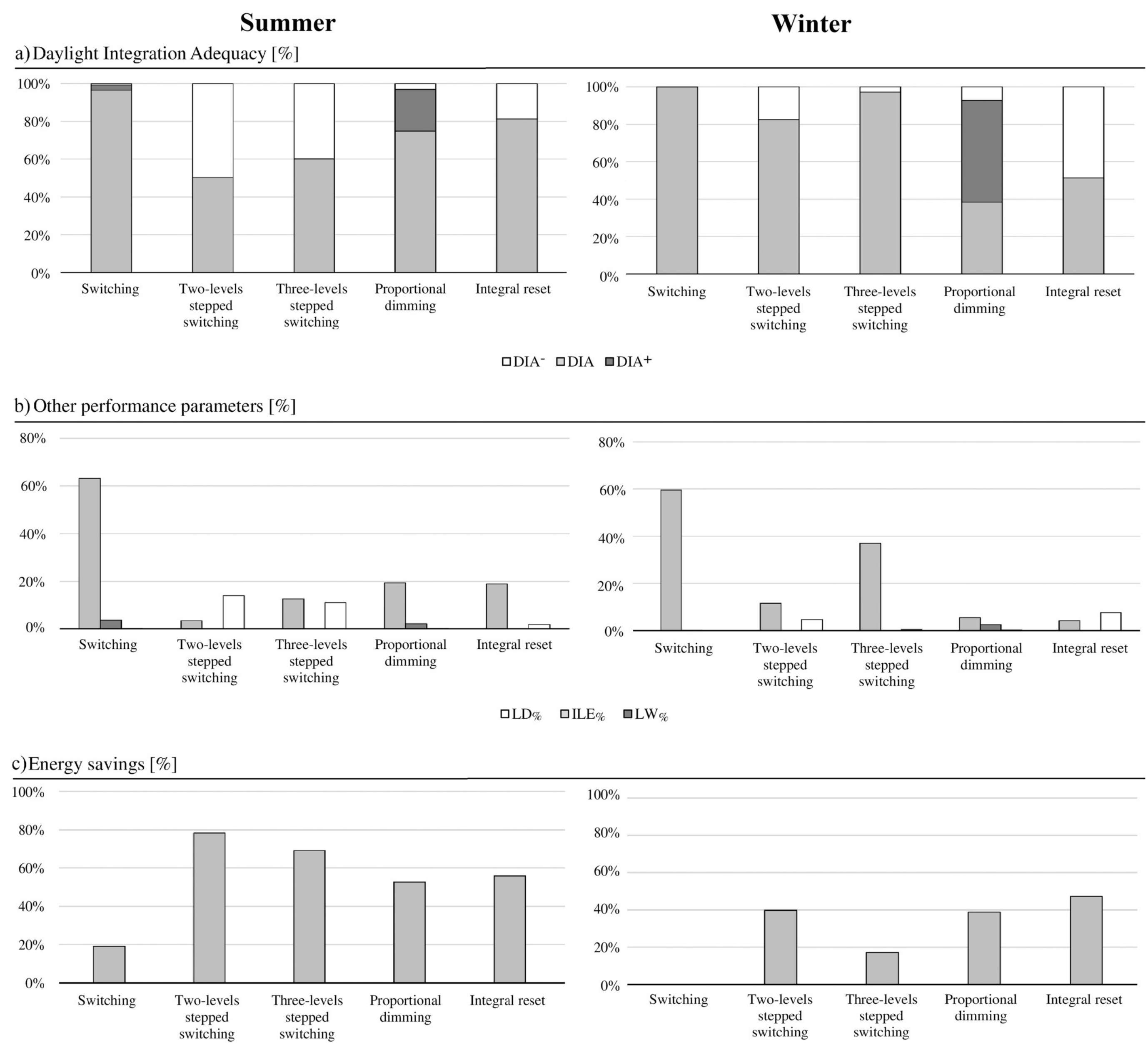

Fig. 14. Control systems performances evaluation – west orientation.

temporarily disabled and luminaires work at full capacity. These aspects would deserve a specific treatise, since their effect on DLCSs performances, both in terms of energy savings and DIA, $ILE_{\%}$, $LW_{\%}$, $LD_{\%}$ could be significant. Moreover, further measurements should be performed in order to verify if the observed DLCSs performances are representative of other periods of the year, as well.

Another important issue underlined by the paper is that selected control systems determine really different indoor light conditions. For example, dimming systems tend to maintain the total work-plane illuminance constant, whereas switching systems, keeping steady electric light levels, allow to better appreciate the outdoor daylight variations. Even though both control typologies guarantee work-plane illuminances prescriptions achievement, the corresponding luminous scenarios can be completely dissimilar. This underlines the necessity to investigate people preferences about these issues. Used parameters help to study DLCSs performances and to improve them during both design and commissioning. Once an appropriate functioning is guaranteed, the following step is to verify occupants' opinions about control strategies, in order to understand their preferences and further improve lighting systems characteristics.

Currently, the typical approach of DLCSs is to maintain constant the work-plane illuminance, and proposed performance parameters are based on this issue, i.e. they help to evaluate DLCSs capability in guaranteeing task illuminance, integrating daylight and electric light. Research agrees that the maintenance of certain illuminance levels at the work-plane is not alone sufficient to achieve comfort conditions. For example, a DLCS could be set in order to obtain specific illuminance values at users' eyes level. This could be useful to consider also non-visual light effects due to light. Furthermore, previous researches underlined that sometimes people prefer illuminance levels not steady but variable during the day. A DLCS could be calibrated in order to adapt illuminance levels to specific variable daily illuminance profiles. Anyway, even if the reference parameter the control is based on was not the illuminance, the proposed methodology, using the concept of ideal and reference systems, could be easily modified to adapt itself to different control criteria. It would be sufficient to consider the tendency of the control system to fall down or overcome the thresholds limits of the chosen control parameter, in the same way, in this case, the tendency to fall down or overcome the task illuminance was considered.

Appendix A

In this section the entire procedure to evaluate $LD_{\%}$, $ILE_{\%}$ and $LW_{\%}$ is reported. The symbols, that are not specifically described here, are all reported in the Nomenclature.

$$\text{Percentage Light Deficit} = LD_{\%} = \frac{LD}{LR} \bullet 100\ [\%] \tag{1}$$

$$\text{Percentage Intrinsic Light Excess} = ILE_{\%} = \frac{ILE}{LR} \bullet 100\ [\%] \tag{2}$$

$$\text{Percentage Light Waste} = LW_{\%} = \frac{LW}{LR} \bullet 100\ [\%] \tag{3}$$

where:

$$LR = \text{Light Requirement} = \overline{E}_m \cdot \text{system operating hours}\ [lx \cdot h] \tag{4}$$

$$LD = \text{Light Deficit} = \int_T \Delta E^-(t)dt\ [lx \cdot h] \tag{5}$$

with:

$$\Delta E^-(t) = \begin{cases} 0 \ \text{ if } \ \overline{E}_{A,el}(t) \geq \overline{E}_{A,el,id}(t) \\ -\Delta E(t) \ \text{ if } \ \overline{E}_{A,el}(t) < \overline{E}_{A,el,id}(t) \end{cases} [lx] \tag{6}$$

$$\Delta E(t) = \overline{E}_{A,el}(t) - \overline{E}_{A,el,id}(t)\ [lx] \tag{7}$$

$$\overline{E}_{A,el.id}(t) = \overline{E}_m - \overline{E}^*{}_{A,dl}(t)\ [lx] \tag{8}$$

$$\overline{E}^*{}_{A,dl}(t) = \begin{cases} \overline{E}_m(t) \ \text{ if } \ \overline{E}_{A,dl}(t) \geq \overline{E}_m \\ \overline{E}_{A,dl}(t) \ \text{ if } \ \overline{E}_{A,dl}(t) < \overline{E}_m \end{cases} [lx] \tag{9}$$

$$ILE = \text{Intrinsic Light Excess} = \int_T \Delta E^+{}_{intr}(t)dt\ [lx \cdot h] \tag{10}$$

with:

$$\Delta E^+_{intr}(t) = \begin{cases} 0 \text{ if } \overline{E}_{A,el}(t) < \overline{E}_{A,el,id}(t) \\ \Delta E^+_{ref}(t) \ \text{ if } \ \overline{E}_{A,el}(t) \geq \overline{E}_{A,el,id}(t) \ \text{ and } \ \overline{E}_{A,el,ref}(t) \leq \overline{E}_{A,el}(t) \\ \Delta E^+(t) \ \text{ if } \ \overline{E}_{A,el}(t) \geq \overline{E}_{A,el,id}(t) \ \text{ and } \ \overline{E}_{A,el,ref}(t) > \overline{E}_{A,el}(t) \end{cases} [lx] \tag{11}$$

$$\Delta E^+_{ref}(t) = \overline{E}_{A,el.ref}(t) - \overline{E}_{A,el,id}(t)\ [lx] \tag{12}$$

$$\Delta E^+(t) = \begin{cases} 0 \ \text{ if } \ \overline{E}_{A,el}(t) \leq \overline{E}_{A,el,id}(t) \\ \Delta E(t) \ \text{ if } \ \overline{E}_{A,el}(t) > \overline{E}_{A,el,id}(t) \end{cases} [lx] \tag{13}$$

$$LW = \text{Light Waste} = \int_T \Delta E^+{}_{waste}(t)dt\ [lx \cdot h] \tag{14}$$

with:

$$\Delta E^{+}_{waste}(t) = \begin{cases} 0 \text{ if } \overline{E}_{A,el}(t) < \overline{E}_{A,el,id}(t) \\ 0 \text{ if } \overline{E}_{A,el}(t) \geq \overline{E}_{A,el,id}(t) \text{ and } \overline{E}_{A,el,ref}(t) \geq \overline{E}_{A,el}(t) \\ \Delta E^{+}(t) - \Delta E^{+}_{intr}(t) \quad \text{if} \quad \overline{E}_{A,el}(t) \geq \overline{E}_{A,el,id}(t) \quad \text{and} \quad \overline{E}_{A,el,ref}(t) < \overline{E}_{A,el}(t) \end{cases} \quad [\text{lx}] \tag{15}$$

$\Delta E_{ref}{}^{+}(t)$ calculation is based on the simulation of a reference system. The reference system is a system for which it is verified that all the produced excess is intrinsic. Consequently, to calculate $\delta_{ref}(t)$, it is necessary to neglect excess due to the deviations of the $\overline{E}_{A,dl}(t)/S_{dl}(t)$ ratio from the $\overline{E}_{A,dl,tc}/S_{dl,\ tc}$. So, it must be assumed that at each time t:

$$\frac{\overline{E}_{A,dl}(t)}{S_{dl}(t)} = \frac{\overline{E}_{A,dl,tc}}{S_{dl,tc}} \tag{16}$$

and consequently:

$$S_{dl}(t) = \overline{E}_{A,dl}(t) \cdot \frac{S_{dl,tc}}{\overline{E}_{A,dl,tc}} \tag{17}$$

Based on this assumption, the illuminance determined by the reference system can be calculated as:

$$\overline{E}_{A,el.ref}(t) = \delta_{ref}(t) \cdot \overline{E}_{A,el,100\%\,[lx]} \tag{18}$$

where $\delta_{ref}(t)$ is the light output of the reference system. It is evaluated according to the equations reported in Table 1, but substituting $S_{dl}(t)$, i.e. the actual daylight component of the photosensor signal, with the value calculated according to Eq. (17).

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