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Evaluating performance of daylight-linked building controls during preliminary design

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ABSTRACT

Thanks to the spread of new light sources and of smart dynamic control systems, automation sector has begun to play a fundamental role in lighting design. In this regard, daylight-linked control systems (DLCSs) represent a particularly interesting research field, since they offer great opportunities both in obtaining energy savings and in improving visual comfort conditions. However, their use is not so spread, because of the difficulties in predicting their functioning during the design process and in evaluating their effective energetic and economic advantages: available technical solutions are so many that design choices can be very hard for specialists. To overcome these obstacles, a precise assessment methodology is needed. Given these premises, the goal of the paper is to show the effectiveness of new performance parameters (Daylight Integration Adequacy, Percentage Intrinsic Light Excess, Percentage Light Waste and Percentage Light Deficit) in order to evaluate DLCs performance and to underline which factors mostly affect their functioning.

1. Introduction

Over the last years, technological innovation has made great strides in Building Automation Systems (BASs) field. According to the observed increase trend, "*global commercial building automation product and services revenue is expected to grow from $67.1 billion in 2016 to $102.0 billion in 2025*" [1]. Different technology segments have been involved in this automation process: heating, ventilation and air conditioning (HVAC), fire and life safety, security and access controls. Obviously, lighting is involved as well: Thanks to the spread of new light sources and of related electronic management systems, sophisticate lighting controls use is increasing so that the revenue from installation of lighting control systems, considering all building types globally, is supposed to grow at 14.3% compound annual growth rate between 2017 and 2026 [2].

The most interesting implication of this automation process is the tendency to link together different BASs in integrated control networks (Building Management Systems - BMSs), defining, in this way, an "artificial brain" able to completely manage all building services. Despite being an amazing challenge, connected design problems are clearly a lot. Each one of the systems belonging to the network, has specific functioning issues and, in order to guarantee that the entire system operates correctly, a cooperation between different specialists is fundamental: Information technology experts, engineers, architects have to work together to optimize BMSs performances, assuring occupants comfort conditions. However, sometimes this fruitful debate does not occur, and different design aspects are consequently not well balanced.

In this respect, lighting control systems design is a valid example: lighting engineering is rapidly evolving but aspects connected to light quality are often neglected and the old quantitative design approach is even now common. So, studies aiming to deepen lighting control systems design methodologies are fundamental.

Among lighting control systems, daylight-linked ones (DLCSs) represent an interesting research branch. Over the last decades, studied about these systems have been increased. The awareness of the benefits linked to daylight penetration in indoor environments, in terms both of users' comfort conditions improvement [3–6] and of energy savings optimization [7–12], has encouraged researchers to focus their attention on design strategies able to maximize daylight use. This implies, on one hand, the optimization of the building envelope (finding a balance between glazed components, opaque surfaces and shading devices) and, on the other hand, the spread of new strategies to integrate electric light and daylight.

DLCs are crucial in this sense. They are control systems based on the use of photosensors detecting incident light and controllers processing photosensors signals to regulate luminaires flux emission. Despite potentialities of these systems, their use is not so common as it was expected [13], because dynamics of their functioning are not still completely understood [14,15].

A lot of factors influence DLCSs performances [16,17]. On one hand,

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Nomenclature

A	reference area located at the workplane height and corresponding to the activity area or to the area lit by a given control group, [m^2]
T	defined time period, [h]
$\overline{E}_m$	average maintained illuminance at the area A according to standard prescriptions, [lx]
$\overline{E}_{A,dl}(t)$	average daylight illuminance referred 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]
$LR_{el,id}$	ideal electric light requirement, [lx·h]
$\overline{E}_{A,el}(t)$	average electric light illuminance provided by the actual lighting system to the area A, [lx]
$\overline{E}_{el,ref}(t)$	electric light illuminance of a reference system. The reference system is a system operating such that all the produced excess is intrinsic, [lx]
$\Delta E(t)$	$\Delta E(t) = \overline{E}_{A,el}(t) - \overline{E}_{A,el,id}(t)$, [lx]
DIA	Daylight Integration Adequacy, [%]
LD	Light Deficit, [lx·h]
ILE	Intrinsic Light Excess, [lx·h]
LW	Light Waste, [lx·h]
$LD_{\%}$	Percentage Light Deficit, [%]
$ILE_{\%}$	Percentage Intrinsic Light Excess, [%]
$LW_{\%}$	Percentage Light Waste, [%]
$\delta(t)$	luminaires light output set by the control system, [%]
$\delta_{ref}(t)$	luminaires light output of the reference system, [%]
$S_{dl}(t)$	daylight component of photosensor signal, [lx_{pfv}][1]
$S_{el}(t)$	electric light component of photosensor signal, [lx_{pfv}]
$S_{tot}(t)$	photosensor signal, sum of $S_{dl}(t)$ and $S_{el}(t)$, [lx_{pfv}]
δ_{max}	maximum luminaires light output, [%]
$S_{el,\delta max}$	electric light component of photosensor signal when luminaires are turned on at δ_{max}, [lx_{pfv}]
$\overline{E}_{A,el,\delta max}$	average electric light illuminance at the area A when luminaires are turned on at δ_{max}, [lx]
$S_{el,\delta=1}$	electric light component of photosensor signal when $\delta = 100\%$, [lx_{pfv}]
$\overline{E}_{A,el,\delta=1}$	average electric light illuminance at the area A when $\delta = 100\%$, [lx]
$S_{dl,tc}$	daylight component of photosensor signal during calibration, [lx_{pfv}]
$\overline{E}_{A,dl,tc}$	average daylight illuminance at the area A during calibration, [lx]
δ_{tc}	dimming level necessary to integrate $\overline{E}_{A,dl,tc}$, [%]
$\overline{E}_{A,el,tc}$	average electric light illuminance at the area A when luminaires are turned on at δ_{tc}, [lx]
S_{on}	photosensor signal corresponding to switch-on action in switching systems, [lx_{pfv}]
S_{off}	photosensor signal corresponding to switch-off action in switching systems, [lx_{pfv}]
δ_{min}	minimum light output in dimming systems, [%]
S_{lim}	signal corresponding to δ_{min} according to the slope of the algorithm curve in dimming systems, [lx_{pfv}]
$\delta_{1/3max}$	light output equal to $\delta_{max}/3$, [%]
$\delta_{2/3max}$	light output equal to $2/3 \cdot \delta_{max}$, [%]
S_{up}	photosensor signal corresponding to switch-on action in stepped systems, [lx_{pfv}]
S_{down}	photosensor signal corresponding to switch-off action in stepped systems, [lx_{pfv}]
$S_{up\text{-}1/3}$	photosensor signal corresponding to switch-on action at $\delta_{max}/3$ light output in open-loop stepped systems, [lx_{pfv}]
$S_{up\text{-}2/3}$	photosensor signal corresponding to switch-on action at $2/3 \cdot \delta_{max}$ light output in open-loop stepped systems, [lx_{pfv}]

the extreme variability of daylight makes difficult for automated systems to flawlessly complement daylight. On the other hand, DLCSs behavior strongly varies depending on their components technical characteristics, first and foremost photosensors. More insights on this topic can be found in previous works. For instance, Doulos et al. [18] evaluated the impact on energy savings of photosensors spectral response; some studies focused on their spatial response [19,20] or on their location [21]; others highlighted issues connected to the commissioning phase [20,22]. Moreover, controls functioning can be affected by lighting systems characteristics, such as the ballast typology, as it was demonstrated in [21,23], or by the luminaires zoning as it was reported in [24]. This makes the evaluation of these systems performance really difficult, especially during first design stages, and often the prediction of the achievable energy savings is a really difficult task. Moreover, the achieved energy saving is not sufficient to evaluate the proper functioning of the system. For example, two identical control systems, installed in two rooms characterized by the same optical and geometric characteristics, but differently oriented, can provide different savings. This does not necessarily represent a warning of improper functioning of one of the two systems, but it is likely to depend on different daylight availability conditions. Moreover, high energy savings could be determined by an improper functioning of the system that does not assure the fulfilment of light requirements and determines insufficient illuminance levels at the workplane.

So, a DLCS should be evaluated not only according to the provided savings but also based on its capability to maintain proper indoor lighting conditions, that is strictly correlated to its capability to complement daylight.

To accurately assess DLCSs, it is necessary to define a standardized design methodology and unambiguous and shared parameters useful to describe controls way to operate. These new parameters should relate specifically to the characteristics of the control system and not generically to the indoor daylight availability. For example, parameters like the Useful Daylight Illuminance (UDI) [25] or the Daylight Autonomy [26] are fundamental to evaluate the indoor daylight availability characteristics of a specific space, but alone, are not able to inform about the convenience to install a DLC. Indeed, DA represents the percentage of the occupied hours during a year when the task illuminance is achieved by daylight alone; UDI represents the percentage of the occupied hours of a year when daylight illuminances are comprised in a range defined useful (100–2000 lx), i.e. corresponding to light levels not too dark nor too bright to determine discomfort. Obviously, they are useful during control systems design, since the higher daylight availability is, the more useful the DLC installation is supposed to be, but in order to obtain more accurate information about DLC functioning, more specific parameters are needed.

In this respect, Doulos et al. [27] suggested two additional parameters worth to be considered: 1) the correlation between workplane illuminance and photosensor signal; 2) the lighting adequacy which is defined as “*the percentage for occupied time with total illuminance*

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[1] A photosensor is a photosensitive device detecting incident light and producing an electrical signal proportional to the received luminous stimulus. In this paper, photosensor signal is evaluated by means of dynamic daylight simulations software, which calculates illuminance at the photosensor and not the corresponding electrical signal. Consequently, the corresponding unit of measurement is lux. Moreover, photosensors commercially available, generally have a spatial response different from 2πsr, but software evaluates illuminance and, consequently, detects light coming from the entire hemisphere. So, to account for photosensors spatial response and reduce light at the calculation points, proper black shields were modeled around the points. To highlight that light detected by the photosensor comes from a solid angle corresponding to the spatial response, photosensor signal unit of measurement, i.e. lx, is indicated with the pfv subscript [lx_{pfv}], meaning photosensor field of view.