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Lighting control systems: factors affecting energy savings' evaluation

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Abstract

The use of automated lighting control systems allows to reduce lighting costs and to achieve significant energy savings. The energy performances of controls are affected by many factors, the impact of which is very difficult to account for during the design process. The goal of this paper is to describe the factors that influence the control systems' energy performances, to analyze how the currently available calculation tools take them into account and finally to propose a simple method to adjust results obtained from the simulation software.

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Keywords: daylight, lighting control systems, energy savings

1. Introduction

Energy-related operating costs of lighting systems can represent a large slice of buildings' total energy costs and they vary depending on a building's function. A recent scientific and policy report, published by the Joint Research Centre, demonstrated that in the EU 27 lighting has a 10% impact on total energy costs for residential buildings and a 21% impact for the tertiary sector [1]. The use of automatic control systems can significantly reduce energy consumptions thanks to the regulation of luminaires' emitted luminous flux and to the reduction of operating hours depending on users' presence-absence or indoor daylight availability.

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These systems are generally divided in three categories: timers, occupancy-based controls and daylight-linked controls [2, 3]. Timers automatically turn on and off lights depending on time schedule. Occupancy-based controls regulate lights thanks to the use of occupancy sensors. Finally daylight-linked controls switch on and off or dim electric light as a function of the indoor daylight provision detected by photosensors [2].

According to previous studies referred to offices applications, savings due to control systems' installation can range from 9% to 30% considering dimming daylight-linked controls and from 3% to 38% considering occupancy-based ones [3]. The great variation in the reported data are due to many factors: daylight availability, occupancy patterns, lighting systems' characteristics, controls' settings. Some of these affecting factors can influence the functioning of all control systems' types (e.g. the lighting systems characteristics), whereas others strictly depend on the chosen control technology (e.g. photosensors' spectral and spatial response in daylight-linked systems). During the design process it is very difficult to account for all these parameters and to predict the achievable energy savings. Consequently it is hard to evaluate the subsequent payback period and the economic advantages of a specific design solution [4]. One of the method to calculate energy consumptions and then the corresponding savings related to different control strategies is the use of climate-based daylight modelling (CBDM), indeed calculation tools like Daysim, DIVA or SPOT [5, 6, 7] allow to simulate the annual functioning of basic control systems. However previous studies demonstrated that the use of different software may determine discordant energy savings results [4].

Given these premises, the goal of this paper is on one hand to analyze the affecting factors that influence the energy performances of different control systems and on the other hand to analyze which of them are considered by simulation software and which not. Finally, considering that tools' approximations influence the evaluation of calculated energy savings, the paper proposes to adjust software results through the use of correcting factors defined on the basis of the mentioned affecting parameters.

Nomenclature

S_E	Expected savings due to the use of a control system
S_S	Savings simulated by means of a calculation software
$F_1, F_2 ... F_n$	Correcting factors that consider the approximations due to the software's calculation model

2. Control systems' affecting factors

There are a lot of factors that influence a control system functioning and, as already mentioned in the introduction, for each category of controls there are different parameters to account for, in order to evaluate the lighting systems' energy performances. The analysis and the classification of these factors is a complex task. Table 1 groups the affecting factors in three different categories: factors depending on the control system's typology, factors depending on the lighting system's characteristics and factors depending on the indoor daylight provision. Furthermore it indicates which of the three main types of automatic systems (timers, occupancy-based, daylight- linked) is affected by the factors listed in the second column. The classification in the table was proposed because it allows to better compare affecting factors with software's calculation parameters analyzed in the paragraph 3.

Table 1. Control systems' affecting factors.

Affecting factors' category	Affecting factors	Timers	Occupancy-based controls	Daylight-linked controls
Factors depending on the control system's typology	Control strategy	x	x	x
	Occupancy pattern	x	x	-
	Sensor's typology	-	x	x
	Sensor's location	-	x	x
	Sensor's spatial response	-	x	x
	Sensor's spectral response and sensitivity	-	x	x

	Sensor's time-delay	-	x	x
	Control algorithm	-	-	x
	Calibration process	-	-	x
Factors depending on the lighting system's characteristics	System efficacy	x	x	x
	Variation in absorbed power depending on systems' setting (total installed power, stand-by power, power corresponding to different luminous scenes, etc)	x	x	x
	Relationship between power consumption and related light output	-	-	x
	Relationship between sensor signal and related light output	-	-	x
	Location and zoning of luminaires	-	x	x
Factors depending on the indoor daylight availability	Outdoor daylight availability (site's latitude and longitude, day of month and time of day, sky cover)	-	-	x
	External obstructions	-	-	x
	Room's typology (geometric and optical characteristics, orientation)	-	-	x
	Glazing and shading typology	-	-	x

The first category reported in Table 1 includes factors depending on the control system's typology, i.e. those factors that generally are not common to all the control types. The choice of the control strategy consists in establishing which are the information detected by the system and the corresponding actions to actuate. Control strategies are classified in on/off switching, dimming and scene control [2]. Depending on the control type, actions are actuated according to a scheduling or to a sensor signal. A different absorbed power corresponds to each different system's action and then energy performances are strictly linked to the adopted control strategy. The occupancy pattern influences the performances of timers and occupancy-based controls. It has a great impact on the energy performances particularly for those spaces only occasionally occupied, for which the use of occupancy-based control allows to switch off lights for most of the day. Occupancy-based and daylight-linked controls are particularly influenced by the sensors characteristics. For daylight-linked controls, considering that indoor daylight levels are generally characterized by significant gradients, the efficacy of the system depends on the ratio between the light detected by the sensor and the illuminance on the task area [2]. For this reason it is fundamental to calibrate the system in order to make the signal of the photosensor as much representative as possible of the workplane illuminance. The amount of light detected by a sensor depends on several characteristics: the sensor's typology (photosensors are divided in open-loop or closed-loop sensors, i.e. sensors that detect only daylight or both daylight and electric light), the sensor's location (photosensors can be mounted outdoor, indoor, at ceiling, integrated in the luminaires), the spatial response (i.e. the field of view of the photosensor) and the spectral response. Daylight-linked systems' performances are influenced also by the type of control algorithm and by the calibration procedure, which consists in registering the photosensor signal corresponding to a specific daylight condition occurring at calibration time. Consequently the calibration procedure has a fundamental role in defining the functioning of the system and then its performances. As regards occupancy-based controls, sensors' typologies are several: Passive Infrared (PIR), Ultrasonic, Acoustic, Microwave. Also new technologies like Radio Frequency Identification (RFID) and digital imaging are spreading [3]. Each different technology presents pros and cons, for example PIR sensors are characterized by "False-off" errors, i.e. they switch lights off despite users' presence. On the contrary, Ultrasonic sensors are prone to "False-on" errors because they are very sensitive and they can be triggered by outside leaves movements or also by air turbulence generated by the air conditioner. These errors affect the performances of the system, then the sensor must be correctly positioned in the space considering its typology, its angle of view and its sensitivity in detecting motion. In occupancy-based controls the control algorithm is similar for all sensors' technologies, but similarly to daylight-linked systems it is fundamental to correctly set a time-delay, i.e. "the period of time over which the sensor must continuously register a shutoff reading before [an] action may occur" [8]. A slow time-delay avoids annoying and continuous fluctuations in system's setting but reduces energy savings. For example Richman et al. [9] demonstrated that by using ultrasonic sensors, changing the time-delay from 5 to 20 minutes, energy savings can vary from 50% to 3% in private offices and from 86% to 73% in restrooms. The increase of energy savings due to the reduction of time-delay is higher for spaces characterized by more regular occupancy patterns [3]. This means that the efficacy of the system is affected by the interrelation between these two factors.

The second category reported in Table 1 includes factors concerning lighting systems' characteristics. The installation of an automatic control determines the necessity to use compatible equipments, e.g. controls based on dimming strategy need suitable ballasts and the choice of a ballast typology or another can influence the control operation [10]. This group of factors affects all categories of controls, since the achievable energy savings can obviously be incremented by choosing highly efficient luminaires and by a proper design. Furthermore considering that the automatic systems are dynamic, it is necessary to know the variations of the equipment's technical characteristics as a function of the operating conditions. This means that the designer has to focus not only on the total installed power, but also onto the variations of the absorbed power due to the application of a control strategy. For example, in the case of daylight-linked control, the NLPIP Specifier Report on Photosensors [8] suggests to use switching systems for those applications for which "annual average daylight illuminance is more than twice the minimum required illuminance produced by the electric lights" [8]. In this case electric lights are turned off for most of the year and switching systems require very little stand-by power compared with dimming ones. Moreover, when the control can set different luminous scenes, it is fundamental to correctly calibrate the absorbed power referred to each scene. Furthermore in daylight responsive dimming systems, where the emitted luminous flux is continuously regulated by dimming ballasts, the energy performances are also influenced by the correlation between the power consumption and the corresponding light output and by the relationship between the sensor signal and the corresponding light output. Choi et al. [10] monitored the performances of a fluorescent lighting system controlled by a photosensor and equipped with different ballasts. They demonstrated that, even though the general relationship between the power and the corresponding light output was almost linear, considering values of consumed power between 30% and 90%, "the relative values of consumed power and corresponding light output did not match exactly" [10]. Moreover they concluded that the use of different ballasts determines different light output even though the sensor generates the same control voltage signal. Also the location and zoning of the luminaires have an impact on the energy performances. For example, in a daylight-linked control, the luminaires must be grouped considering the daylight gradients in the space. In these cases the system can control only a group of luminaires (generally those next to the windows) or all the fixtures in a room. Moreover it is possible to control different luminaires rows depending on the distance from the window. Obviously, different energy costs correspond to each zoning criterion. Similar observations can be applied to the occupancy-based control. For example in open-space offices, lighting fixtures are usually located in order to guarantee on one hand a general uniform and diffuse lighting and on the other hand a direct lighting on each workplace. In this case controllers can regulate the functioning of the direct lights whereas the general lights can be always switched on in order to avoid excessive and annoying light levels' gradients. Then, also in this case, it is fundamental to correctly locate and zone different luminaires.

Finally, the last mentioned category reported in Table 1 includes factors due to the evaluation of indoor daylight provision. The amount of daylight entering a space varies based on many conditions: site's latitude and altitude, day of month and time of day, sky cover, building's orientation, external obstructions, room's geometric and optical characteristics, windows' and glazings' typology, shadings.

3. Affecting factors modeling

As already mentioned in the introduction, nowadays the most widespread calculation method used to evaluate energy consumptions of different control systems is the use of CBDM based on software as Daysim or DIVA [5, 6]. These software do not allow to account for all the affecting factors described in previous paragraph and, depending on the complexity of the specific control system, they approximate system's functioning with more or less precision. As regards affecting factors depending on the control system's characteristics, available software allow to simulate both switching and dimming strategies. The occupancy patterns are described through a scheduling that must be defined by the designer for each simulation. This time-sheet does not account for users' random absence that can have a great impact on the performances of occupancy-based systems. The greatest calculation simplifications are those related to sensors characteristics. It is not possible to choose between different sensors' typologies both for occupancy-based and the daylight linked systems. In more detail, as for daylight-linked controls, software allow to select a point belonging to workplane calculation grids. Starting from daylight illuminances registered at this point, they determine the corresponding electric lights requirements and consumptions. Spectral and spatial responses are neglected, time-delay is not considered and the implications due to the calibration procedure and the variations of the ratio between photosensor signal and task illuminance are ignored. Ehrlich et al. [11] proposed a method to simulate the angular sensitivity of the photosensor based on the generation of two 180° and 360° fisheye images. However this method cannot be applied by using a dynamic approach because this complexity would determine very long calculation time. Rogers presented a simulation tool called SPOT (Sensor Placement + Optimization Tool) [12]. This Excel Macro helps the designer to choose photosensor's typology and to establish its correct location and contains a database of real sensors available on the market, classified by the NLPIP Specifier Report on Photosensors [8]. Despite its great attention to photosensors' characteristics, the modeling of the environment's geometric properties and of the daylight characteristics are simplified.

As concerns factors depending on the characteristics of the lighting system, software base the analysis of the variation in absorbed power on three different parameters: Lighting Power, Standby Power and Ballast Loss Factor. Once these parameters are set, as for the dimming systems, the software assumes that there is a linearity between light output and absorbed power but as already mentioned, this is not always true [10]. As for luminaires zoning, some software such as DIVA allow to set different control groups [6].

Considering factors depending on the indoor daylight availability, software's validation studies demonstrated that differences between simulated results and measured values are acceptable [13, 14]. These approximations depends on a lot of parameters: the chosen weather data file, the adopted sky model, the algorithm that defines light interaction phenomena, the way to model materials' optical characteristics [15, 16, 17, 18, 19]. Despite these approximations are considered negligible for daylight simulation purposes, they add uncertainty to the calculation of the control systems' energy performances.

Given these premises it is clear that not all the software take into account the same affecting factors. This determines calculation uncertainties and also discrepancies in results obtained with different software. Doulos et al. [4] compared energy savings calculated with SPOT, RELUX and Daysim, referred to an office equipped with a dimming daylight-linked system; they found that "SPOT values are 15% on the average more than Daysim ones while RELUX underestimates lighting energy considerably especially during winter months" [4].

Obviously calculation imprecision has a greater weight considering integrated control strategies e.g. a daylight-linked control coupled with an occupancy-based one. Furthermore software also simulate the impact of shading devices on indoor daylight availability and the methods used to simulate the shading devices' control can also determine calculation uncertainties. Another important issue to consider is that completely automated controls do not exist and that users' behavior has always a great impact on energy performances of controls. Indeed they can vary the settings or disable automated control according to their preferences and comfort conditions. Even the most accurate behavioral model available does not allow to accurately predict users' actions [20].

4. Evaluation of energy savings

Given the previous paragraphs' premises, in order to obtain a more realistic evaluation of the energy savings, it would be necessary to evaluate how all the considered factors affect the calculation and which weight each of them has. Once defined these weights, the Expected Savings (S_E) due to the use of a control system would be calculated as:

$$S_p = S_s \cdot F_1 \cdot F_2 \cdot ... \cdot F_n \tag{1}$$

Where S_S represents savings calculated thanks to the use of a software and F_1, F_2 ... F_n are correcting factors that consider the approximations due to the software's calculation model.

This approach could allow to consider the factors that affect a system control performances but that software neglect. For example one of them could take into account the impact on the energy savings due to the sensors' characteristics, others could consider the effect on the system's functioning of the calibration procedures and the control algorithms. Also the impact of human behavior should be considered. The definition of these parameters is a challenging goal and it could be achieved only thanks to a specific research project. These studies should list all the correcting factors and define different ranges of applications depending on the specific strategy controls.

5. Conclusions

The paper underlines the difficulties connected with the design of a lighting control system and with the evaluation of its energy performances, due to the amount of the affecting factors. Furthermore it describes the main factors which are not taken into account by the calculation software. It makes clear that further studies are necessary to deepen the analysis of the problems listed in this brief review. The efforts of future researches would be focused on one hand to implement calculation software in order to make results more similar to systems' real performances and on the other hand to propose new methods for the energy savings evaluation in order to account for the limitations of currently available software. For example the paper proposes a simple method to adjust results obtained from the simulation software, based on the use of correcting factors. These factors should account for parameters not considered by calculation software but that affect controls' performances and that can depend on control system's typology, lighting systems' characteristics or indoor daylight availability. Future studies should define these correcting factors and their ranges of application. In this way it would be possible to predict energy savings due to the use of different control systems with more reliability and with less approximation then that determined by nowadays available calculation methods. This could help designers in the comparison of different technical solutions and in the choice of the most appropriate one depending on the specific design requirements.

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