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Lighting Control Systems for Energy Saving and User Acceptance

State-of-the-art and future directions

Niko Gentile

Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
Faculty of Engineering LTH, 2015
Report EBD-T--15/20

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 116 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 7 500 employees and 47 700 students attending 287 degree programmes and 2 200 subject courses offered by 69 departments.

Division of Energy and Building Design

Reducing environmental effects of construction and facility management is a central aim of society. Minimising the energy use is an important aspect of this aim. The recently established division of Energy and Building Design belongs to the department of Architecture and Built Environment at the Lund University, Faculty of Engineering LTH in Sweden. The division has a focus on research in the fields of energy use, passive and active solar design, daylight utilisation and shading of buildings. Effects and requirements of occupants on thermal and visual comfort are an essential part of this work. Energy and Building Design also develops guidelines and methods for the planning process.

Lighting Control Systems for Energy Saving and User Acceptance

State-of-the-art and future directions

Niko Gentile

Licentiate Thesis

Keywords

Indoor lighting, lighting control system, lighting control, energy saving, energy efficiency, user acceptance, human factor, occupancy strategies, absence sensor, presence sensor, lighting switch, manual switch, daylight harvesting system, daylight-linked system, photoelectric dimming, photosensor.

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Abstract

Lighting accounts for one-fifth of global electricity use. In Sweden, energy demand for lighting corresponds to 20% of the total electricity use in office buildings. Lighting retrofit measures are considered to be among the most cost-efficient way to reduce energy use in buildings. In particular, the use of advanced lighting control systems promises energy savings of between 2 and 60%, but system failures and poor user acceptance have been significant limitations so far.

This thesis uses literature reviews and field studies to investigate the effect of lighting control systems on energy use and user acceptance. In the first part of the thesis, an extensive literature review on lighting control systems indicates that manually controlled systems are generally more accepted by the users. Systems with high automation and no manual override tend to be deactivated or even sabotaged. Consequently, user behavior plays a fundamental role in ensuring proper function and actual energy savings of the lighting control system. The review also showed that presence and absence detection are often combined under the overarching category 'occupancy strategies', although they yield very different energy savings. The review of daylight harvesting systems highlighted critical issues relating to design and commissioning.

Two field studies in individual offices were conducted. Absence and presence detection, daylight harvesting and a simple task light were tested in a real-life work environment, where energy use and user acceptance were monitored. The studies showed that the definition 'occupancy strategies' is not completely appropriate, since 'absence' and 'presence' detection yield different energy savings and user acceptance. The second field study showed that daylight harvesting systems could perform well, on condition that careful design and commissioning are performed along with provision of a manual override. However, the field study showed that the use of sensors and microcontrollers raised the energy demand for parasitic power (standby), which might be significant in relation to final energy use, especially with low occupancy rates and high-efficiency light sources.

Lighting control systems based on wireless networks and integrated in the building management system are expected to increase during the

coming years. This will overcome many of the current issues with advanced lighting control systems, but it will also require additional skills on the part of the designer and installer. In the meantime, occupancy strategies represent a good alternative in energy-efficient lighting retrofit.

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List of publications

Paper I: Dubois, M.-C., Bisegna, F., Gentile, N., Knoop, M., Matusiak, B., Osterhaus, W., Tetri, E., 2015. Retrofitting the electric lighting and daylighting systems to reduce energy use in buildings: a literature review. *Energy Research Journal* 6(1) , 25–41. doi:10.3844/erjsp.2015.25.41

Paper II: Gentile, N., Dubois, M.-C., Laike, T., 2015. *Daylight Harvesting Control Systems: Design recommendations based on a literature review*, Environment and Electrical Engineering (EEEIC), 2015 IEEE 15th International Conference on, Rome, IEEE Conferences Proceedings. IEEE, , pp. 632–637. doi:10.1109/EEEIC.2015.7165237

Paper III: Gentile, N., Håkansson, H., Dubois, M.-C., 2013. *Lighting control systems in individual offices at high latitude: measurements of lighting conditions and electricity savings*. Proceedings of IEEECB 2012, Frankfurt, Publications Office of the European Union, pp. 333–344. doi:10.2790/77021

Paper IV: Gentile, N., Laike, T., Dubois, M.-C., 2014. Lighting Control Systems in Peripheral Offices Rooms at High Latitude: Measurements of Electricity Savings and Users Preferences. *Energy Procedia*, 2013 ISES Solar World Congress 57, 1987–1996. doi:10.1016/j.egypro.2014.10.063

Paper V: Gentile, N., Laike, T., Dubois, M.-C., 2015. Lighting control systems in individual offices rooms at high latitude: measurements of electricity savings and occupants' satisfaction. *Solar Energy*. Under review

Other related publications

Paper VI: Govén, T., Gentile, N., Laike, T., Sjöberg, K., 2014. *Energy Efficient and Study Promoting Lighting in High School: Preliminary Results*. Proceedings of CIE 2014, Kuala Lumpur, pp. 772–779.

Paper VII: Gentile, N., Dubois, M.-C., Osterhaus, W., Stoffer, S., Amorim, C., Geisler-Moroder, D., Hoier, A., Jakobiak, R., 2015. Monitoring protocol to assess the overall performance of lighting and daylighting retrofit projects. *Energy Procedia*, Proceedings of IBPC 2015, Turin. In print..

The author's contribution to the papers:

Paper I: The section on lighting control system was written by the author. The review was coordinated by Marie-Claude Dubois.

Paper II: The review was written by the author. The paper was written by the author under the supervision of Marie-Claude Dubois and Thorbjörn Laike.

Paper III: The study was designed by the author under the supervision of Marie-Claude Dubois. The equipment installation and the technical part were carried out by the author under the supervision of Håkan Håkansson. Data collection, data analysis and interpretation of the results were carried out by the author under the supervision of Marie-Claude Dubois. The paper was written by the author under the supervision of Marie-Claude Dubois.

Paper IV, V: The study was designed by the author under supervision of Marie-Claude Dubois. The equipment installation and the technical part were carried out by the author. The methodology for the user satisfaction assessment was designed by the author under the supervision of Thorbjörn Laike. Data collection, data analysis and interpretation of the results were carried out by the author under the supervision of Marie-Claude Dubois. The paper was written by the author under the supervision of Thorbjörn Laike and Marie-Claude Dubois.

Paper VI: The study was designed by Tommy Govén and Thorbjörn Laike. The field measurements, including both technical and

psycho-biological assessments, were carried out by the author. The author was contact person regarding information about the research project. The paper was written by the author under the supervision of Tommy Govén on technical aspects, Thorbjörn Laike on the psychological assessment, and Klas Sjöberg on biological aspects.

Paper VII: The monitoring protocol was developed by Marie-Claude Dubois in collaboration with the author as well as other IEA Task 50 experts. The IEA Task 50 experts contributed equally to the final version proposed in the paper. The paper was written by the author under the supervision of Marie-Claude Dubois, Werner Osterhaus and Roman Jakobiak

1 Introduction

> *"[…] enhanced global awareness of […] science and technologies of light are vital for addressing challenges such as sustainable development, energy and community health, as well as for improving the quality of life in both developed and developing countries, […]". United Nations, 2013*

With these words, the General Assembly of the United Nations adopted in December 2013 the resolution A/RES/68/221, which proclaimed year 2015 as the 'International Year of Light and Light-based Technologies' (United Nations, 2013). A few months later, the Nobel Prize in Physics 2014 was awarded to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura *"for the invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources"* (Nobel Media AB, 2015). These recognitions highlight the importance of lighting in relation to global energy and social issues.

Some figures regarding energy use are noteworthy. A report by the IEA stated that nearly 3000 TWh/year of electricity – about 19% of global electricity use – were used for electric lighting (IEA, 2006). The IEA also projected an alarming increase to 4250 TWh/year for global electricity use for lighting by 2030 if current energy policies prevail. Electric lighting also entails expenditures on energy corresponding to some 0.54% of the global GDP (Tsao et al., 2010).

Two points regarding social aspects need to be highlighted:

- In developing countries, increased access to lighting is needed, since 1.3 billion people, i.e. 18% of the global population, still have no access to electric lighting (IEA, 2014). Electric lighting is needed, both to replace lighting produced by dangerous and pollutant sources such as gasoline and kerosene, and to support economic development of society (Barnes and Floor, 1996).
- In industrialized countries, electric lighting is needed to maintain services and the modern economy. Visual and biological effects of light on the circadian rhythm in indoor lighting applications, or improved safety in outdoor lighting applications, are key issues (Boyce, 2014).

Energy and social aspects relating to electric lighting are interconnected, while environmental and economic implications of energy production from fossil fuels can jeopardize the social and political arena. The interconnections between the social and energy aspects are sometimes overlooked. Several authors have warned about the risk of a rebound effect when energy efficiency is improved (Hanley et al., 2009; Holm and Englund, 2009; Lin and Du, 2015; Winther and Wilhite, 2015). The rebound effect may even yield a so-called Jevons paradox, where the absolute increase in energy use is greater than the savings achieved by increase in efficiency, as outlined by Jevons in 1856 (Jevons, 1865 via Alcott, 2005).

In the field of lighting, Tsao et al. (Tsao et al., 2010) observed that, over the past three centuries, the growth in demand for lighting has almost completely cancelled out the increased luminous efficiency, i.e. an almost 100% rebound effect, although this may have generated welfare gains (Saunders and Tsao, 2012). More recently, and with focus on developed countries, Schleich et al. surveyed over 6000 German households. They found that older light bulbs were being replaced with more efficient ones, but the latter were 24% brighter on average, (luminosity rebound) and their burning time was prolonged by about 23% (burning time rebound) (Schleich et al., 2014).

In other words, reduction of global energy use by means of technical efficiency might be spoiled by social factors. Such concerns can be studied even on a smaller scale of investigation, such as an office or a home environment. In this case, it would be more appropriate to refer to behavioral models rather than social factors. In summary, any improvement regarding energy efficiency in lighting cannot be seen as a mere technical problem; social aspects are important and they should always be considered in any lighting assessment, as is the case in this Licentiate thesis.

Recently, the European Parliament stipulated that the Member States must commit to a binding improvement in energy efficiency of 40% within the EU's 2030 climate and energy policy framework through cost-effective measures (European Parliament, 2014). Such a decision will have an impact on the lighting sector, since lighting retrofit measures have been identified as some of the most cost-effective ways to reduce carbon dioxide emissions (Enkvist et al., 2010). A study by Goldman et al. (2005) even indicated that energy service companies (ESCOs), whose revenue is based on cost-effective energy saving investments, very often decide to start their building retrofit projects by changing the light sources. Indeed, up to 40% energy can be saved by replacing fluorescent T12 with fluorescent T5 (Belysningsbranschen, 2008), and the figure reaches 50% when retrofitting T5 with new LEDs (Dubois et al., 2015).

However, the energy conservation potential in indoor lighting is not limited to improved light sources. A review of lighting-saving strategies for low-energy offices at high latitude (Dubois and Blomsterberg, 2011) indicated that between 20-60% of energy can be saved through suitable lighting control systems (LCSs), with relatively short payback periods (Chow et al., 2013; Yang and Nam, 2010).

LCSs include any strategy to adjust electric lighting to provide illumination where and when it is needed. LCSs for energy savings are traditionally used to dim lights or to switch them on or off. They can be operated manually (e.g. door switches, manual dimmers), automatically (e.g. presence sensors, photoelectric sensors) or use a combination of the two strategies (e.g. manual switch-on and automatic switch-off).

In recent years, the area of lighting controls has developed significantly through an increase in sophisticated technologies. These rely increasingly on automatic features despite the fact that research has indicated that a high level of automation and reduction of personal control are detrimental on the user side. Consequently, there is a need for research and development of highly energy-efficient LCSs that are also user-friendly. This thesis makes a contribution in this area by investigating the technical and non-technical issues relating to the most common LCSs used in lighting retrofit in non-residential buildings.

1.1 Objective

This Licentiate thesis investigates the energy efficiency of LCSs through field and laboratory studies, addressing both technical aspects (such as energy use) and user satisfaction. This work provides an overview about LCSs designed for energy savings in indoor applications for the non-residential sector, with a strong focus on user acceptance.

The final aim of this thesis is to identify the most promising LCS technologies in terms of energy savings and user acceptance. In a broader perspective, this work helps to support the political goals of efficiency and energy reduction for the lighting sector stipulated by the Swedish Energy Agency, which targets a reduction of 6 TWh of electricity for lighting by year 2020, to be achieved through high quality solutions (Energimyndigheten, 2011).

1.2 Research questions

The main research question addressed in this thesis is:

- Which are the most favorable LCS technologies available today in terms of both energy-efficiency and user acceptance?

Secondary research questions are:

- Which are the state-of-the-art technologies in the field of LCSs and how do they function?
- What are the limits of automation in LCSs in terms of energy savings? What are the additional benefits and savings provided by automation?
- What are the key elements to consider in designing and commissioning LCSs, and how do these elements relate to various types of indoor environments?

1.3 Hypotheses

The main hypotheses are:

- Relatively simple LCSs, with a degree of manual control, might be almost as efficient as fully automatic systems, while yielding a much higher level of user acceptance.
- High level of automation leads to higher risks of failure and decreased user acceptance.

1.4 Limitations

The field studies in this thesis are carried out in individual office rooms or school classrooms. The conclusions might differ in other contexts, such as large landscape offices or atria.

The field studies in individual offices involve a small sample of participants and relatively short monitoring time. This limitation is somehow minimized through an appropriate experimental design, i.e. semi-structured interviews and by using a representative time frame. Also, field settings were chosen to retain the ecological validity of the studies, but control variables were harder to isolate from external factors such as system failures and human errors.

Finally, this work implicitly focuses on lighting retrofit per se. For example, some of the findings regard the role of standby losses for sensors

over the total energy use, but when an integrated Building Management System (BMS) for heating, cooling, ventilation is applied, sensors are used for more purposes than illumination, and some of the conclusions drawn might not be appropriate.

1.5 Thesis structure

This Licentiate thesis consists of a collection of scientific papers.

The section 'Previous research on lighting control systems' provides a brief overview of the topic.

The appended papers, which consist of reviews and field studies, have the same theoretical basis as that described in the chapter 'Theoretical considerations'.

A summary of each appended paper, including methodology, discussion and conclusions on LCSs, is presented in the section 'Appended papers'. This section also includes a brief summary of other papers produced on lighting that did not focus directly on LCSs but discuss some issues relating to the topic.

Finally, the section 'General discussion and conclusions' addresses the common thread of the appended studies, including some additional considerations before drawing some conclusions. Based on such conclusions, a proposal for 'Future work' is presented.

2 Previous research on lighting control systems

A lighting control system is a strategy that allows provision of lighting at the time, place and in the amount needed. LCSs are useful to maximize energy savings and to provide a correct luminous environment (DiLouie, 2007). Generally, a LCS for energy savings establishes whether a light source should be turned on or off and, if possible, whether it should be dimmed. Auto-tuning systems that change the correlated color temperature of the light sources have also been proposed, but as yet they do not provide energy savings (Ellis et al., 2014; Logadóttir et al., 2013).

The most common strategies used for controlling electric lighting are (Figure 2.1).

- Manual switch, such as the classic wall switch or user-driven remote controls.
- Presence (or on/off) strategy. The lights are switched on or off according to the presence or absence of people in the space.
- Absence (or switch-off or vacancy) strategy. The electric lighting is turned on manually and off automatically when the occupant leaves the space. Absence and presence strategies are often confused and called 'occupancy' LCSs, although they produce quite different results in terms of energy savings.
- Time-scheduling. The electric lighting system is partially or totally switched on or off according to a pre-defined usage patterns, e.g. part of the lighting is automatically switched off at night in office buildings.
- Daylighting on-off, i.e. a photosensor that switches the electric lighting on or off according to a daylight availability threshold.
- Institutional switch. This LCS works centrally from the top, e.g. if there is an electricity overload, the energy management system might decide to switch off the secondary lighting systems.

Once the electric lighting is switched on, it might be dimmed by means of:

- Manual dimmers;

- Daylight Harvesting System (DHS) (also known as daylight-linked, daylight dimming, daylight equi-illumination, photoelectric dimming, constant lighting, etc.) is a system that adjusts the electric lighting output according to daylight availability;
- Institutional dimming, i.e. when the energy management system dims part of the electric lighting in response to electricity overloads or to save energy.

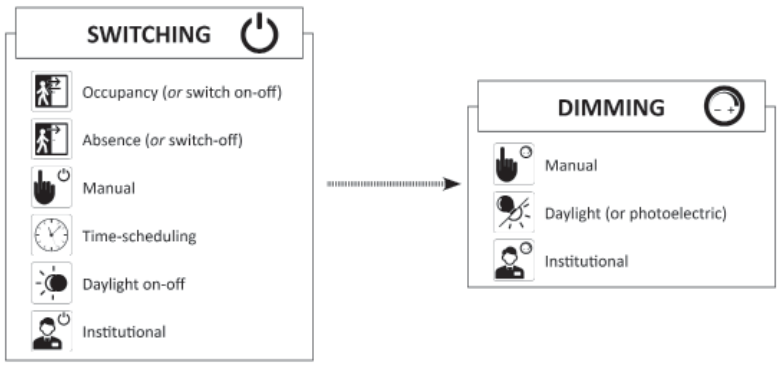

Figure 2.1 *Main categories of LCSs for indoor applications (elaboration on www.flaticon.com original designs)*

In actual installations, the cited strategies are often combined to maximize the energy savings. Most studies estimate the potential energy savings for lighting through a LCS to be high. A recent review on LCSs for commercial buildings reported the following average energy savings: 24% for occupancy strategies, 28% for daylight strategies, 31% for personal control (manual on/off, manual dimming, etc.), 36% for institutional control (mainly time scheduling), and 38% for multiple approaches (Williams et al., 2012). However, studies show wide variations in the reported savings, mainly due to:

- slight differences in the LCSs used (e.g. different switch-off time delay for occupancy strategies);
- differences in the space function (e.g. individual or landscape offices);
- differences in the calculation baseline for the energy savings (e.g. comparison between 100% lights on or with realistic settings);
- studies performed through simulations or field studies.

In particular, the latter leads to quite considerable differences. For example, the average reported savings for simulated and actual installations are 48%

and 28% respectively in the case of daylighting strategies, 32% and 24% respectively for occupancy strategies, and 78% and 31% respectively for systems with manual controls (Williams et al., 2012).

These differences are essentially due to the unpredictability of technical aspects as well as great variation in user behavior in different contexts. On the technical side, the system might not be properly designed or incorrectly installed, as shown by Gentile et al. (2013). On the user side, it has been reported that users tend to prefer manually adjustable systems (Escuyer and Fontoynont, 2001) and they are even likely to sabotage LCSs if these are disturbing (Galasiu and Veitch, 2006).

3 Theoretical considerations

Energy demand can be reduced through improved technology and behavioral changes of occupants and stakeholders (Bertoldi et al., 2013). In a theoretical analysis of effective energy policies, Oikonomou et al. differentiated between these two aspects, naming them energy efficiency and energy conservation (Oikonomou et al., 2009). Energy efficiency means the ratio between the primary energy fed to the system and the maximum energy output of the system, so is merely a technical description. In contrast, the terms 'energy conservation' or 'energy savings' mean the complex of energy-related behaviors from the technology investors, consumers and end-users, triggered by economic and psychological considerations. Policies and regulations should always consider energy efficiency and energy savings in order to successfully encourage energy conservation.

Based on these definitions, this section frames the existing knowledge in terms of energy efficient LCSs and the role of users in energy savings. The policies and regulations at EU level are subsequently addressed in order to explain how this knowledge is currently considered in the regulatory framework.

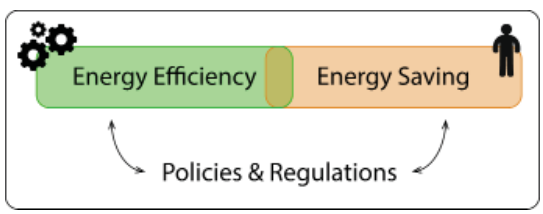

Figure 3.1 Theoretical framework for effective energy policies

3.1 Energy efficient lighting control systems

Previous research has addressed some technical and design issues of LCSs, especially in relation to automatic features. A system with high efficiency that fails once installed has little value.

The focus of past research has been mostly on occupancy and daylight harvesting strategies. For occupancy strategies, previous research mostly investigated the performance of presence detection sensors. In particular, several studies examined the sensor technology and the best switch-off time delay in order to avoid frequent switches and thereby save more energy.

Guo et al. (Guo et al., 2010) published a review of occupancy-based strategy performance. A first part of the review investigated the sensor technology and concluded that, for economic reasons, the most used sensor typology is based on PIR technology (Passive Infrared Technology), though other solutions offer higher detection accuracy. The second part of their work examined the best switch-off time delay, finding that the shortest time that could successfully be adopted in a field study was seven minutes (Floyd et al., 1996). In their study, Guo et al. (2010) concluded that the detection accuracy could be largely improved with networks of intercommunicating sensors.

On a similar theme, Dikel and Newsham (Dikel and Newsham, 2014) recently explored a high-resolution motion sensor network, with the aim of detecting presence in the most accurate way possible, by setting the switch-off time delay to zero. They simulated a windowless office space with six workstations, each provided with a proper occupancy sensor connected to the office network. In this experiment, they achieved up to 48.6% energy savings compared to when the light was fully on between 07:00 and 19:00, by setting the time delay as low as 0 seconds. Since this might not work in reality because of the risk of false-off, they argued that the one-minute delay would be a good balance between protection from false-off and energy savings (which would be 45.8% in that case).

The dimming of a light source requires ballasts or led drivers, which might also impact on the energy efficiency (Chiu et al., 2010; Choi et al., 2005; Doulos et al., 2008a). The dimming is usually set either manually or automatically. One of the most common automatic dimming systems is the daylight harvesting system (DHS). The DHS normally comprises a photosensor that senses the illuminance at a spot, and then sends this information to a micro-controller, which defines the need for electric lighting to maintain a pre-defined target illuminance.

Photosensors and controllers might present some technical issues as well. For example, commercial photosensors are supposed to match the human eye sensitivity, but several studies demonstrated that there is a huge variation in terms of spectral and spatial response. Doulos et al. (Doulos et al., 2008b) tested several commercial photosensors and found differences in the readings between 36% and 118%, which would lead to very different values of maintained illuminances once the DHS is installed. Theoretically, the photosensor output can be calibrated through a suitable micro-controller algorithm, but some authors claimed that this might not be a sufficient solution (Bierman and Conway, 2000; Doulos et al., 2008a). The appended review 'Daylight Harvesting Control Systems: Design recommendations based on a literature review' (Gentile et al., 2015a) provides a more comprehensive discussion on technical, architectural and human-related factors regarding DHSs.

Finally, since complex lighting controls entail additional sensors and controllers, some authors warned about the risk of increasing standby (or parasitic) losses. The total energy used by the LCSs for purposes other than illumination should be taken into consideration, since this amount can be substantial. For example, in a study of individual office rooms, standby losses represented 80% of the total energy used by a DHS (Gentile et al., 2015b, 2014), and similar findings were reported by Aghemo et al. (Aghemo et al., 2014) in a field study in larger spaces.

To conclude, LCSs should provide electric lighting only where, when and in the amount needed, in order to achieve high energy savings. In the past years, this has resulted in the systems becoming increasingly complex, including the use of additional sensing devices (presence detectors, photosensors, etc.) and related complications on the design and commissioning side. Generally, it appears that the increasing technical complexity of LCSs can provide additional gains in energy performance, but only up to a certain level. Beyond that level, smaller additional savings generally entail greater efforts in technical terms and higher risk of failures (red line in Figure 3.2). The most promising and readily available technologies (low-hanging fruits) are theoretically located just before the inflection point in Figure 3.2.

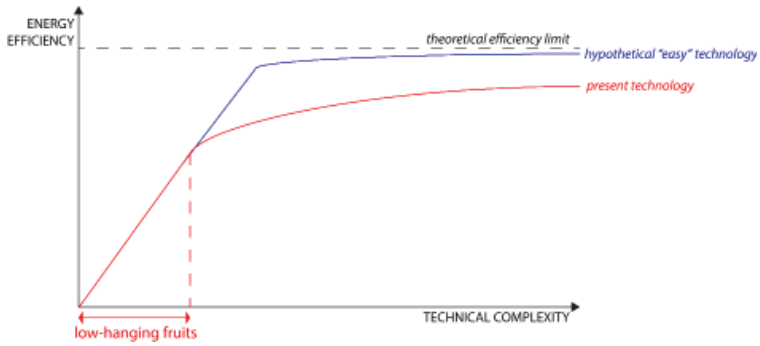

Figure 3.2 *Energy efficiency as a function of technical complexity for existing LCSs (red) and ideal future LCSs (blue)*

Such generalization assumes that technical complexity always translates into design and commissioning complications, which is quite common in today's LCS technology. Future technologies should propose very complex yet reliable systems that are easy to design and install (e.g. plug-and-play self-calibrating systems), as represented by the hypothetic curve in Figure 3.2.

3.2 User role in the energy savings

The 'low-hanging fruits' in Figure 3.2 are defined by technological factors. Many LCSs might have equal efficiency and technical complexity, but user acceptance and behavior might differ, with fallouts on the energy side. The role of users as energy saving agents should be taken into account at this stage.

Some studies seek to improve the use of LCSs through an improved design interface (Maleetipwan-Mattsson, 2015; Yılmaz et al., 2015). Others tested feedback systems to promote energy efficient behaviors (Darby, 2001), while some research focused on technology acceptance, as in the present thesis (Cowan and Daim, 2011; Islam et al., 2015). Several theories in the field of psychology have been proposed to explain the technology acceptance and the user behavioral intention.

In 2003, Venkatesh et al. (Venkatesh et al., 2003) reviewed eight well-known models and theories of individual acceptance, and proposed a Unified Theory of Acceptance and Use of a Technology (UTAUT). In particular, they used validated items based on the eight theories and

performed longitudinal field studies on 215 individuals introduced to new technologies in their workplaces. They found that seven of the core constructs of the reviewed theories were direct determinants of intentions or usage, and they theorized that just four of those would play a significant role in determining the acceptance. Such theory was successfully cross-validated by using the same data sample.

According to the authors, the four significant determinants of user acceptance of a technology are:

- Performance expectancy, i.e. the degree to which the user believes that a given technology will contribute in improving job performance. The mediating factors are gender and age.
- Effort expectancy, i.e. how easy it is to use the technology. The mediating factors are gender, age and experience of the individual.
- Social influence, i.e. the degree to which the user considers the use of the technology as important in relation to others' beliefs. The mediating factors are gender, age, experience and voluntariness of use.
- Facilitating conditions, i.e. the degree to which the user considers that support is available regarding the technology use (e.g. customer support). The mediating factors are age and experience.

According to this model, the four determinants affect the behavioral intention and thereby the behavior when using the technology. Note that the UTAUT has been widely used to study acceptance of modern IT equipment and devices.

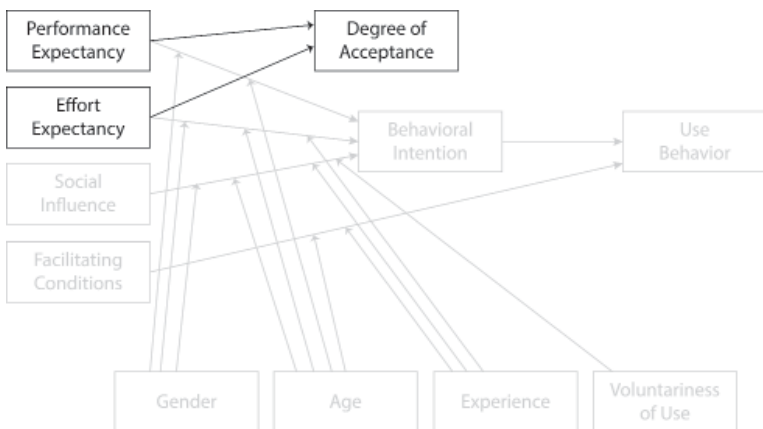

Figure 3.3 Simplified UTUAT as theoretical framework for the appended studies

This model is quite complex, so it has been simplified in the context of this thesis. In particular, the field studies resulted in Papers III, IV and V, which investigated the performance expectancy and the effort expectancy determinants in the UTAUT model, while controlling the social influence and facilitating conditions as well as the mediating factors (Figure 3.3). In such studies, the behavioral intention and the user behavior were not investigated, but it was assumed that if the user accepts the system, i.e. the system allows the user to work efficiently with little or no effort, then the system will most probably work as expected. In contrast, a LCS that creates hassle or requires a lot of effort on behalf of the user, will cause dissatisfaction and then trigger reactions such as protests and sabotage, as already shown in previous acceptance studies on LCSs (Howlett et al., 2006).

3.3 Policies and regulations

In Europe, work to promote more efficient end-use of energy in buildings started to emerge a few decades ago. Member states adopted advanced legislative frameworks for energy efficiency in residential and non-residential buildings already in the early 1990s (Italian Parliament, 1991). The directive 93/76/CEE proposed energy efficiency in buildings as a measure against the increasing levels of carbon dioxide in the atmosphere (European Communities, 1993). This directive was later supported by the European Directive 2002/91/EC, the Energy Performance of Building Directive (EPBD), which introduced energy certification of buildings (European Parliament, 2003).

The EPBD represented a milestone for energy efficient buildings. Some key aspects are worth mentioning: a) it required a common methodology for the energy performance calculation, b) it obliged member states to adopt an energy certification system, and c) it required minimum standards of energy performance for new and existing buildings undergoing major renovations. In particular, the common methodology explicitly requires taking lighting into account, besides many other aspects such as heating, cooling, ventilation, etc. However, the quality performance requirements for lighting established by the standard EN12464-1 (CEN, 2011) were not made mandatory by the EPBD. Consequently, low-performance lighting systems could still be used under the EPBD framework. In fact, the norm has been mostly effective in improving the efficiency of heating, cooling and water heating.

The first powerful legislative intervention on lighting was through the Ecodesign Directive 2005/32/EC, a norm which regulates the efficiency of appliances sold in the EU (European Parliament, 2005). Within the

Ecodesign Directive framework, member states decided in 2008 on a progressive phase-out of incandescent bulbs by 2012. More recently, the ban was extended to halogen lamps and any light source with efficiency lower than class B. Although much criticized, this command-and-control legislative approach to light sources has actually paved the way for increasing awareness of lighting-related issues, including both energy efficiency and lighting quality.

In 2010, the EPBD was updated through the European Directive 2010/31/CE (EU, 2010), largely known because it obliges newly constructed buildings to be 'nearly-zero energy' by 2020. The directive was later supplemented by the Commission Delegated Regulation 244/2012 (EU, 2012). These documents introduced the concept of cost-optimal levels of minimum energy performance requirements for buildings and building elements. In practice, cost-efficient actions for energy conservation are promoted. The new legislative scheme, besides the aforementioned 2030 framework for climate and energy policies (European Parliament, 2014), will encourage investments in lighting for the building sector.

The European Directives require a calculation framework, which is usually provided by the European Committee for Standardization (CEN). This committee publishes and updates some standards regarding energy efficiency and quality of lighting installations. For indoor spaces, EN 12464-1:2011 'Light and lighting - Lighting of work places - Part 1: Indoor work places.' (CEN, 2011) and EN 15193:2015 'Energy performance of buildings – Energy requirements for lighting', which is currently under revision (CEN, 2015), are particularly relevant.

EN 12464-1 mostly provides recommendations on the photometric requirements for indoor work places, such as values of illuminance, luminance or illuminance uniformity. The standard does not directly mention LCSs, although the LCS design should follow the standard. On the other hand, EN 15193, currently under revision, specifies the methodology to assess energy requirements of lighting systems. This uses the Lighting Energy Numerical Indicator (LENI), expressed in kWh/m^2y. The standard offers three assessment methodologies: calculated, quick calculated and measured method. While the latter comprises the simple installation of a separate electricity meter for lighting, the two calculated methods use a relatively complex model requiring knowledge of some indexes. These indexes provide information on the lighting system, products (light fixtures), system design, and operating conditions.

For the LCSs, the factors F_D (daylight dependency) and F_O (occupancy dependency) are particularly important. These factors mainly consider the space geometry to predict daylight availability and occupancy patterns, in order to estimate the use of electric lighting. The factor values are chosen on the basis of the category of LCS used.

To conclude, there is a normative framework for lighting in Europe, but this is quite new and is constantly evolving. So far, measures have either consisted of a ban on inefficient light sources or requirements regarding the maximum final energy intensity for lighting. LCSs contribute to the LENI value as defined by the EN 15193 standard, but there are no obligations regarding the use of certain LCSs.

European norms and standards for lighting are currently mainly based on energy efficiency rather than energy savings. Nevertheless, the development of research in the area of human factors, including user behavior, technology acceptance, circadian effects of lighting, feedback systems and lighting control interfaces design, suggests that the normative framework will evolve further in the near future, by taking into account the role of occupants in energy conservation.

4 Appended papers

4.1 Outline of the appended papers

Paper I is a general review of advanced solutions for lighting retrofit. It includes a section on LCSs and served as a basis for exploring state-of-the-art technology for LCSs.

One of the main outcomes of Paper I was that DHSs probably offer the highest saving potential in indoor applications. Nevertheless, several failures in actual installations, such as wrong design and commissioning, were outlined. Paper II therefore involved a more extensive review of DHS technology. The review was arranged as a guideline for designing and commissioning a DHS, with a focus on technical, architectural and human aspects.

Two field studies in individual office rooms (Papers III, IV and V) were designed. They were based on the knowledge acquired during the review. The studies were performed in a real-life setting and included a user acceptance assessment based on diaries and semi-structured interviews, taking the simplified UTUAT framework into account.

4.2 Summary of the papers

This section summarizes the papers appended to this thesis. Some studies were designed within other research projects, so they did not focus solely on LCSs. For the sake of clarity, a 'LCSs – conclusions at a glance' paragraph has been added to each summary.

4.2.1 Literature review

Paper I – Review of efficient solutions for lighting retrofit

Goals

The aim of this literature review was to provide an overview of the state-of-the-art technologies in lighting and strategies used in retrofit projects. Specifically, the review aimed to: a) identify existing databases of case studies, b) identify previous studies about lighting and/or daylighting retrofit,

c) update key information on lighting strategies for energy saving in retrofit projects, and d) summarize the saving potential for different strategies.

Methods

This literature review is the result of a joint effort of the participants in the IEA-SHC Task 50 'Advanced lighting solutions for retrofitting buildings'. It included most of the available lighting technologies for retrofit projects and also included a section on LCSs.

The review was based on the following key words: 'lighting retrofit', 'energy efficient lighting', 'relamping', 'luminaires', 'lamps', 'lighting control', 'light sensors', 'dimming', 'daylight retrofit', and 'daylighting systems'. The search was limited to published literature between 1993 and 2013. The focus was on peer-reviewed journal articles, conference papers, reports and relevant earlier IEA, European or national projects. For the scientific publications, the search was extended to several databases, including ScienceDirect, Compendex, and Inspec. The process resulted in retrieval of over 350 publications, which were subsequently narrowed down to about 160 documents used in the final review.

The section on LCSs investigated manual controls, occupancy controls and daylight-linked controls (or DHSs). Priority was given to studies that reported payback calculations of the retrofitting measures, although it was found that research in this area was rather limited. The focus was on energy saving potential, and strengths and weaknesses of each control typology.

Discussion and conclusions

The review indicated that up to 60% of the final electricity consumption in commercial buildings is attributable to lighting. The savings potential is high, although it varies widely according to building type, function and other factors. Due to the risk of rebound effect, energy saving measures should entail some training for the occupants or a feedback system. Also, the lighting retrofit should be supplemented by additional improvements to the building envelope, since electric lighting reductions normally yield an increase in heating demand. Finally, it was found that the energy savings from different strategies combined are normally lower than the simple sum of savings separately provided by each strategy.

Potential energy savings for LCSs are difficult to predict, since they depend on the context and building type. However, one finding is that simulation studies generally overestimate the savings, especially with advanced technologies. The review also indicated that manual controls might achieve both unexpectedly high energy savings and occupant satisfaction, especially in individual spaces. Nevertheless, the potential for energy savings

is difficult to predict with any level of precision, which yields problems for the planning and financing stage of any project.

Occupancy strategies offer an interesting savings potential, especially in rarely occupied spaces. The technology is fairly reliable and quite well accepted in common practice. The switch-off time delay is an important variable in the system design and it should always be kept below 20 minutes to avoid unnecessary waste, but over seven minutes to prevent dissatisfaction and sabotage. One very important variable is the detection setting, i.e. presence or absence, but very few studies have addressed this question. In general, presence detection appears to be profitable in large, irregularly occupied spaces, while absence detection is somehow more appropriate for smaller rooms such as individual office rooms.

Finally, the review indicated that DHSs promise very high energy savings of up to 93%. However, many field studies report failures with DHS and user complaints. In particular, several documents highlighted difficulties in designing and commissioning the DHSs, as well as issues with the controller devices (photosensors and micro-controllers). Also, a high rate of user dissatisfaction has been reported with these systems.

Lighting Control Systems – Conclusions at a glance

- LCSs present a high energy saving potential, but the savings are difficult to estimate in practice, which yields difficulties when planning and financing the retrofit projects.
- Presence and absence detection is often named under the overarching category 'occupancy strategies' in the literature, which needs to be specified since each technology yields specific energy-saving results.
- DHSs are very promising in terms of energy savings, but present significant design and commissioning issues.
- Manual controls are generally preferred over automatic ones.

Paper II – Design recommendations for DHSs

Goals

One of the main outcomes from Paper I was that daylight harvesting systems (DHS) need proper design and commissioning, which is rarely carried out in practice. A better understanding of DHSs was needed and motivated a literature review on the subject. This literature review focused mainly on design and commissioning aspects with the aim to propose some recommendations for DHSs installations.

Methods

The review was based on the following key words: 'daylight harvesting', 'daylight linked', 'photoelectric dimming', 'photoelectric sensor' and 'photosensor'. The search was limited to published literature between 1995 and 2015, although some older publications on this topic were also included. The focus was on peer-reviewed articles found by searching databases such as ISI Web of Knowledge, Scopus, IEEE Xplore and ScienceDirect. A few conference papers were also included.

About 150 articles were selected based on their abstract. These were further scrutinized and 57 articles were finally selected. The papers were organized in different clusters: articles with information on the energy-saving potential, articles with technical guidance on photosensors and light fixtures, articles with architectural recommendations, and articles on user assessments.

Discussion and conclusions

The energy saving potential of DHSs varies widely according to the space function, climate, illuminance threshold, operation hours, proper commissioning, and saving calculation baseline. Generally, the energy saving potential lies between 20% and 60%.

The DHS design should take into account three aspects: technical robustness, architectural integration and human acceptance. At the moment, technical problems with DHSs are rather minor, although some commercial devices present a lower standard. Nevertheless, due to lack of knowledge among designers and practitioners, the real installations do not always perform as anticipated. This is often due to architectural and user-related issues, which can be solved through appropriate training of professionals and users. The review concludes with a proposal for a flow chart to support practitioners during the initial design of a DHS. It is a five-step procedure, comprising: 1) space evaluation, 2) design of the system, 3) choice of the components (commercial availability), 4) payback calculation (economic feasibility), and 5) monitoring and verification.

Given the intrinsic complexity of DHSs, recommendations are provided. For example, DHSs should only be used in suitable spaces and with proper design and commissioning. The use of cheap DHS in individual offices, small spaces or rarely occupied rooms is strongly discouraged, as the standby energy losses over the year might be significant in relation to the energy savings. The importance of always installing DHSs with manual controls or override is also outlined at the end of the review.

Lighting Control Systems – Conclusions at a glance

- DHS saving potential lies between 20-60%.
- Design and commissioning of DHS should entail three aspects: technical, architectural and human.
- The rate of occupancy is an important variable, since the standby losses over the energy for illumination might be significant due to the control system devices.
- DHS should be used in large indoor spaces and supplemented with manual controls (override).
- DHS design, commissioning and installations require expertise.

4.2.2 Field studies

Paper III – Winter study in individual office rooms

Goals

The aim of the study was to investigate the general performance of some common LCSs in terms of energy use and user acceptance, in the context of a field study.

Methods

Four individual office rooms with identical geometry and similar daylight conditions were equipped with four different LCSs:

1. Presence detection,
2. Absence detection,
3. DHSs with presence detection,
4. Dimmable task lamp and no general or ambient lighting.

The installation was commissioned to a reliable local lighting company. The rooms were occupied by employees who rotated between the four rooms every week over a one-month period. In this way, each occupant tested each LCS for one whole week. At the end of each week, the occupants filled a self-reported diary developed by Maleetipwan-Matsson et al. (Maleetipwan-Mattsson et al., 2013). During the day, the occupants also completed a table where they indicated the position of the roller blinds. A data logger recorded indoor and outdoor horizontal illuminances, as well as energy consumption.

Discussion and conclusions

The main idea behind this study was to investigate the performance of some LCSs in an uncontrolled, real-life setting. The results were not as

anticipated. For the DHS, some severe malfunctioning occurred. The system was installed by a reliable lighting company, which was later asked to solve the problem. This experience showed that the installer had neither knowledge of the product nor instruments for the calibration. Consequently, the system did not match the target illuminance during the period of monitoring and task area illuminance fluctuated greatly. In addition, the diaries from occupants indicated general dissatisfaction with the DHS. They considered the electric lighting to be generally glaring, tiring and distractive. The presence detection connected to the DHS resulted in energy wastage, since lights were turned on even when not needed. This system achieved just 6% energy savings compared to the most energy-intensive system, which in this study turned out to be the presence detection system.

Another important result was that the two occupancy strategies – presence and absence detection – resulted in very different energy savings. The presence detection was highly wasteful in terms of energy use, since lights were turned on even when sufficient daylight was present in the space. These systems were also perceived as stressful for the occupants for the same reason. On the other hand, the absence detection used 33% less energy compared to the presence detection, and it was highly appreciated by the occupants. The occupants' complaints about the presence detection system were very similar to those expressed in the case of the DHS, and they expressed most dissatisfaction about not having control over the lighting situation.

Finally, it should also be mentioned that the task lamp option (without general lighting) was rejected by the occupants, since light levels in the room were unacceptably low. The occupants complained of insufficient light levels especially at the beginning and end of the day, despite the good daylight architecture of the rooms. Nevertheless, the occupants did like the possibility of controlling the light, and stated that during spring and summer time, it might be possible to use this system successfully. Note that the task lamp performed well in terms of energy use, since it saved 95% energy compared to the presence detection.

LCSs – Conclusions at a glance

- Presence and absence detection yielded very different energy performances.
- Absence detection achieved the best energy and user acceptance performance.
- Automatic controls were usually disliked by users.
- Manual controls were preferred by the users.

- The DHS was not properly installed by the company hired for this purpose, and the installer lacked the knowledge or equipment to calibrate the system.
- Task lighting with no complementary general or ambient lighting does not provide sufficient light levels during the winter at this high latitude, even for computer-based tasks.

Papers IV, V – Spring study in individual office rooms

Goals

Based on the results of Paper III, a second field study was performed during the spring season. The experimental design was slightly improved, while keeping the same study aim, i.e. to investigate the general performance in terms of energy use and user acceptance of some common LCSs, in the context of a field study.

Methods

Four individual office rooms with identical geometry and similar daylight conditions were equipped with four LCSs:

1. Presence detection,
2. Absence detection,
3. Daylight harvesting with absence detection this time,
4. Dimmable task lamp with no general or ambient lighting.

Four employees tested each LCS for a two-week period, so the monitoring lasted two months in this case. In contrast to the winter study, the employees worked in the same room for the whole two months while the LCSs were rotated every second week. This way, external dissatisfaction factors, such as discomfort with the new office environment, were excluded.

Following some complaints about false-off in the previous study, the switch-off delay for systems 1, 2 and 3 was extended to 15 minutes. The DHS was also combined with an absence detection this time, since the winter study identified the presence detection as one of the reasons for high energy use and dissatisfaction. The lamps' microcontroller, which did not function well in the winter study, was changed and a proper calibration was performed by the authors. The task lamp was tested again, as some occupants suggested that it might have worked well during the spring season when daylight is available for a longer period of time during the day.

The self-reported diary was replaced by semi-structured interviews despite a small occupant sample. Research shows that, although semi-structured interviews are time-consuming, they might lead to information saturation with even fewer than six subjects, especially if these are field

experts (Guest et al., 2006). Additionally, the objective data collection was supplemented by the logging of occupants' presence in each room.

Discussion and conclusions

This study showed that the presence detection system was the most energy intensive LCS over the two-month period. In comparison, the absence detection achieved 75% energy savings, the DHS resulted in 79% energy savings while the task lamp obtained 97% savings. In terms of both energy use and user acceptance, the presence and absence detection showed the same results as the previous winter study, i.e. the presence detection system yielded dissatisfaction while the absence detection system yielded satisfaction from the users' side.

The DHS worked properly and it could actually maintain the target illuminance during most of the time. This indicates that the system itself might work as anticipated, provided that the design and commissioning are perfect. However, a closer look at the energy data of the DHS indicated that most of the energy use was attributable to standby losses (around 80% of the total energy used). This was due to the more complex sensing device (photosensor and microcontroller), which ran on higher power. Considering that these systems are difficult to commission, the extent to which complex lighting controls are advisable is debatable, especially with the introduction of highly efficient light sources, such as LED. Indeed, the efforts in saving energy for illumination might be spoiled by the parasitic consumption of the auxiliary devices.

Besides the technical aspects, the DHS was liked by the occupants in this case, for two main reasons: the lighting environment was appropriate and the occupant could control the lighting status (on/off) through a manual control. Note that these findings are in line with previous results in this field (Granderson et al., 2010).

The study showed that, even in this spring case, the task lamp could not provide a satisfactory light environment, despite the good daylight availability. Consequently, this solution is not recommended at high latitudes.

LCSs – Conclusions at a glance

- Presence and absence detection yielded very different energy performances.
- The standby losses with complex LCSs might be significant in relation to total energy use.
- DHSs can function well when properly designed and commissioned, yielding both energy savings and occupants' acceptance.
- LCS must include some manual control (override).

- Task lamp without general or ambient lighting cannot guarantee sufficiently high light levels at high latitudes even in a well daylit individual office room during the winter and spring.

4.3 Other related papers

Other research activities on lighting were performed during the doctoral studies. They resulted in peripheral publications, which are not strictly related to LCSs, and they were not appended. Nevertheless, they provided some additional information indirectly related to the topic of LCSs. The following is a brief summary of these papers and the conclusions at a glance that are relevant for LCSs.

Paper VI - Test of two different lighting concepts in high schools

The study concerned the pupils' psychological and biological response to different lighting settings in real-life classrooms, which also included the evaluation of the energy saving potential. The referenced paper presents some preliminary results, while a more comprehensive document is in the submission phase.

A state-of-the-art fluorescent T5 light system with direct/indirect light distribution was compared to a prototype of fully indirect LED light fixtures. Both installations were designed with a DHS, which dimmed the fixtures closest to the sidelit windows. The DHS was installed with the dual purpose of a) saving energy and b) reducing the risk of glare due to the combination of electric lighting and daylighting. The lighting installations also presented a scene-setting control system, i.e. possibility to use part of the lighting during specific activities (for example only half of the fixtures on if a projector is in use), which was not directly aimed at energy conservation.

LCSs – Conclusions at a glance

- DHS significantly reduced the perceived glare from electric lighting on the students' desks.
- The scene setting was very much used, but this kind of lighting control has no energy saving purposes.
- Due to the low occupancy rate of the rooms and the advanced lighting installations, the standby losses represented a significant portion of total energy use.
- As the energy spent for illumination was rather low, the DHS achieved only 1% energy savings compared to the same system with no dimming.

Paper VII - Monitoring protocol for the evaluation of lighting retrofit

This work aims to create a common methodological framework for the evaluation of lighting retrofit in non-residential indoor spaces. The protocol was developed as part of the activities of IEA-SHC Task 50 'Advanced lighting solutions for retrofitting buildings' - Subtask D 'Case studies'. One of the Subtask duties was to show some exemplary daylighting and electric lighting retrofits from around the world. Those examples were to be monitored and presented within a common layout for easier reading, comprehension and comparison.

The protocol is structured as a five-step procedure: initial visit survey, decision phase, preparatory phase, monitoring process and analysis phase. The monitoring process takes into account four items: energy, costs, photometry and users. In particular, for the user assessment, the protocol considers interviews and a questionnaire. The latter includes six questions on lighting controls. The questions are quite general as the questionnaire should be applied to different cases.

After intense collaborative work to develop the monitoring protocol, a first draft of the protocol was edited. The application of the monitoring protocol for several case studies around the world was then initiated. The monitoring campaign, which is still ongoing, is providing information on strengths and weaknesses of different lighting retrofit solutions. The conclusions reported here refer to some of the ongoing case studies where the protocol has been applied, rather than to the document itself.

LCSs – Conclusions at a glance

From the majority of the case studies where the protocol has been applied:

- It is difficult to define the payback period of LCSs

Indeed, most of the lighting retrofits have been achieved in the context of larger refurbishments, including furniture, architecture, and ventilation. Usually, the client has a complete picture of the refurbishment costs, but cannot really identify the share assigned to lighting. In such a context, it is even harder to identify a) the costs of the sole LCSs rather than the complete installation, and b) the savings specifically attributable to the LCSs.

From a specific case study of an open-plan office:

- Presence detection is not an appropriate strategy for individual desks.
- Installers and occupants are often unaware of the way LCSs function.
- Manual dimmers need proper interface design and/or user training to be correctly used.

The office workstations were retrofitted with T5 ceiling pendants over the desks. The workstations were gathered in groups of four desks with a fixture on top of each desk. Each fixture had a built-in occupancy detector and a manual dimmer (actionable through a hanging rope). The installers set all the fixtures on presence detection with a 20-minute switch-off delay. In the interview and questionnaires, the users complained that the lighting was always on and that the illumination was very different from desk to desk. Indeed, the presence detection had a wide field of view, so that even if a single employee was working in one of the four-desk groups, the four light fixtures were turned on. Sometimes, the fixtures switched on when a person was just passing by.

In addition, some of the fixtures were slightly dimmed, which justified the reported differences in illumination. Further inquiry revealed that the hanging rope from the fixture would switch lighting on or off with a sharp tug (overcoming the presence detection), while the rope would dim the light if it was pulled gradually. Many employees dimmed by mistake and said they did not realize how the mechanism worked, so they were unable to return to the original setting.

5 General discussions

5.1 Main findings

Although very promising according to simulation results, advanced LCSs might not perform correctly in real-life installations

Advanced LCSs might be very efficient, but this research indicates that they are not yet reliable unless an expert installer is involved and proper commissioning is performed. The introduction of a multitude of sensing devices requires additional design and installation skills, which are often lacking in real-life projects. This may partly explain why simulation studies, which assume that the system is working as supposed, generally overestimate performance.

In addition, advanced LCSs generally require higher maintenance. For example, even a well-designed DHS, correctly positioned, installed and calibrated, will work well only if the space layout is kept the same. If changes occur in furnishing, colors, etc, i.e. changes in the reflectance of surfaces, the calibration needs to be adjusted, which requires involving an expert. Recently, studies on feedback systems for self-calibration in sensor networks have appeared (Pandharipande et al., 2014; Wang and Dasgupta, 2015), but the research is still at an early stage.

Advanced LCSs currently show a technical complexity that translates into complexity on the designer and user side. Work to develop technically advanced controls with easy installation and user-friendly interface is needed.

Presence and absence detection should be distinguished

Occupancy strategies have been promoted in building codes for a long time, but a clear distinction between presence and absence detection has only appeared in the past 2-3 years, see e.g. (ASHRAE, 2013; CEN, 2015). The review has shown that research has focused mainly on switch-off time delay and reduction of false-off. Nevertheless, the field studies in individual office rooms highlighted substantial differences between the two occupancy strategies, with higher energy savings and user acceptance for the absence detection system. These results are only valid in individual office rooms.

Shared spaces, where the switches are not easily reachable and the responsibility over the light environment is not on a single occupant's shoulders, could probably work better with presence sensors, but this remains to be demonstrated. Further research is needed to identify the key parameters and to provide a decision tool.

The losses for standby energy losses with complex LCSs might be significant in relation to total energy use

A review on energy efficiency of information and communication technologies by Koomey et al. (Koomey et al., 2013) expressed energy use of low-energy computing in terms of power used during active task time, active power, standby power and transition time. Similarly, the power use of the lighting system can be expressed as a combination of power for illumination and standby power (Figure 5.1). Practitioners are very much used to thinking in terms of power. In the US, for example, a maximum Lighting Power Density (LPD, W/m2) is expressed as a requirement in the building code (ASHRAE, 2013). However, the electricity bills are paid as total energy use [kWh]. The energy used for lighting is represented by the colored area in Figure 5.1. The aim of a lighting control system should be to reduce the energy use, rather than the power installed. This could be achieved in different ways, such as by i) reducing the power for illumination, ii) minimizing the occurrences of active task time, or iii) reducing the standby power.

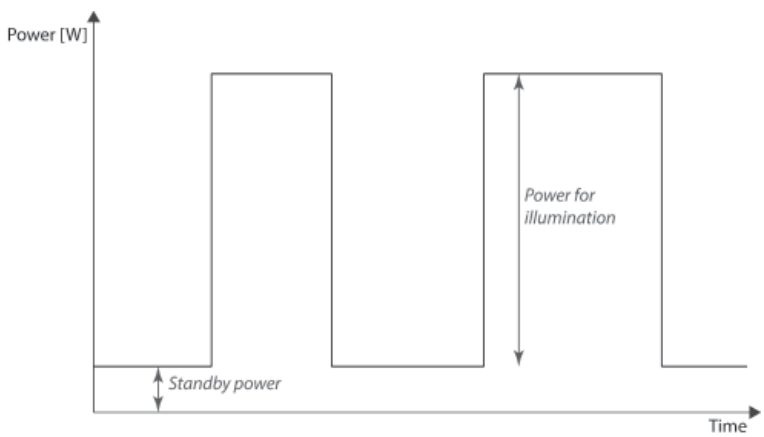

Figure 5.1 Power absorbed [W] for lighting, i.e. standby plus illumination

Traditionally, a LCS is operated i) by dimming the light source, or ii) through occupancy detection or photoelectric dimming. This implies the

installation of additional sensing devices that increase the standby power. With the introduction of very efficient light sources, such as light-emitting diodes, the power required for illumination will be substantially reduced. On the other hand, more sophisticated LCSs will increase the standby power. The final achievable saving with LCSs will largely depend on the occurrence of power for illumination. For example, a space that is often occupied will probably require more switch-on time and occurrences, making the harvesting of energy through advanced LCSs advantageous.

The occupancy of the space therefore becomes a fundamental variable in the choice of LCS. The attached studies reported occupancy rate as low as 10% of the total time in school classrooms (Govén et al., 2014) and 40% of the working time, i.e. roughly 8% of the total time (24/7), for individual office rooms (Gentile et al., 2015b). These values are in line with results obtained by researchers in other countries (Chang and Hong, 2013; Duarte et al., 2013).

Manual controls are preferred by users

The field studies showed that higher user acceptance is obtained for systems with manual controls. It was expected, though not verified, that low acceptances would trigger system deactivation or sabotage, which has been previously suggested by other studies (Cunill et al., 2007; Howlett et al., 2006). On the other hand, some automatic features will contribute to energy savings. For example, in the appended field studies, an absence sensor worked as planned, switched lights off, and thereby compensated for users forgetting to switch lights off (Gentile et al., 2015b, 2014; Gentile et al., 2013). Other LCSs could combine daylight harvesting for the general lighting with manual controls for the task or private lighting (Granderson et al., 2010). Escuyer and Fontoynont (2001) claimed that automatic dimming with manual illuminance threshold setting and task lighting would represent an optimal solution. In general, it appears that any kind of automatic system might be accepted as long as a partial manual control or a manual override is provided.

Designers and installers need training

The position of sensors, the knowledge of their optical characteristics, the programming of controllers, the system calibration, the knowledge of networks, etc. are notions that do not traditionally belong to designers' and installers' knowhow. Several published studies, including a field investigation appended to this thesis, highlighted the lack of knowledge among practitioners, which is the main reason for system failures. The training of designers and installers needs to be improved in the short term if we are to achieve the energy saving targets of current policies.

5.2 Optimal controls for fast retrofit

The appended review on energy efficient lighting retrofit reported the potential energy savings for different LCSs (Dubois et al., 2015)which covers around 160 research articles, addresses the following themes: 1. In particular:

- Manual controls: generally 23-77%, though unpredictable
- Occupancy strategies: 20-93%, largely conditioned by occupancy patterns and switch-off delay
- Daylight harvesting: 10-93%, with huge variation depending on design and commissioning

In the theoretical framework, a hypothetic efficiency versus complexity curve (Figure 5.2) was proposed. In this figure, manual controls might be located in the lower part of the curve, as they offer relatively moderate energy savings with little complexity. Occupancy strategies are certainly located somewhere before the inflection point. The energy saving potential is high, though variable, and the technology is pretty mature. In comparison, DHSs are located somewhere close to the inflection point. While their saving potential is established by previous research, DHSs are exposed to the risk of failures because of technical, architectural and human-related factors (Gentile et al., 2015a).

Besides the technical efficiency, this thesis has highlighted that user acceptance plays a fundamental role in the energy performance of LCSs. LCSs that are completely manual might also save energy as shown by (Maleetipwan-Mattsson and Laike, 2015), but the savings are unpredictable, since users have very different individual preferences and attitudes toward lighting (Boyce et al., 2006, 2000; Newsham et al., 2008). Automatic controls perform very well in simulation and laboratory settings but, due to design issues, they often fail (Gentile et al., 2013) or are deactivated because of the low acceptance (Howlett et al., 2006). As a consequence, a correct balance seems to be an automatic system with a certain degree of manual control or even with a manual override (Granderson et al., 2010; Maleetipwan-Mattsson and Laike, 2015). For example, an open plan office might be designed with a DHS system for the general lighting, plus individual manual control – maybe with absence detection – for the individual workstation lighting, as suggested by (Parise and Martirano, 2011).

In December 2014, the Subtask C 'Method and tools' of IEA Task 50 'Advanced lighting solutions for retrofitting buildings' distributed an international online survey about lighting retrofitting in practice. Up to summer 2015, over 1000 lighting practitioners from around the world

had completed the survey. The respondents were involved in lighting retrofit in many different ways, and included designers, engineers, academic, and installers. A section of the questionnaire considered the main retrofit strategies used in their current practice. The results are shown in Figure 5.2

Although the strategies do not just involve the adoption of LCSs, the most cited choice was the use of switch-off occupancy sensors. It should be mentioned that, while the survey proposed only the switch-off option, practitioners tend to confuse presence and absence strategies.

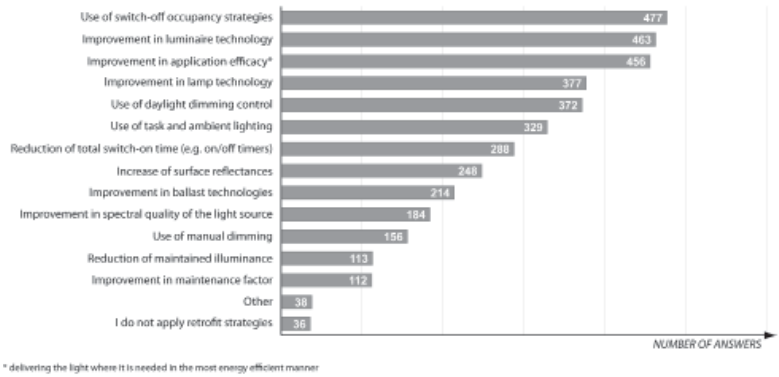

Figure 5.2 *Main retrofit strategies used by lighting practitioners (source: IEA-SHC Task 50 Subtask C)*

Other strategies based on lighting controls are also popular: daylight harvesting, use of timers or use of manual dimmers. This figure suggests that the use of LCSs is popular among practitioners, but also that the adoption of occupancy strategies are still a preferred option in lighting retrofits. A clearer distinction of presence and absence settings would therefore be beneficial for achieving savings in the short term.

6 Conclusions

This Licentiate thesis aimed to collect information on state-of-art technologies in the field of LCSs through scientific reviews, field studies and case studies. In view of the urgency to reduce energy use in buildings at a low cost, the knowledge gained through this thesis leads to the general conclusions that LCSs with reliable energy saving potential and good acceptance should be recommended. Attention should be paid to the role of standby losses, especially when using a number of sensors and high-efficiency light sources. Given the spread of occupancy strategies among practitioners, these might be appropriate solutions.

In the long term, it is expected that advanced LCSs, especially systems based on wireless networks and integrated in the Building Management System, will become more reliable and efficient. They will most likely spread in the market. This will require greater skills and competence on behalf of the designers and installers and it will bring the tempting risk of full automation of lighting. Resources should be allocated to training designers and installers to the coming technologies, with emphasis on the importance of understanding the system's functions and calibration and the need for manual control over lighting on the user side.

7 Future work

There is general confusion about distinguishing between presence and absence strategies, which are commonly considered under the overarching category 'occupancy strategies'. This thesis emphasized that these systems yield different outcomes in terms of energy performance and user satisfaction. The optimal strategy for any space depends on many parameters, such as the occupancy patterns, the space function, and the energy requirements of the lighting system.

Some avenues for future research in this area are:

- Multi-criteria model to support LCS selection according to space.
- Further testing and development of the most promising LCS for other types of spaces through experiments.

Sammanfattning

Belysning står för en femtedel av den globala elanvändningen. I Sverige motsvarar efterfrågan på energi för belysning i kontorsbyggnader 20% av den totala elanvändningen.
Utbyte av gamla belysningsanläggningar anses vara bland de mest kostnadseffektiva sätten att minska energianvändningen i byggnader. I synnerhet utlovar användningen av avancerade ljusstyrningssystem energibesparingar på mellan 2 och 60%, men systemfel och låg användaracceptans har hittills begränsat besparingsmöjligheterna.

Denna avhandling har genom litteratur- och fältstudier undersökt effekten av ljusstyrningssystem på energianvändning och användaracceptans. I den första delen av avhandlingen visar en litteraturgenomgång på ljusstyrningssystem att manuellt styrda system är i allmänhet mer accepterade av användarna. System med hög automatisering och utan möjlighet till manuell omställning tenderar att deaktiveras eller saboteras. Därför spelar användarbeteendet en avgörande roll för att säkerställa god funktion och faktisk energibesparing av ljusstyrningssystem. Genomgången visar också att närvaro- och frånvarostyrning ofta förs samman under en övergripande kategori kallad ”brukarstrategi”, även om de gav mycket olika energibesparing. Genomgången av dagsljuskontrollsystem framhäver kritiska frågor rörande design och drift.

Två fältstudier i cellkontor genomfördes. Frånvaro- och närvarodetektering, dagsljusstyrning och enbart platsbelysning testades i en verklig arbetsmiljö, där energianvändning och användaracceptans undersöktes. Studierna visar att definitionen ”brukarstrategi” inte är helt lämplig eftersom frånvaro- och närvarodetektering uppvisar olika energibesparing och användaracceptans. Den andra fältstudien visar att dagsljusstyrningssystem kan fungera bra under förutsättning att noggrann design och drift genomförs tillsammans med möjligheten till manuell styrning. Fältstudien visar emellertid att användningen av sensorer och mikro-kontroller ökade energianvändningen för parasitisk ström (standby), vilket kan vara viktigt i relation till slutlig energianvändning, speciellt i miljöer med låg närvaro och högeffektiva ljuskällor.

Ljusstyrningssystem som bygger på trådlösa nätverk och integrering i byggnadens totala styrsystem väntas öka under de kommande åren. Detta kommer att hantera många av de aktuella frågor som tagit upp här med avancerade ljusstyrningssystem, men det kommer också att ställa krav på ytterligare kompetens hos ansvariga designers och installatörer. Under tiden är brukarstrategier ett bra alternativ som ersättning för gamla belysningssystem för att erhålla energieffektiv belysning.

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