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TECHNICAL REPORT

Decision Scheme for Lighting Controls in Non-Residential Buildings

CIE 222:2017

UDC: 28.97.972

Descriptor: Interior lighting

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This Technical Report has been prepared by CIE Technical Committee 3-49 of Division 3 "Interior Environment and Lighting Design" and has been approved by the Board of Administration as well as by Division 3 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique CIE 3-49 de la Division 3 "Environnement intérieur et étude de l'éclairage" et a été approuvé par le Bureau et Division 3 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

Dieser Technische Bericht ist vom Technischen Komitee CIE 3-49 der Division 3 "Innenraum und Beleuchtungsentwurf" ausgearbeitet und vom Vorstand sowie Division 3 der Commission Internationale de l'Eclairage gebilligt worden. Das Dokument berichtet über den derzeitigen Stand des Wissens und Erfahrung in dem behandelten Gebiet von Licht und Beleuchtung; es ist zur Verwendung durch CIE-Mitglieder und durch andere Interessierte bestimmt. Es sollte jedoch beachtet werden, dass das Dokument eine Empfehlung und keine Vorschrift ist.

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DECISION SCHEME FOR LIGHTING CONTROLS IN NON-RESIDENTIAL BUILDINGS

Summary

This report offers guidelines in order to balance lighting quality, user comfort and energy efficiency in lighting controls solutions for lighting in non-residential buildings (i.e. for commercial, institutional and industrial buildings).

It provides a decision scheme with a focus on the user requirements (visual comfort, performance, personal control) to determine the most applicable control solution, including the consequences for possible savings. In this, it assumes that there are no technological or financial hurdles. The decision scheme identifies 16 possible control strategies, for both daylight and electric lighting, and provides guidance for which strategy would be most effective in each of the 12 cases defined by space usage and occupancy.

AIDE A LA DECISION POUR LES SYSTEMES DE CONTROLE DE L'ECLAIRAGE DANS LES BATIMENTS NON RESIDENTIELS

Résumé

Ce rapport propose des recommandations permettant d'équilibrer qualité de l'éclairage, confort de l'utilisateur et efficacité énergétique, dans les bâtiments non résidentiels (ex.: bâtiments commerciaux, administratifs et industriels) où l'éclairage est contrôlé par des systèmes de gestion.

Il fournit une méthode d'aide à la décision basée sur les besoins des utilisateurs (confort visuel, performance, contrôle individuel) permettant de déterminer la stratégie de contrôle la plus adaptée tout en présentant les économies potentielles associées. La méthode fait l'hypothèse qu'il n'y a pas de restrictions financières ou techniques. Elle s'appuie sur 16 stratégies de contrôle possibles couvrant aussi bien l'éclairage naturel que l'éclairage électrique, elle indique quelle stratégie serait la plus efficace pour 12 cas d'usage et d'occupation d'un espace.

ENTSCHEIDUNGSSHEMA FÜR BELEUCHTUNGSMANAGEMENT IN NICHTWOHNGEBÄUDEN

Zusammenfassung

Dieser Bericht beinhaltet einen Leitfaden zur Abstimmung von Lichtqualität, Nutzerkomfort und Energieeffizienz von Lichtmanagementlösungen in Nichtwohngebäuden (z.B. gewerblichen, öffentlichen und industriellen Gebäuden).

Mit Blick auf die Nutzererwartungen (Sehkomfort, Leistungsfähigkeit und persönlicher Kontrolle) stellt der Bericht Entscheidungskriterien vor, um die bestmögliche Lichtsteuerung zu finden und dabei den Einfluss auf mögliche Einsparungen zu berücksichtigen. Technologische und finanzielle Einschränkungen bleiben unbeachtet. Das Entscheidungsschema identifiziert 16 mögliche Kontrollstrategien sowohl für Tageslicht als auch für elektrische Beleuchtung und gibt Anleitungen, welche Strategie in jedem der 12 Fälle, die durch Raumnutzung und Belegung definiert sind, am effektivsten ist.

1 Introduction

Lighting controls in non-residential buildings, particularly more complex systems, have shown slower uptake than many had hoped for, and a fairly low acceptance level. This could be due to the experience with early controls and a lack of knowledge about newer technology. The general theme of this Technical Report is to extend knowledge about the potential effect of lighting controls on lighting quality, user comfort and energy efficiency, by analysing the behaviour of each control strategy.

The use of all lighting control strategies will have an effect on the energy consumption. The actual use of energy will depend on the type of control applied, but also on the context (e.g. building, geographical location, climate, combination of controls and user behaviour) these controls are being used in. Therefore it is not possible to give one single number for the amount of possible energy consumption or savings.

The majority of existing energy efficiency evaluations and the resulting choice for the control strategy are made from a technology viewpoint only, whereas the user can greatly affect the actual savings. Based on an extensive literature review, this Technical Report presents a decision scheme to determine the most applicable control solution for a specific situation, taking lighting quality, user comfort and energy efficiency into account.

2 Terms of reference

In June 2009 a proposal for a new CIE Technical Committee (TC) *Decision Scheme for Lighting Controls for Non-Residential Lighting in Buildings* was approved with the following terms of reference:

- Offer guidelines in order to balance lighting quality, user comfort (acceptance) and energy efficiency in lighting controls solutions for non-residential lighting in buildings (i.e. for commercial, institutional and industrial buildings).
- Work on a decision scheme with focus on the user requirements (visual comfort, performance, personal control) to determine the most applicable control solution, including the consequences for possible savings.

3 Scope

Within this document, energy efficiency, user acceptance and lighting quality are evaluated on a qualitative scale from 'none' to 'very high'. The document will not result in a calculation method to assess energy consumption.

The aim of this Technical Report is to provide information about the effect of lighting controls and to promote the use of these controls to increase energy savings, user comfort and lighting quality in indoor applications. It is assumed that there are no technological or financial constraints. Developments in technology, ease of commissioning, user interfaces as well as costs are such that the currently perceived constraints will become less onerous in the near future.

This report focuses on energy savings for lighting only. Savings from an integral approach including other building services are not considered in this report. Research indicates that reducing the use of electrical lighting during the summer might have a beneficial effect on energy consumption for cooling, whereas additional required heating in winter seems to be minimal (e.g. Sullivan et al. 1992, Lee et al. 1997).

4 Lighting control strategies

Lighting controls are electrical devices added to the installed lighting circuit to manipulate the light output of the luminaires according to a pre-planned program or automatic detection regime or to operator managed actions. The control devices may be placed remotely or be incorporated into the luminaires. In general they consist of detectors (photoelectric, passive infrared, etc.), signal carriers (mains borne, wireless or wired, etc.) and activators (switch, dimming ballast, DALI ballast, etc.).

In most cases, lighting controls offer positive benefits to the surrounding environment as well as positively affecting occupants. There are four main reasons to apply lighting controls in commercial, institutional and industrial buildings:

- Make use of potential energy savings (e.g. occupancy sensing, daylight harvesting, time scheduling, demand response).
- Improve user satisfaction, mood and performance (e.g. personal control, daylight glare control, user demand control, algorithmic stimulation lighting).
- Support building appearance, ambience and company image (e.g. scene setting).
- Increase safety (e.g. when the lighting control system offers emergency lighting, or the lighting prevents feelings of danger or uncertainty, for example through occupancy sensing).

Each of these reasons will interest a different group of decision makers, such as facility managers and building owners, human resource managers and health specialists for occupational safety and health services, architects, lighting designers, marketing managers and product designers, as well as end users.

The lighting control strategies, discussed in more detail in Clause 4, are listed in Table 1. For each control strategy a short explanation and its way of working is included (☑ = automatic control, ✎ / ☑ = manual control, ⬤ = switching on / off, ◐ = dimming, x = characteristic available in lighting control strategy, (x) = typically automatic control, sometimes with a possibility to manually switch on).

Table 1 – Lighting control strategies

Strategies of lighting controls					Explanation
Personal control		x	x	x	Most simple control, manual control, using switch or dimmer; conscious user expected
Daylight harvesting, or daylight responsive control	x	(x)	x	x	Switching off when daylight reaches the limiting value, or dimming to combine daylight and artificial light to a predefined lighting level, both measured by a sensor. Switching on by the user or by the system
Occupancy sensing	x	(x)	x	x	Lighting switches off or dims down when a person leaves the field of a sensor. The lighting is switched on by the user (personal control) or by the system
Constant light	x			x	Output of luminaire is automatically kept on a constant level
Tuning	x			x	The installed lighting solution is providing a higher light level than the minimum required as a result of the lighting design, either based on allowed installed power or outdated illuminance requirements. These over-specified lighting installations are dimmed down to reduce energy consumption while still provide required lighting levels with reduced energy consumption
Load shedding, or demand response	x			x	Automatic reduction of energy demand by an external signal
Time scheduling	x	(x)	x	x	Time setting of predefined scenes or time based on and off
Task demand control		x	x	x	Lighting (including blinds) adjusted to the actual task or demand by the user
Algorithmic lighting	x			x	Automatic changing of lighting (e.g. light level or colour temperature) according to predefined rules
Scene setting	x	x		x	Setting of predefined static or dynamic lighting scenarios, typically for a number of different types of luminaires, to create different atmospheres
Daylight glare control	x	x			Control of incoming daylight to reduce glare and heating by adjusting blinds automatically or manually by the user

A meta-analysis was performed by Williams et al. (2011)¹ looking into literature presenting the energy savings potential of personal control (see also 4.1), occupancy sensing (4.3), daylight harvesting (4.2), tuning (0) or a combination of controls. The overview given in Table 2 shows the savings for lighting energy achieved in field studies, and indicates that energy savings between 30 % and 45 % are possible for each strategy. Only studies that included savings in percentage or a baseline and test case energy use were taken into consideration in the review.

The meta-analysis of Williams et al. (2011) looked into the difference between savings achieved in field studies and those determined through simulations, and indicated that simulations likely overestimate the savings potential in case of daylight harvesting, but are informative for personal control, occupancy sensing and tuning. Similar results were found in the VERU project by Fraunhofer Institute for Building Physics (IBP) (Erhorn et al. 2007). The study showed that daylight savings are higher than simulations predict if switch-on is manual by the user, and the dimming down and switch-off is controlled by daylight availability.

Energy saving is often the major driving factor as well as the most tangible and objective justification for lighting controls. Nonetheless, it must not create a detrimental effect. The occupant's performance should not suffer due to a reduced lighting quality. Lighting quality is understood in its common meaning as discussed in the first CIE Lighting Quality Symposium (CIE 1998): Lighting quality is the degree of excellence in a lighting design or installation, in this case meeting the human needs, such as task visibility, glare control and non-visual effects of lighting. The criteria of lighting quality are included in more detail in Table 5 of this document. In order to properly design for lighting controls (and to maximize potential energy savings), the designer should have an understanding of occupant behaviour towards lighting control. This document will give arguments to support a decision for the holistic use of lighting controls.

Table 2 – Lighting energy savings in percent of energy consumption of the study specific baseline, achieved in field studies (based on meta-analysis by Williams et al. 2011, Table 7 *Energy savings by building type – final filter*)

	Office	Warehouse	Commercial lodging	Education	Retail, other than mall	Healthcare, outpatient	Public assembly
Personal control	35 % (n = 13)			6 % (n = 2)			
Daylight harvesting	27 % (n = 18)	28 % (n = 1)		29 % (n = 7)	29 % (n = 3)		36 % (n = 1)
Occupancy sensing	22 % (n = 23)	31 % (n = 4)	45% (n = 2)	18 % (n = 5)		23 % (n = 1)	36 % (n = 2)
Tuning	36 % (n = 11)				60 % (n = 1)		
n: number of studies							

Table 3 shows the influence of the control strategies on lighting quality and user acceptance.

¹ Related to energy savings potential of control strategies, this Technical Report will refer to the results of the meta-analysis of Williams et al. (2011), and additionally point out research or publications of interest, as well as add information on user acceptance and lighting quality.

Table 3 – Outlining space performance: Potential positive influence of lighting control strategies on lighting quality (LQ) and user acceptance (UA)

S- small positive influence, H – high positive influence,
 none – no positive influence, n.a. – not applicable
 (detailed information in Table 5, Table 6, and Tables 7 to 18)

Strategies of lighting controls		Office	Warehouse	Hotel room	Education	Retail, other than mall	Hospital room	Public assembly
1 - Personal (switching, dimming, manually on / off)	LQ	H ²	H ³	H	H	H ²	H ¹	H ²
	UA	H	H ²	H	H	H ²	H	H ²
2 - Daylight harvesting (switching, auto off, auto on)	LQ	S	S	n.a.	S	S	S	S
	UA	none	none	n.a.	none	none	none	none
3 - Daylight harvesting (switching, auto off, manually on)	LQ	S ¹	n.a.	n.a.	n.a.	n.a.	S ¹	n.a.
	UA	none	n.a.	n.a.	n.a.	n.a.	none	n.a.
4 - Daylight harvesting (dimming, auto off / on),	LQ	S	S	n.a.	S	S	S	S
	UA	none	S	n.a.	S	S	none	S
5 - Daylight harvesting (dimming, auto off, manually on)	LQ	S ¹	n.a.	n.a.	n.a.	n.a.	S ¹	n.a.
	UA	none	n.a.	n.a.	n.a.	n.a.	none	n.a.
6 - Occupancy sensing (presence detection: auto off / on)	LQ	S	S	n.a.	S	S	S	S
	UA	S	S	n.a.	S	S	S	S
7 - Occupancy sensing (absence detection: auto off, manually on)	LQ	S ¹	n.a.	n.a.	S	n.a.	S ¹	n.a.
	UA	S-H	n.a.	n.a.	S-H	n.a.	S-H	n.a.
8 - Constant light control	LQ	S	S	n.a.	S	S	S	S
	UA	S	S	n.a.	S	S	S	S
9 – Tuning	LQ	S	n.a.	n.a.	S	n.a.	S	n.a.
	UA	S	n.a.	n.a.	S	n.a.	S	n.a.
10 - Load shedding, or demand response	LQ	none	none	n.a.	none	none ⁴	none	none
	UA	S	S	n.a.	S	S ⁴	S	S
11 - Time scheduling	LQ	S	S	n.a.	S	S	S	S
	UA	S	S	n.a.	S	S	S	S
12 - Task demand control (manual)	LQ	H ¹	n.a.	H	H	H ⁵	H ¹	n.a.
	UA	H ¹	n.a.	H	H	H	H ¹	n.a.
13 – Algorithmic Lighting	LQ	H	n.a.	H	H	H	H	n.a.
	UA	H	n.a.	H	H	H	H	n.a.
14 – Scene setting	LQ	H ¹	H	H	n.a.	H	H ¹	H
	UA	H ¹	H	H	n.a.	H	H ¹	H
15 – Daylight glare control (manual)	LQ	H ¹	n.a.	H	H	H ²	H ¹	n.a.
	UA	H ¹	n.a.	H	H	H ²	H ¹	n.a.
16 – Daylight glare control (automatic)	LQ	H	H	H	H	H	H	H
	UA	S-H	S-H	S-H	S-H	S-H	S-H	S-H

² For lighting solutions that offer lighting conditions for 1 – 2 persons (single cell office, owned area in open plan office)

³ For central controllers only

⁴ For larger applications, such as supermarkets, otherwise not applicable

⁵ For smaller applications, such as shops, otherwise not applicable

As described in the previous paragraph, there are a number of reasons to apply controls. Research has indicated that the effectiveness of these controls is not achieved if the user does not have the feeling of being able to intervene with the controls when required (Moore et al. 2004). Personal control is essential when applying (other) lighting control systems. When automatic controls are combined with manual controls, the users of these systems become more positive towards these systems (Moore et al. 2002a, Moore et al. 2003).

User acceptance is much better if the system is optimally designed and well explained to the user. A project on people-friendly lighting controls found that scene setting was quite unpopular with users, because it hadn't been explained to them what the scenes meant (King et al. 2014).

The lighting control strategies are described in this clause. Their effectiveness in terms of energy efficiency, user comfort and lighting quality is listed in Table 5.

4.1 Personal control

Strategy: 1

Personal, or individual, control covers a wide range of technology including rocker switches, push buttons, pull cords, infra-red, radio, sonic, ultrasonic and telephone handset controls. Traditional control is by a switch panel near the door, but more recent systems offer flexible control by individual occupants using pull cords on the luminaires, hand-held controllers, smart phones, tablets or computers. Compared to conventional switching, flexible control can reduce wiring costs and allows flexible partitioning of open plan areas.

Personal control is an important lighting control strategy used for both energy savings and the comfort and satisfaction of users. Extensive research has been carried out on this subject, mostly focusing on the potential for energy savings and the photometric results created on work surfaces as well as the effect of lighting controls on the mood, satisfaction and performance of users. Studies by Tregenza et al. (1974) and Bordass et al. (1994) show that occupants prefer the ability to choose the lighting conditions rather than being forced to accept conditions chosen for them, even if these are objectively better.

There is a consensus on the occurrence of a wide range of preferred lighting levels by individuals, which justifies the need for individual controls. Research indicates that the preferred illuminance chosen by users is affected by the illuminance range offered by the lighting design and the illuminance level available before adjustment by the user (Fotios et al. 2011, Logadottir et al. 2011). The average preferred illuminance increases when the maximum illuminance of the offered range increases, or when the preceding illuminance is high, and the user is dimming down. This bias effect might have influenced results of studies on preferred illuminance levels. Some studies report chosen illuminance levels that are above current standards (e.g. Begemann et al. 1997), the majority of studies indicate that users work under illuminances that are below recommended lighting levels, resulting in savings of 35 % on average (meta-analysis by Williams et al. 2011), up to 54 % (Moore et al. 2003). A study by Newsham et al. (2008a) implies that manual control of electric lighting in a daylight space results in higher levels of energy savings compared to a space without daylight. In combination with other controls, such as occupancy sensing and/or daylight harvesting, additional savings through personal control of 11 % to 29 % (Galasiu et al. 2007, Jennings et al. 2000, Maniccia et al. 1999) were found. From an analysis of a number of studies, Boyce et al. (2006) propose a maximum mean illuminance of 700 lx in offices, offering almost all individuals their preferred illuminance and savings potential in not permanently occupied, daylight areas with electric lighting solutions that provide a uniform illuminance distribution.

The most apparent and important finding in the literature is the positive effect of personal controls on the satisfaction, comfort and performance of users (Moore et al. 2002a, Boyce et al. 2000, Galasiu et al. 2007, Newsham et al. 2008a, Moore et al. 2004, Boyce et al. 2006). Research by Veitch et al. (2008, 2010) showed that personal controls could increase the user's satisfaction with the lighting and the environment. Their field studies showed that this can result in better mood, less health problems and increased job satisfaction amongst employees. Thus, the use of personal control indirectly affects organizational productivity.

While most studies report improved satisfaction and performance of users, it is also important to note that with the complexity of control systems, there may be a detriment to the performance

of users as well. Building Use Studies (1993) showed that the productivity of the users decreased when they found conditions that they could not control uncomfortable. The study by Moore et al. (2002b) showed a strong correlation between the avoidance of using controls for fear of conflict and feelings of dissatisfaction with the perceived degree of control. A more recent report by Nordman et al. (2010) assessing existing lighting control user interfaces states that in order to maximize energy savings and reduce the annoyances of the users of these interfaces, a single designed language for lighting controls is very important. The literature strongly shows that systems should be designed so as to maximize the likelihood that all users feel equally empowered to use the controls (Moore et al. 2004). Even the simplest lighting control can cause confusion if it is not a familiar one for the user. People value the opportunity to have control, but to avoid difficulties the simplest is usually the best (King et al. 2014). Another important fact found in studies is that the frequency of occupant switch off at the end of the working day was minimal (Moore et al. 2003). There are conflicting research results on the activation and deactivation of systems with manual control. While in some studies occupants set an initial preferred illuminance level and rarely changed it afterwards (Maniccia et al. 1999, Moore et al. 2003, Boyce et al. 2006), other studies indicate a more frequent use of lighting control systems (Boyce 1980, Escuyer and Fontoynt 2001). In addition, manual switching probabilities are said to be dependent on time of day and minimum daylight factor (Hunt 1979, Hunt 1980).

4.2 Daylight harvesting

Strategy: 2, 3, 4, 5

Some studies show that users tend to switch lighting on or off only when entering or leaving the room (e.g. Reinhard and Voss 2003). Workplaces close to windows or other sources of daylight can normally, at least part of the day, be sufficiently illuminated with daylight only so the electric lighting can be completely switched off. During the rest of the day or during unfavourable weather conditions the temporary supplementary artificial lighting needs to be used to assure the minimum needed illuminance levels. In larger rooms some of the workplaces are positioned so far away from daylight that they need additional artificial lighting during all working hours to balance the brightness distribution in the room. This technology is called P.S.A.L.I. – Permanent Supplementary Artificial Lighting of Interiors (Hopkinson et. al. 1966). In both cases a lighting control system (daylight harvesting control) is used to maintain the required illuminance on the workplace and to reduce electrical energy use for lighting. Switching or dimming in daylight harvesting can be completely automatic (strategy 2 and 4) or automatic off, manually on (strategy 3 and 5).

Daylight availability is strongly associated with the sun's position in the sky and weather conditions, which means that geographical location and climatic zones have to be specified when considering daylight utilization. Effectiveness of daylight harvesting in interiors depends on:

- shapes, dimensions and placements of windows in the enveloping constructions,
- dimensions and shape of rooms,
- dimension and location of obstructions in front of windows,
- vegetation and its seasonal changes,
- window orientation,
- optical properties of transparent materials in apertures,
- optical properties of relevant indoor and outdoor reflective surfaces,
- optical properties of devices for shading, redirection and transport of sun light and sky light indoors,
- visual task requirements and glare protection in interiors,
- dimensions and location of workplaces,
- working time,
- maintenance of the transparent materials, daylight devices and lighting control system.