Lighting Control Systems to Save Energy in the non-Residential Sector

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Lighting Control Systems to Save Energy in the non-Residential Sector

State-of-the-art, Field Studies, and Simulations

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Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
Faculty of Engineering LTH, 2017

Report EBD-T--17/21

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.

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Niko Gentile

Doctoral Thesis

Keywords

Indoor lighting, lighting control system, lighting control, energy saving, energy efficiency, user acceptance, degree of acceptance, human factor, occupancy strategy, presence strategy, absence strategy, daylight harvesting, daylight-linked, daylight, photoelectric dimming, photosensor, manual switch, functional illumination, standby.

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Abstract

This thesis examines the energy-saving potential for lighting when using traditional indoor LCSs in non-residential buildings. In the study, an overarching theoretical framework is used that distinguishes between energy efficiency and energy saving, as well as between energy use for lighting and functional illumination. This framework also includes the hypothesis that user acceptance is a determinant of energy saving for lighting, so an examination of the user role is included in the thesis.

In the first part of the research, a literature review explores technical and non-technical issues relating to lighting control systems. The review concludes that the energy-saving potential of LCSs lies between 10-93% compared to no lighting control. In general, simulation studies overestimate the savings compared with field studies, possibly because of design, commissioning and installation issues in real-life scenarios. Properly working systems need some degree of manual control or override to improve acceptance, while malfunctioning systems lead to very low levels of acceptance and are apparently subject to sabotage. To overcome such issues, the literature review also proposes a design workflow for the specific case of daylight harvesting systems.

The second part of the research includes field and case studies in real-life scenarios, which confirmed most of the literature review findings. The studies highlight that the overarching definition of 'occupancy strategies' may be misleading, whereas a clear semantic differentiation between 'presence' (automatic on-off) and 'absence' or 'vacancy' (automatic off) is needed, even in scientific publications. As an additional conclusion, the field studies showed a controversial role of auxiliary devices for advanced LCSs, since they may lead to high energy use for standby. In extreme cases, the standby may offset the gain from adoption of more efficient light sources.

The issue of standby is addressed in the third and final part of the thesis, consisting of simulations based on real occupancy data in individual office rooms. The simulations show that, at growing efficiency of light source, the additional savings afforded by LCSs become smaller. In such a situation, the standby may account for over 30% of the total energy use for lighting. Standby can be reduced or eliminated by choosing the right LCS, inte-

grating it in the Building Management System (BMS), and designing the electrical system so that the lighting system can be completely switched off.

To secure savings from LCSs through a high degree of user acceptance, the thesis concludes that proper training of specialists of LCS designs is required. Such specialists should be involved from, preferably, the early design stage of the BMS. Finally, proper budgets for monitoring and verification activities should be allocated, as this would allow timely tackling of project issues and iteratively add knowledge in the field.

Contents

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From the administrative staff in the Department of Architecture and Built Environment to the staff of the Division of Energy and Building Design and the Division of Environmental Psychology, the list of co-workers and colleagues who helped with different matters became extensive over these years. To those who left and to those who stayed, I can just say that I found sincere friends beyond fellow workers. I hope they can find my best thanks in the delight I showed when coming to the workplace every day.

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My work is often filled with grammar conditionals. I owe this careful approach to two very important people in my life. The first is my role model, Prof. Dario Ambrosini (University of L'Aquila), supervisor for

my MSc dissertation, who convinced me to replace all the 'certainly' words in the MSc dissertation with a more careful 'it seems to be', just few hours before the dissertation was printed. It took a couple of days to understand, but I owe a lifetime of thanks to him. The second is Giulia, my 'best-friend-forever' (her words), who once demolished me with a terse "never say 'obvious' again! It is the worst word in the dictionary. Nothing is obvious." She was so right. Years later, she transmuted from best-friend-forever to my lovely wife. To her, and to our adorable daughter Lucia, goes my final and biggest thank you.

Credits

Cover image, as well as Figures 2.4, 3.1, 3.3, 4.1 and 5.2 include design elements provided by www.freepik.com, www.vexels.com and www.flaticon.com. The design elements are distributed under CC-BY 3.0 license.

Figure 2.2, ‘Light Man’, 2017, has been specifically created for this thesis by Kevin Zanni.

List of publications

All articles are published in peer-reviewed journals or peer-reviewed conference proceedings.

Appended 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), pp. 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*, In Environment and Electrical Engineering (EEEIC), 2015 IEEE 15th International Conference on, Rome, IEEE Conferences Proceedings, 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*. In 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., 2016. Lighting control systems in individual offices rooms at high latitude: Measurements of electricity savings and occupants' satisfaction. *Solar Energy*, 127, pp. 113-123. doi: 10.1016/j.solener.2015.12.053

Paper V: Gentile, N., Goven, T. & Laike, T., 2016. A field study of fluorescent and LED classroom lighting. *Lighting Research and Technology*. doi: 10.1177/1477153516675911

Paper VI: Dubois, M. C., Gentile, N., Amorim, C. N. D., Osterhaus, W., Stoffer, S., Jakobiak, R., & Tetri, E. 2016. *Performance Evaluation of Lighting and Daylighting Retrofits: Results from*

IEA SHC Task 50. In Energy Procedia, 91, pp. 926-937. doi: 10.1016/j.egypro.2016.06.259

Paper VII: Gentile, N., Dubois, M.-C., 2017. Field data and simulations to estimate the role of standby energy use of lighting control systems in individual offices, *Energy and Buildings* (2017), in press. doi: 10.1016/J.enbuild. 2017.09.28.

The author's contribution to the appended publications

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

Paper II: The author carried out the review and wrote the article.

Paper III: The author designed the study. The author completed the equipment installation and technical aspects under the supervision of Håkan Håkansson. The author also collected and analysed the data, and wrote the article.

Paper IV: The author designed the study and he was responsible for equipment installation and technical aspects. The author collected and analysed the data, and interpreted the results. The author wrote the article.

Paper V: The study was designed by Thorbjörn Laike and Tommy Govén. The equipment was installed by Fagerhults Belysning AB. The biological samples were analysed under the supervision of Klas Sjöberg. The author collected and analysed the data, and he interpreted the results. The author wrote the article.

Paper VI: The author assessed the Swedish case studies. The author wrote the section on the monitoring protocol and the sections on the Swedish case studies. The editing of the paper was coordinated by Marie-Claude Dubois.

Paper VII: The author designed and performed the study, and he wrote the article.

Other publications by the author in the field of lighting

Gentile, N., Dubois, M.-C., Osterhaus, W., Stoffer, S., Amorim, C.N.D., Geisler-Moroder, D. & Jakobiak, R., 2016. A toolbox to evaluate non-residential lighting and daylighting retrofit in practice. *Energy and Buildings* 123, pp. 151-161. doi:10.1016/j.enbuild.2016.04.026

Pacheco Diéguez, A., Gentile, N., von Wachenfelt, H. & Dubois, M.-C., 2016. Daylight Utilization with Light Pipe in Farm Animal Production: A Simulation Approach. *Journal of Daylighting* 3, pp. 1-11. doi:10.15627/jd.2016.1

Von Wachenfelt, H., Vakouli, V., Pacheco Diéguez, A., Gentile, N., Dubois, M.-C. & Jeppsson, K.-H., 2015. Lighting Energy Saving with Light Pipe in Farm Animal Production. *Journal of Daylighting* 2, pp. 21-31. doi:10.15627/jd.2015.5

1 Introduction

In recent decades, global electricity use has increased at an alarming rate, by as much as 20% between 2000 and 2013 according to the IEA (2014; 2016). In the European Union, 48% of electricity is produced from fossil fuels, and 27% from nuclear energy (Eurostat, 2016b). Despite the economic crisis, European electricity prices grew by around 10% between 2008 and 2016 (Eurostat, 2016a), and further increases are expected due to the uncertainty around future oil prices (European Parliament, 2008). There are strong environmental and economic reasons to implement energy conservation measures, to prevent catastrophic environmental impacts as well as economic instability.

Among energy conservation measures, the area of electric lighting offers considerable potential for savings. Global electricity use for lighting was about 2000 TWh in 2013, which represented 20% of global electricity use. According to CISBE (2015), about 75% of all indoor lighting installations in developed countries are outdated with respect to current technological standards and know-how. Lighting retrofit is seen as one of the most promising energy conservation measures. Studies have shown that investments in lighting retrofit are amongst the most cost-effective energy conservation measures (Enkvist et al., 2010; IEA, 2015). Considering the foreseen 47-55% lighting cost reduction predicted in the next two decades due to technological advances (solid-state lighting), this strategy is expected to be consolidated in the future (IEA, 2015).

Within the area of energy-efficient lighting retrofit, the implementation of advanced lighting control systems (LCSs) offers considerable energy saving potential. LCSs consist of two units: a sensor, controller and actuator unit, and an illuminating unit (DiLouie, 2007). Both elements are currently undergoing rapid development. On the sensing and actuation side, a rapid increase of interconnectivity of gears at building level is currently observed. Wireless communications of sensors and actuators (Baronti et al., 2007) in connection to the Internet of Things (Gubbi et al., 2013), or recent advances in Visible-Light Communication (VLC) through LED lighting (Zhou et al., 2012; Komine and Nakagawa, 2004) offer considerable potential for the development of LCSs. On the illumination side, the market growth of solid-state lighting is completely changing the field. Besides energy-efficiency, solid-state lighting may provide high quality lighting and flexibility in colour and light distribution (Pust et al., 2015; Nobel Media AB 2014, 2015), and offer other interesting advantages, such as the implementation of VLC (Warmerdam et al., 2016).

While there is little doubt that LCSs are attracting the interest of the scientific community and lighting industry, their market penetration is still quite slow, since building owners are reluctant to deal with the complexities of these systems (Zografakis et al., 2012). One of the barriers to rapid market penetration is uncertainty regarding the achievable energy savings, which generally lie between 30 and 40% (Williams et al., 2012), with a high rate of failure (Bellia et al., 2016). This leads to uncertainty regarding the payback time for the investments. Generally, investments that cannot be calculated with precision at the design stage are more difficult to implement, as it is more difficult to convince decision makers about these investments early in the design process (ETUI, 2015). Other barriers are related to the design process and commissioning of these systems. At the moment, it is difficult to tackle the complexity of LCSs at the design stage, while simultaneously solving other complex issues such as the building envelope, the shading device properties and operation, the overall electric lighting design, and the overall building and interior design (Dubois, 2017). LCSs also need to be commissioned properly once installed and there is usually no budget for this in the project or no professional responsible for the task (Dubois, 2017).

Several reasons may explain the wide range of projected energy savings attributable to LCSs, but building type and configuration, occupancy pattern, occupant behaviour, and design and commissioning are crucial aspects (Galasiu & Veitch, 2006; Escuyer & Fontoynont, 2001). To estimate the effect of these aspects, Williams et al. (2012) performed a meta-analysis on reported savings from 88 research articles and case studies about LCSs. They found, for instance, that simulations overestimated energy savings compared to actual installations. In the case of daylight harvesting systems (DHSs), they reported average energy savings of 48% for simulations and 28% for actual installations. In some cases, controls were deactivated by the users (Heschong Mahone Group, 2006), while in others, the systems were not properly installed or calibrated (Gentile et al., 2013; Dubois & Gentile, 2016a).

Most of the newer solutions provide technical innovations, for example technologies that achieve a stable and custom illumination on the work plane (Tan et al., 2017), or reductions in the false-off occurrences for occupancy sensors (Nagy et al., 2015; Dikel & Newsham, 2014). This will help improve user acceptance of the systems and, consequently, minimize misuse or sabotage, thereby making the energy savings more robust and predictable. However, these advanced technologies bring two additional issues:

- Over time, designs and installations become increasingly complex and designers and installers are not always trained to manage the complexity of the systems.
- With increasing luminous efficacy of LEDs and good daylighting design, additional savings on electric lighting by complex LCSs become marginal in relation to the total cost of lighting. Moreover, gears might require additional (standby) power that can jeopardize the savings, which is the focus of this thesis.

1.1 Aim

This thesis contributes to measures supporting the current target of the Swedish Energy Agency to reduce electricity use for lighting by 6 TWh by 2020 (Swedish Energy Agency, 2011), as well as the Ministry of the Environment and Energy commitment in the Global Lighting Challenge, GLC (Regeringskansliet, 2016).

Given this context, the aim of this thesis is to provide a critical overview and review of existing LCSs, emphasizing their energy-saving potential in relation to users' acceptance. The thesis includes literature reviews, field studies, and simulation studies. The thesis provides information regarding the extent and conditions that are necessary for LCSs to provide both the required energy savings and user acceptance.

The thesis considers only existing technologies and focuses on the non-residential building stock. The scope of the work is limited to small spaces, such as individual office rooms, although one large classroom and one landscape office are included in the field study investigations.

1.2 Research question

Based on the overall aim of this thesis, and given the outcomes of the first part of this PhD research (Gentile, 2015), the main research question can be formulated as follows:

- What are the main determinants of energy savings for lighting using LCSs?

This leads to the following related questions:

- Which are the most commonly used LCSs and how do they function?
- What is energy saving for lighting?
- What is the role of the user in achieving energy savings for lighting?
- What is the role of system automation in achieving energy saving for lighting?
- How does the energy saving for lighting from LCSs vary when the demand for energy for illumination decreases?

1.3 Hypotheses

The main hypotheses are:

- Simple LCSs, with partial manual control, can achieve high savings while fostering user acceptance.
- An increased level of complexity and automation leads to an increased risk of system failure and decreased user acceptance.
- When good daylight design is provided and very efficient light sources are used, the additional savings from LCSs are marginal.

1.4 Limitations

Due to the experimental design, this work has a number of limitations:

- The field studies were carried out in individual office rooms and school classrooms located in Sweden. The findings might not be applicable to other space typologies or geographical areas.
- The simulation study is based on real occupancy data of individual office rooms, which were occupied by teachers, administrative staff and doctoral students. Most of the staff is employed full-time, but given the nature of the work with typically low occupancy rate, the results might not be generalizable to other contexts or professions.
- Overall, the work investigates LCSs independently from other building systems. The lighting management system is considered as autonomous with respect to the Building Management System (BMS). Some of the

conclusions might not be appropriate for BMS where a single sensor may provide input to several building services, e.g. lighting and ventilation.

1.5 Thesis structure

This doctoral thesis consists of a collection of scientific papers. It also includes knowledge gained in the context of IEA SHC Task 50, 'Advanced Lighting Solutions for Retrofitting Buildings' Subtask D 'Case Studies'.

The first section, entitled 'Lighting control systems for energy saving', provides an overview of the field, including its most recent developments.

The second section provides the theoretical framework used in the thesis.

The third section consists of a thesis outline, which provides summaries of the appended papers and describes the connections between them.

The final sections contain a general discussion and conclusions.

2 Lighting control systems for energy saving

Lighting control systems consist of four basic elements: a sensor, a controller, an actuator, and a light source (Figure 2.1)

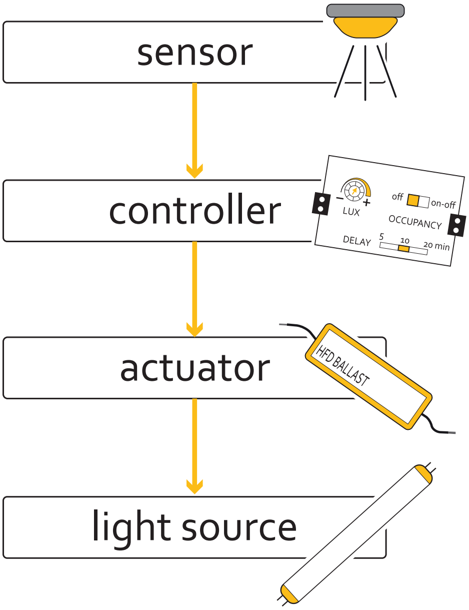

Figure 2.1 Main elements of a LCS

- The sensor detects environmental information, typically space occupancy or illuminance.
- The controller receives and elaborates the sensor inputs. The result is sent to the actuator.

- The actuator, usually a ballast or a LED driver, switches, dims or tunes the light source.
- The light source is the actual illuminating component.

Manual switch control is the simplest LCS. In such LCSs, the eye behaves as sensor, the brain as controller, and the hand and switches as actuators (Figure 2.2). More advanced LCSs have greater automation and may include several sensors, controllers, and actuators that drive several other actuators

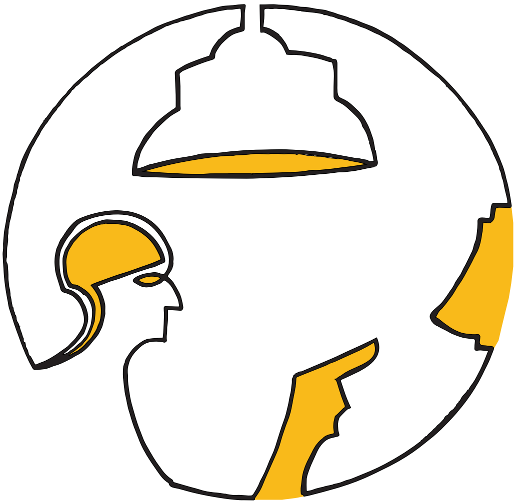

Figure 2.2 Manual switch control: the simplest LCS.

Based on such actions, lighting controls can be classified as in Figure 2.3.

Figure 2.3 Typology of LCSs

Research has focused on both energy-saving potential and users' acceptance of different LCSs solutions. The following sections provide a brief historical overview of research on LCSs.

2.1 Manual controls

Early research on LCSs investigated occupants' switch on-off occurrences, mainly in relation to daylighting. In spaces with more occupants, Hunt (1979a) and, later, Boyce (1980) and Andersson et al. (1987) found that the switch-on probability correlates with daylight levels, but not the switch-off; once switched on, the occupants tend to leave the lights on even with abundant daylight. Hunt (1980) developed a probabilistic switch on-off function and estimated that a forced switch-off at midday would greatly reduce electric lighting usage. Focusing on individual differences, Pigg et al. (1996) argued that two typologies of users can be observed: active and passive. An active user will tend to switch off the light when leaving the space, but a passive user will not bother about switching lights off when leaving the space. Similar findings were obtained in more recent field studies of manual switches and use of blinds in private offices (Reinhart & Voss, 2003; Boyce et al., 2006). These outcomes resulted in the Lightswitch-2002 model for private offices (Reinhart, 2004). This model provides probabilistic switching patterns of electric lighting, and is now used in simulation software such as Daysim (Reinhart & Breton, 2009).

When manual dimming is provided, people have different preferences in terms of preferred illuminance (Boyce et al., 2000), although they tend to choose lower illuminances if daylight is provided (Escuyer & Fontoynont, 2001). Individuals also seem to reduce the preferred illuminance when the maximum available illuminance and the initial value (or anchor point) of illuminance is lower (Logadottir et al., 2011). This may be translated into potential energy saving. For example, in a study conducted by Logadottír (Logadóttir, 2015), subjects starting with lights off dimmed the lights upwards and generally stopped at 193 lux (anchor point = 0 lux), while subjects starting from lights turned on (anchor point = 500 lux) dimmed down and generally dimmed to 455 lux on average. Consequently, the anchor point of 0 lux resulted in energy savings of more than 50%.

Other research on manual controls has focused on the switch interface design and its positioning to enhance the use of manual switches (Dugar & Donn, 2011; Dugar et al., 2011; Dugar et al., 2012; Yılmaz et al., 2015; Maniccia et al., 1999; Cılasun Kunduracı & Kazanasmaz, 2017), as switch accessibility seems to be a further driver for energy saving (Maleetipwan-Mattsson et al., 2016; Maleetipwan-Mattsson et al., 2017; Sadeghi et al., 2016).

The energy-saving potential of manual controls has not attracted much research attention, probably because they are the simplest LCS typology (Lowry, 2016). However, most occupants usually seem to be good energy savers (Moore et al., 2002a; Tzempelikos, 2010; Williams et al., 2012), although the provision of forced midday switch-off or an absence sensor may improve savings for passive users. Other architectural and design solutions regarding anchor point, position, and interface appearance may enhance savings of simple manual controls.

Finally, on the acceptability side, there is little debate on manual controls, as they are widely accepted by users (Moore et al., 2002b; Moore et al., 2004; Escuyer & Fontoynont, 2001).

2.2 Occupancy strategies

According to Hunt's findings, a forced switch-off at midday would greatly reduce the energy demand for lighting (Hunt, 1980). Several more recent studies focused on the implementation and improvement of occupancy strategies.

Occupancy strategies can be based on time scheduling, e.g. lights always off during night time, or using an occupancy detection that actuates the on-off switch for the lighting. Time scheduling can save energy during non-working hours, while occupancy detection should also provide additional savings during work hours.

While time scheduling is undoubtedly effective in terms of energy conservation (Jennings et al., 2002; Rubinstein & Karayel, 1984), occupancy detection is more debated. Its potential for energy savings depends on the space typology and occupancy patterns, where infrequently occupied spaces are usually more suitable (Neida et al., 2001). In extreme cases, occupancy detection may be less effective than traditional manual controls (Floyd et al., 1996).

Occupancy detection strategies can be based on:

- presence (or automatic switch on-off), i.e. the electric lighting is automatically turned on or off based on the occupancy, or
- absence (or automatic switch off or vacancy), i.e. the electric lighting is manually switched on by the user and automatically switched off if the occupancy is not detected for a defined period.

Occupancy detection strategies are usually promoted by building codes and standards, see e.g. EN15193-1 (CEN, 2017), but a clearer distinction between presence and absence strategies appeared only recently in the regulatory framework (ASHRAE, 2013). Presence detection is more appropriate for large and irregularly occupied spaces, while absence detection is usually best in regularly occupied spaces with few occupants (Gentile et al., 2016a).

One of the main occupancy detection design objectives is to minimize false switch on-off events, as they lead to very low user acceptance and spoil the energy savings (Guo et al., 2010). False switch on-off events are minimized by properly selecting the sensor technology, by correctly positioning the sensor, and by setting an appropriate switch-off time delay (Guo et al., 2010). The most common sensor technology is Passive-InfraRed (PIR) (de Bakker et al., 2017) due to its reliability and low cost. By combining a PIR sensor with other sensor technology, the false on-off events are reduced (Manzoor et al., 2012a; Manzoor et al., 2012b; Labeodan et al., 2016a). The correct sensor positioning depends, again, on the sensor technology, on its capacity to pass physical barriers, and on the field of view of the specific sensor (Guo et al., 2010).

Researchers have found that reducing switch-off time delays from 20 to 5 minutes may increase energy savings from 26% to 33% in regularly occupied spaces (Chung & Burnett, 2001), and almost double the saving in irregularly occupied spaces (Richman et al., 1996). As optimal time delay depends on individual activities, some researchers have proposed adaptable time-delay sensors, which can provide an additional 5% energy savings compared to fixed time-delay (Garg & Bansal, 2000). Other researchers have shown that the design of sensor networks with an optimized field of view is a very effective way to reduce time delay to as low as one minute, which prevents false-off and maximizes savings (Guo et al., 2009; Labeodan et al., 2016b; Dikel & Newsham, 2014; Dodier et al., 2006). Innovative occupancy strategies are moving from traditional ceiling-based sensors to occupancy detected by other means, such as chair sensors (Labeodan et al., 2016a) or a combination of 'desktop sensors', such as webcam, mouse, and illuminance (Newsham et al., 2017).

With appropriate design, occupancy detection strategies are claimed to save about 30% energy use for lighting compared to traditional manual systems (Williams et al., 2012). Their acceptance is strongly linked to proper design and commissioning, i.e. to the correct choice between presence and absence detection (Gentile et al., 2016a; Dubois et al., 2016) and minimization of false switch on-off events.

2.3 Daylight-linked systems

In spaces where daylight is abundant, the electric lighting can be either switched on or off depending on whether a target illuminance is met (daylight on-off systems). Electric lights may also be dimmed to the target illuminance, which is referred to as a daylight harvesting system (DHS).

Daylight-linked systems are the natural step forward after occupancy strategies. Traditionally, daylight-linked systems were based on input from a single photosensor. Daylight-linked systems based on luminance cameras, rather than a traditional photosensor, have been proposed (Sarkar & Mistrick, 2006; Sarkar et al., 2008; Newsham & Arsenault, 2009; Motamed et al., 2017), but they have not yet received commercial attention, due to higher costs as well as privacy issues.

Research into daylight-linked systems is not new (Hunt, 1979b; Rubinstein et al., 1993; Crisp, 1978) but, despite previous forecasts (Verderber & Rubinstein, 1983; Verderber & Rubinstein, 1984), the market is not yet exploited (Bellia et al., 2016). One of the reasons is that these systems require expert knowledge for proper design, installation and calibration (Gentile et al., 2015). Non-perfectly commissioned systems tend to be criticized or even sabotaged by users (Kim & Kim, 2007; Cunill et al., 2007; Heschong Mahone Group, 2006; Gentile et al., 2013). In contrast, exemplary DHS installations have good acceptance (Granderson et al., 2010; Gentile et al., 2016a; Escuyer & Fontoynont, 2001). Several authors claim that DHSs provide better energy performance when combined with dynamic shading (Newsham & Arsenault, 2009; Motamed et al., 2017; Konstantoglou & Tsangrassoulis, 2016), and that they are more likely to be accepted and correctly used if highly accessible manual override is provided (Sadeghi et al., 2016; Konstantoglou & Tsangrassoulis, 2016).

An additional barrier to the spread of daylight-linked systems is the lack of simulation software that can precisely represent the real response of commercial photosensors (Bellia et al., 2016). This leads to differences of about 20% between simulated and actual savings (Williams et al., 2012). In absolute terms, potential savings through DHSs are around 20-60% (Williams et al., 2012).

A more extensive review on DHSs is appended in Paper II.

2.4 Colour tuning

Development of white-tuneable LED (Xie et al., 2007) in the past decade has paved the way for a new type of control over the light source: colour tuning. This control strategy consists of modulating the correlated colour temperature (CCT) of the light source, which is achieved prevalently in manual mode (see e.g. (Logadóttir et al., 2013), as traditional photosensors can only detect differences in illuminance. Nevertheless, automatic tuning is currently undergoing research and development, usually to mimic the instantaneous daylight CCT (Gilman et al., 2013; Miller et al., 2016). Red-green-blue (RGB) photosensors are currently used (Aldrich et al., 2010; Li & Pandharipande, 2015) to the scope. Colour tuning technology is currently in its infancy, so most of the research focuses on technology improvement, i.e. better matching of CCT and illuminance levels (Chen et al., 2015; Lee et al., 2016), rather than testing in field studies.

Colour tuning is mainly intended to improve visual comfort (Imam et al., 2016; Dikel et al., 2014), but it may also offer potential energy savings (Afshari et al., 2014).

2.5 Control networks and integration in the BMS

Traditional LCSs may be combined into control networks and integrated with the BMS. Control networks are not a control strategy, but a different architectural design approach to existing LCSs. Networks can be cabled or wireless. While cabled networks are more reliable, wireless networks are usually less expensive (Pandharipande & Caicedo, 2015) and more convenient in the case of retrofits, as cables between lighting fixtures can be avoided.

One of the advantages of control networks is that input of sensors for lighting control, e.g. occupancy detection, can be shared with other building services, such as HVAC. This reduces the number of sensors and rationalizes the management of building services. On the other hand, control networks may require additional energy to run the control devices and they may be more difficult to switch off completely when lighting is off (Lohaus et al., 2016; IEA 4E SSL Annex Task 7, 2016). Additional information from any activity inside the building may be shared with the BMS, realizing the Internet of Things, IoT (Gubbi et al., 2013). This information may serve to optimize the use of LCSs, for example by modelling individual occupancy patterns through data mining (D’Oca & Hong, 2015; Hong et al., 2016).

A drawback of the IoT is that, relying on classic Wi-Fi networks, data transfer might not be safe (Weber, 2010). There are risks of unauthorized surveillance, uncontrolled data generation and use, and inadequate authentication, and information security risks (Caron et al., 2016). Very recent advances in Visible Light Communication (VLC), also called Light-Fidelity (Li-Fi) transmission have the potential to overcome some of these risks. With this new wireless data transmission technology, data are transferred through high frequency variations of the luminous output of LED luminaire (flicker). This allows the communication of sensors – traditional sensors or even smartphones – and light fixtures in spaces with ubiquitous lighting. In contrast to Wi-Fi, Li-Fi is blocked by opaque surfaces, it has a shorter range (Afgani et al., 2006), does not require a direct line of sight (light can be reflected by a surface), but it does allow greater and faster data exchange (Rajbhandari et al., 2015).

Increased automation in LCSs seems to correspond to decreased user acceptance. However, recent control networks research tried to 'introduce' the user into the network by providing lighting feedback to the individual (Tan et al., 2017; Nagy et al., 2015; Nagy et al., 2016). In other words, the system should predict users' behavioural intention and take appropriate decisions. Large scale acceptance studies of these solutions are not yet available.

Control networks, their integration in the BMS and the IoT, in combination with Li-Fi communication, will determine the future technological landscape of LCSs (Chew et al., 2017).

2.6 Final remarks

Over the years, research on LCSs has focused on systems with increasing technical complexity and greater automation. Integration with daylighting and the BMS has also increased, starting from integrated DHSs and shading devices, and moving towards the IoT (Figure 2.4).

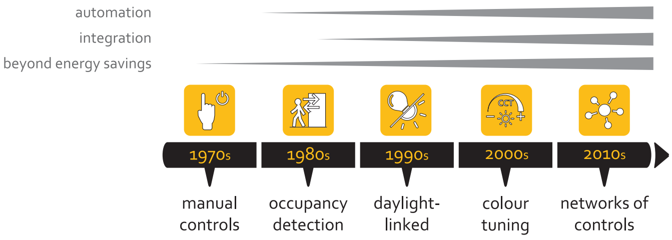

Figure 2.4 History of research on LCSs

Potential energy savings are difficult to estimate with precision, as they depend on the specific case and on the calculation baseline. However, they seem to lie between 20 and 60%, and they increase when more LCSs are combined together, e.g. absence control in combination with DHS (Williams et al., 2012).

Networked controls open a tremendous range of new design possibilities. In this sense, it is notable that LCS design is now going beyond mere energy objectives, as it starts to include visual, physiological and biological (circadian rhythms) targets (Chew et al., 2017).

Although these new possibilities are most welcome, the energy-saving potential paradigm remains of fundamental importance in relation to the global energy and environmental challenges, and one of the most convincing arguments for investing in LCS technology.

3 Theoretical framework

The studies reported in the appended papers were carried out under a common theoretical framework based on two key concepts about energy: energy efficiency and energy savings.

Oikonomou et al. (2009) proposed the following semantic differentiation for energy conservation measures.

- Energy efficiency – ratio between the energy entering and leaving the system, often expressed as η, i.e. a purely technological measure.
- Energy saving (or energy conservation) – the complex of energy-related behaviours from the technology investors, consumers and end-users, triggered by economic and psychological considerations (Figure 3.1).

Energy efficiency has increased by 17-20% over the past 15 years (OECD/IEA, 2016). In October 2014, the European Council defined energy targets to be reached by year 2030, including a 27% efficiency improvement compared to projections of future energy use in the EU (European Council, 2014). The European Union policies have traditionally been strongly oriented towards energy efficiency gains (European Parliament, 2012; Geller et al., 2006), but energy conservation potential may be overestimated by using a purely deterministic energy efficiency approach (Jaffe & Stavins, 1994).

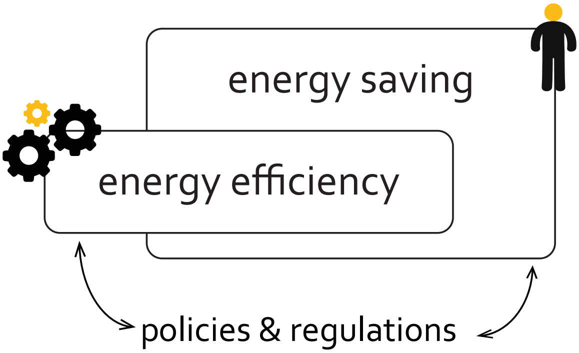

Figure 3.1 *Energy efficiency contributes to energy saving*

The case of light bulbs serves as an example. In 2009, European countries decided to gradually phase out incandescent lamps (European Parliament, 2009). This approach has been generally successful. Electricity use for lighting in Europe dropped by 10.1% in the period 2007-2013, and the average sold luminous efficacy increased by 22% (JRC, 2016). However, many consumers opposed the ban (Broydo Vestel, 2009; Brandston, 2009; Shaw, 2009), and the market responded with some creative solutions such as selling bulbs as 'mini heaters' (Reuters, 2010). On a scientific level, researchers argued that, for low usage time of lighting, the ban would have led to marginal savings but much higher costs for the consumers (Frondel & Lohmann, 2011; Mills & Schleich, 2010). Other research claimed that gains in efficiency would have been offset by the rebound effect (or Jevons Paradox) (Jevons, 1865; Alcott, 2005) for lighting. This means that more energy-efficient light sources would have encouraged higher demand for illumination (luminosity rebound) and longer burning time (burning time rebound) (Schleich et al., 2014). Indeed surveys showed that incandescent bulbs were replaced by 47% more luminous LED lights on average (Mills & Schleich, 2014), and that the burning time of these lights increased by 23% (Schleich et al., 2014). In view of this social dimension of energy use, Mills and Schleich (2014) argued that the rebound effect may be mitigated by appropriate communication to the consumers, to make them aware of the impact of their behaviour on energy use.

In summary, energy efficiency policies may fail because of social and economic factors. Energy savings are achieved when improvements in technology and energy efficiency also encourage energy-conscious behaviours (Bertoldi et al., 2013). Policies and regulations should therefore always consider both aspects.

3.1 Energy savings: degree of acceptance of LCSs

The field studies appended to this thesis investigated user acceptance of different LCSs (Paper III and IV). Acceptance was studied using semi-structured interviews based on the Unified Theory of Acceptance and Use of a Technology (UTUAT) (Venkatesh et al., 2003). This theory is broadly used to study acceptance of new devices.

The UTUAT is based on eight widely accepted behavioural theories. Venkatesh et al. (2003) introduced new technologies in the workplaces of 215 individuals and performed a series of longitudinal field studies. They found that seven of the essential constructs of the eight theories were direct determinants of behavioural intention and thereby of usage. They hypothesized that only four of these constructs would significantly trigger the behavioural intention. This hypothesis was later cross-validated using the same data sample.

The four determinants specified by the UTUAT are:

- Performance expectancy, i.e. expected rewards in terms of improved job performance by using the new technology.
- Effort expectancy, i.e. expected effort to be put into using the new technology.
- Social influence, i.e. expected social rewards and recognition deriving from use of the new technology.
- Facilitating conditions, i.e. expected external support for using the new technology.

Each determinant is mediated by several factors (Figure 3.2).

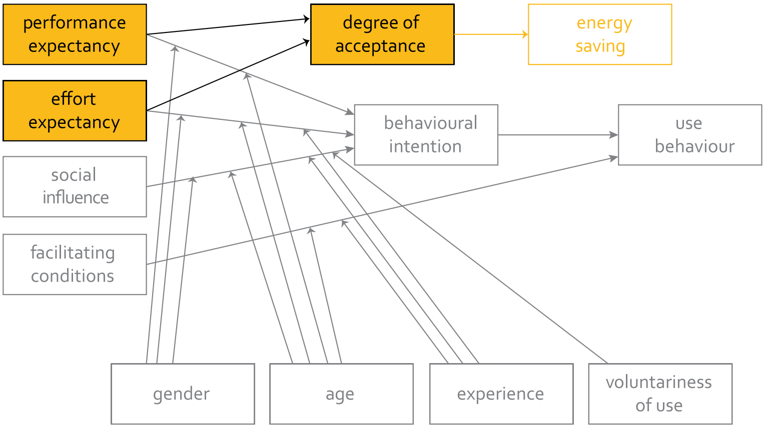

Figure 3.2 Simplified UTUAT

The UTUAT is a complex theory, and the appended studies use it in a simplified form. The social influence, the facilitating conditions, and all the mediating factors were controlled, leaving performance and effort expectancy as the only independent variables in the studies. Consequently, the studies did not fully investigate the behavioural intentions towards a LCS; instead, they determined its degree of acceptance (Figure 3.2). In other words, a LCS which allows the user to work efficiently with little or no hassle has greater acceptance. The degree of acceptance is theoretically correlated to higher energy savings. This assertion was supported by previous research findings claiming that dissatisfaction with the LCS generates protests and sabotage (Cunill et al., 2007; Heschong Mahone Group, 2006; Kim & Kim, 2007).

3.2 Energy for illumination and energy for standby

The European Standard EN15193-1 (CEN, 2017) defines the energy demand for lighting as the sum of:

- Energy demand for functional illumination, i.e. the energy used for actual illumination.
- Energy demand for parasitic use, i.e. the energy required to power non-illuminating devices such as ballasts, controllers, and sensors.

Parasitic use is also named vampire or standby energy use by other sources. For clarity, 'standby' is used throughout this thesis (Figure 3.3).

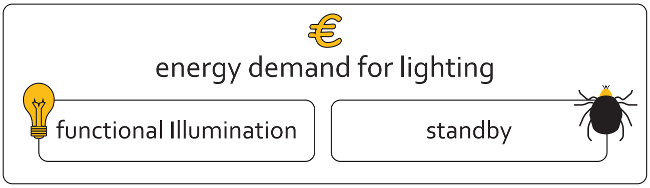

Figure 3.3 *Energy demand for lighting is the sum of energy for functional illumination and energy for standby*

At the design stage, energy demand is usually expressed in terms of power (W), e.g. a light fixture uses 58 W of which 1 W is used for standby. Standby power is usually much lower than power for illumination (Figure 3.4). However, bills are paid in terms of energy use (kWh), i.e. power times time, which is represented by the coloured area in Figure 3.4. Since standby power is often on 24 hours a day and 365 days a year, it may it account for a significant proportion of energy use annually.

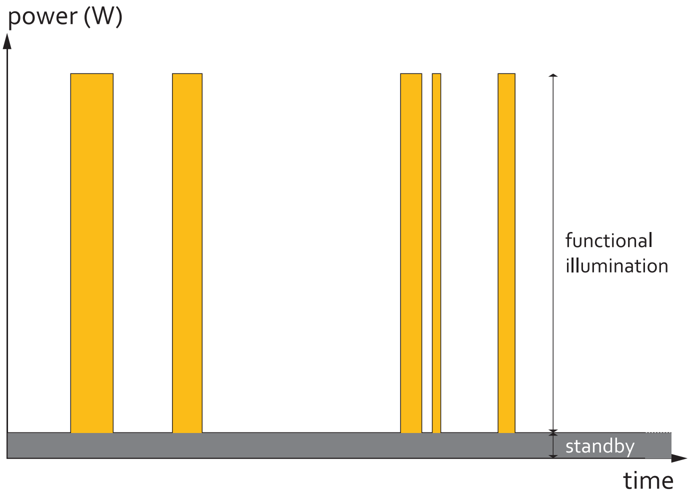

Figure 3.4 Power for standby and functional illumination over time

Standby energy use over the total lighting energy use may increase if:

1. standby power is high (high wattage),
2. illumination power is low (high luminous efficacy of light bulbs and fixtures),
3. electric lighting is rarely used (low occupancy, high daylight penetration).

In Europe, standby energy use of luminaires has been limited since 2014 by the Ecodesign Directive (EU, 2012). However, this directive does not cover auxiliary devices that are not embedded in the fixture, such as timers, sensors, and controllers (Geilinger et al., 2015). In view of increasing networked LCSs, such devices may account for a considerable proportion of the total electricity demand for lighting (Figure 3.5).

One problem with LCSs is that they are traditionally designed to optimize energy use of lighting during illumination hours, with a strong focus on functional illumination. Studies usually report energy savings based on working hours (see e.g. (To et al., 2002; Onaygıl & Güler, 2003; Li et al., 2006; Galasiu et al., 2004; Lee & Selkowitz, 2006; Ihm et al., 2009). Little is known about the standby power energy use. According to some studies, it can be as high as 25-30% of the total electricity use for lighting (Roisin et al., 2008; Aghemo et al., 2014).

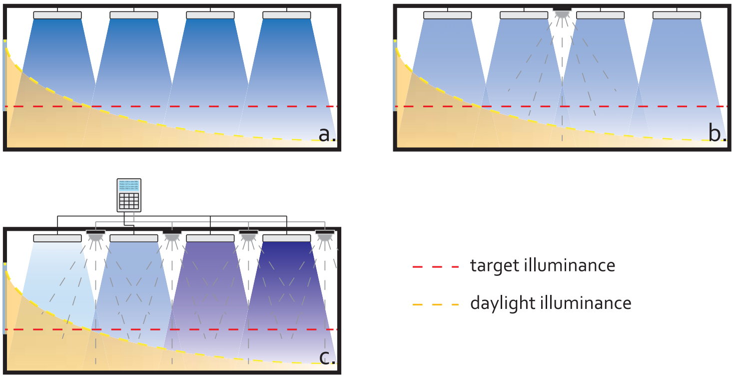

Figure 3.5 *Example of DHS aiming to increase energy savings for functional illumination. In a. there is no photosensor; savings for functional illumination are lower, but there is no standby. In b. a photosensor dims the four light fixtures according to the target illuminance seen in its field-of-view; savings for functional illumination are moderate, and standby for the sensor (and controller) is added. In c. each fixture is controlled by a photosensor and the inputs are all elaborated by a central controller; savings for functional illumination are highest, but additional standby is added.*

The field studies and the simulation study in this thesis assessed the performance of LCSs based on their total energy use for lighting, namely functional illumination plus standby energy use.

3.3 Summary of the theoretical framework

Based on the premises in sections 3.1 and 3.2, the studies presented in this thesis investigated the potential *energy saving* for *lighting* in traditional LCSs.

Figure 3.6 shows the overarching theoretical framework to this thesis. It is hypothesized that the total energy savings for lighting are related to a social and a technical 'complexity' component of the LCS. On the social or user side, it is hypothesized that higher complexity (or lower accessibility) for the user of the LCSs will increase effort expectancy at a higher rate than performance expectancy, which will lower the degree of acceptance. On the technical side, it is hypothesized that LCSs with more networked devices will achieve marginal increases in energy savings, mainly due to the increased energy demand for standby. Figure 3.6 speculates that relatively simple, user-friendly LCSs ('low-hanging fruits') may achieve comparable savings to very advanced systems.

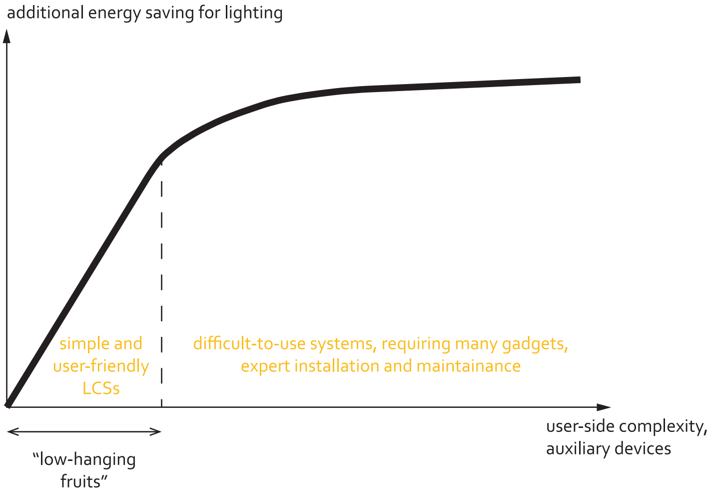

Figure 3.6 Overarching theoretical framework

4 Outline of the thesis and summary of the appended papers

This thesis is based on findings from three main research projects in which the author was involved.

The first project, ‘Robust control systems for electric lighting: inventory of existing technology, laboratory tests and field studies’ (the LCSs Project), represents the core of the doctoral work. The project goal was to demonstrate potential energy savings of lighting control systems, considering technical and non-technical aspects of such systems. The project included an inventory of existing systems and the individuation of barriers for exploiting the energy saving potential. The project proceeded through literature reviews, field studies, and a simulation study, which are appended in Papers I to IV, and VII.

The second project, ‘IEA-SHC Task 50 Advanced Lighting Solutions for Retrofitting Buildings’, IEA-T50 (IEA-SHC Task 50, 2013), was part of a big international project on efficient lighting retrofit. The author participated in Subtask D ‘Case studies’. Findings from this project contributed to the appended Paper VI and to a freely available report (Dubois & Gentile, 2016), which add knowledge to technical and non-technical aspects of lighting control in real-life installations. It should be noted that Paper I, which was produced in the first project, includes sections on other aspects of lighting retrofit authored by other participants in IEA-T50.

The third project, ‘Energy efficient and study promoting lighting at high school’ (the School Project), investigated the effects on mood, circadian rhythm and energy for lighting of two different lighting systems. The project research question did not initially include lighting controls, but the energy use data were insightful for the scope of this thesis. A publication from the study, Paper V, is also appended.

Methods and instruments used are reported in Table 4.1.

Table 4.1 Methods and instruments used in this thesis

	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI	Paper VII
Project	LCSs project + IEA-T50	LCSs project	LCSs project	LCSs project	School project	IEA-T50	LCSs project
Research question(s) or research goal(s)	What is the state-of-the-art technology for LCSs? What is their saving potential? What is the users' acceptance for LCSs?	What are the performance determinants for DHSs? How can DHSs be properly designed, commissioned and installed?	How much energy can LCSs save in realistic individual office scenarios? Can LCSs achieve a high degree of user acceptance?	How much energy can LCSs save in realistic individual office scenarios? Can LCSs achieve a high degree of user acceptance?	Can the experimental LED lighting improve mood, satisfaction, academic performance and support biological functions, while also saving energy, with respect to the control fluorescent T5 lighting?	What are good examples of lighting retrofit strategies, achieving energy savings and user appreciation? What are the opportunities, challenges, and pitfalls of such solutions?	What is the effect of standby for LCSs considered in previous studies? What is the role of LCSs standby in highly efficient lighting installation?
Research strategy	Literature review	Literature review	Field study	Field study	Field study	Case studies	Literature review + simulations
Method(s) or instrument(s)	Review of scientific journals with technical notes	Review of scientific journals with document clustering	Data-logger Self-reported diary	Data-logger Semi-structured interviews	Data-logger BEPS PANAS-X POLQ Saliva cortisol	Several methods included in a monitoring protocol	Qualitative meta-analysis of published articles Real occupancy data Parametric simulations in Daysim via Honeybee
Setting	Several	Several	Four occupied individual offices (plus a control room) A winter month Rotation of the occupants	Four occupied individual offices Two spring months Rotation of the LCSs	Four identical classrooms 2 classrooms with LED, 2 classrooms with T5 1-year monitoring	Several	57 individual offices
Participants	n.a.	n.a.	Four employees (academic staff)	Four employees (academic staff)	72 high school students	n.a.	Academic/administrative staff
Type of control(s)	Manual, occupancy strategies, DHS	DHSs	Presence, absence, DHS + presence, task lamp only	Presence, absence, DHS + absence, task lamp only	DHS, scene setting	Several (presence, DHS, DHS integrated in the BMS, …)	Manual, absence, presence, DHS + absence
Measured variables	Energy saving potential User acceptance	Energy saving potential Challenges and opportunities	Energy saving potential Lighting conditions User acceptance	Energy saving potential Lighting conditions User acceptance	Energy saving potential User mood, satisfaction, and academic performance Cortisol circadian rhythms	Energy saving Retrofit costs Objective light environment (photometry) Perceived light environment (questionnaires/interviews)	Occupancy rates Lighting switch on-off events Energy use for lighting Energy use for functional illumination Energy use for standby

The outcomes of each paper have shaped the study to a certain extent, so the appended papers are connected through the outcome-objective thread as shown in Figure 4.1.

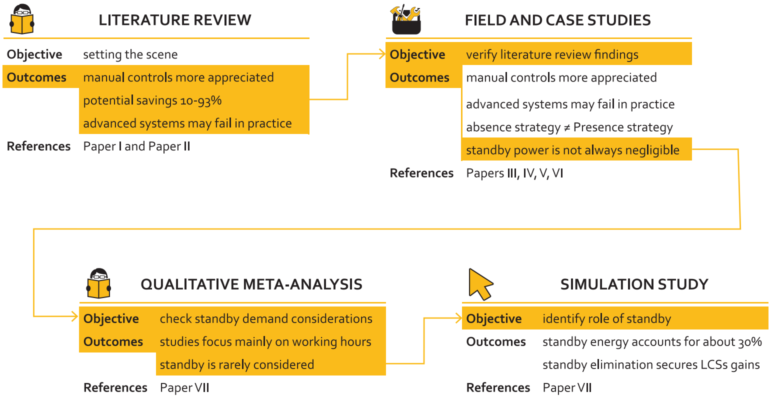

Figure 4.1 *Outline of the thesis*

The following section provides a summary of the main objectives, methods, and lessons learned on the topic of LCSs in each of the appended papers.

4.1 Papers I and II – Literature review on LCSs and on DHSs

Paper I - Retrofitting the electric lighting and daylighting systems to reduce energy use in buildings: a literature review.

This literature review was carried out in the context of the projects 'Robust control systems for refurbishment of existing lighting installations in facilities' and IEA-T50. The part on lighting controls was written by the author, while the rest of the review is a compilation by IEA-T50 Subtask D participants. The aim of the literature review was to provide an inventory of state-of-the-art technologies based on peer-reviewed publications.

Goals

- To identify previous studies about lighting controls.
- To provide key information about user acceptance of controls.

- To summarize the saving potential for different lighting control strategies.

Methods

The articles were retrieved based on the following keywords: '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 and conference papers. For the scientific publications, the search was extended to several databases, including Scopus, 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 DHSs. The focus was on energy-saving potential of LCSs and their technical and non-technical aspects.

Lessons learned relating to LCSs

- Saving potential of LCSs lies between 10 and 93% compared with no lighting control.
- Reported energy savings depend on the calculation baseline used.
- Energy savings are often difficult to accurately predict in practice, which implies difficulties in financing retrofit projects.
- Simulations generally overestimate energy savings compared with field studies.
- Presence and absence (or vacancy) detection are usually named under the overarching definition of 'occupancy strategies'.
- Manual controls may achieve considerable savings.
- Manual controls are generally preferred over automatic ones.
- Good energy performance is associated with DHSs, but they present important design and commissioning issues.

Paper II – Daylight harvesting control systems: design recommendations based on a literature review.

One of the conclusions in Paper I was that DHSs should be properly designed and commissioned, although this rarely occurs in practice. A review of design recommendations for DHSs lighting control systems was presented.

Goals

- To identify challenges and opportunities of DHSs in terms of energy savings and user acceptance.
- To suggest a design workflow for optimal DHSs design, commissioning and installation.

Methods

The review was mainly based on peer-reviewed articles published between 1995 and 2015 and including the keywords: ‘daylight harvesting’, ‘daylight linked’, ‘photoelectric dimming’, ‘photoelectric sensor’ and ‘photosensor’. The following databases were consulted: ISI Web of Knowledge, Scopus, IEEE Xplore and ScienceDirect. A few older papers and conference publications were added, with a total of 57 articles included in the final selection. Key information from the papers was organized in clusters: energy-saving potential, technical guidelines, architectural guidance, and conditions for user acceptance. These clusters are clearly defined in the paper structure.

Lesson learned relating to LCSs

- The energy performance of DHSs depends on three aspects: technical, architectural and human.
- Well-designed and commissioned DHSs achieve high energy savings and high level of user acceptance.
- DHS design, commissioning and installations require specialized training.
- DHSs should be supplemented with manual controls (override).
- DHSs are most effective in spaces with moderate daylight penetration.
- The rate of occupancy is an important determinant of energy savings since, at low occupancy rates, the portion of energy use for standby may be significant in the overall energy balance.

4.2 Papers III and IV – Field studies in individual office rooms

Paper III – Lighting control systems in individual offices at high latitude: measurements of lighting conditions and electricity savings.

The reviews underlined that LCSs can provide considerable energy savings, but they are susceptible to failures due to design and commissioning issues. User acceptance is also a determinant of LCS performance. The conclusions were verified with a field study in occupied individual offices.

Goals

- To validate conclusions from the literature reviews.
- To investigate the energy-saving potential of LCSs in individual offices under realistic conditions.
- To investigate user satisfaction with different LCSs settings.

Methods

Five identical individual offices were used for the test. Four offices were occupied and equipped with different LCSs, while the fifth was used as a control room. The following LCSs were tested:

- Presence detection (automatic switch on-off), plus task lamp.
- Absence detection (automatic switch off), plus task lamp.
- Presence detection with daylight harvesting, plus task lamp.
- Task lamp only (no general lighting).
- No electric lighting and no occupant (daylight control room).

Energy use for lighting, illuminance at three points in the room, and exterior illuminances (global and direct horizontal, and direct vertical on the façade) were recorded every six minutes. The occupants used each office for one week. At the end of the week, occupants completed a self-reported diary (Maleetipwan-Mattsson et al., 2013), which included questions on adjustment to the electric lighting systems, to the blind position, and overall satisfaction with the lighting conditions. The occupants changed room in the following week, to experience another lighting system. The study lasted four weeks during November.

A peculiarity of this study was that the system installation and calibration was entrusted to a practitioner, without the supervision of the authors. The idea was to replicate a realistic lighting retrofit with LCSs.

Lesson learned relating to LCSs

- Presence and absence detection yielded very different energy performances, whereas absence detection performed better in private offices.
- DHS was neither properly installed nor calibrated, leading to poor performance and user dissatisfaction.
- Manually controlled LCS (absence detection) was widely appreciated.

- Task lamp and no general electric lighting did not provide sufficient illumination under the conditions of high latitude and winter time.

Paper IV – Lighting control systems in individual offices rooms at high latitude: Measurements of electricity savings and occupants' satisfaction.

DHS in Paper III failed because of commissioning and installation issues. It was decided to repeat the study with similar settings but during the spring. This time, the DHS was installed and carefully calibrated by the author. The experimental methodology was also improved, where the occupants stayed in their room and the LCSs rotated instead. The paper was first presented at a conference, and then selected for publication in a scientific journal. The journal version is appended to this thesis.

Goals

- To assess the potential energy savings of LCSs in individual offices occupied full time.
- To define the degree of acceptance of different LCSs in individual offices.

Methods

Four identical occupied individual office rooms were monitored over a two-month period (April-May). Each room was fitted with a different LCS, as follows:

- Presence detection (automatic switch on-off), plus task lamp.
- Absence detection (automatic switch off), plus task lamp.
- Absence detection with daylight harvesting, plus task lamp.
- Task lamp only (no general lighting).

Each LCS was moved to another room every second week according to a schedule. The occupants continuously sat in their normal office rooms during work hours, and were subjected to a different LCS every two weeks. At the end of the second week, each occupant was questioned using semi-structured interviews. The energy consumption for lighting, roller-blind position, illuminance on the working plane, illuminances at two points in the room, global, diffuse and direct horizontal illuminance, as well as direct vertical illuminance on the façade were constantly monitored.

Lessons learned relating to LCSs

- Presence and absence detection yielded very different energy performances, whereas absence detection performed better in private offices.
- Manual override largely increased the acceptance of the LCS.
- Good energy performance and user acceptance was obtained with the DHS, when the system was properly designed, commissioned, and provided with manual override.
- Adequate daylight provision lowered the need for electric lighting.
- Low occupancy rates (about 40% of the working hours) reduced the need for electric lighting.
- In these conditions, standby energy use accounted for as much as 80% of the total energy for lighting.
- The task lamp alone could not provide sufficient illumination, even during the spring when daylight was more abundant during the work day.

4.3 Papers V and VI – Lessons learned from field and case studies carried out in other research projects

Paper V – A field study of fluorescent and LED classroom lighting.

The paper reports on a one-year field study on the effects of two lighting systems (fluorescent T5 and LED) on energy use for lighting, as well as effects on high school students' mood, perceived light environment, and circadian rhythm. Both lighting systems were equipped with absence sensors and DHSs, as well as scene-setting control, which did not have an energy-saving purpose. The study findings on energy use by the systems were relevant to this thesis, so are included.

Goals

- To identify the effect of lighting on differences in mood and alertness of the students.
- To ensure that the lighting systems do not interfere with the circadian rhythm of the students.
- To assess the energy-saving potential of new LED lighting installations.

Methods

Four identical classrooms, occupied by four separate classes, were equipped with two lighting systems. Two classrooms were equipped with upward/ downward light distribution fluorescent T5 fixtures (control group). The other two classrooms were equipped with completely indirect LED fixtures (experimental group). The study was designed following Küller's Theoretical Human-Environment Interaction model (Küller, 1991). The evaluation of mood was based on the Basic Emotional Process Scale, BEPS (Küller, 1991), and the Panas-X (Watson et al., 1988). The perceived lighting environment was assessed through the Perceived Outdoor Lighting Quality, POLQ, (Johansson et al., 2014) questionnaires, the latter being adapted for the indoor case. The circadian rhythm was evaluated using saliva cortisol analysis. Finally, the most relevant assessment for the scope of this thesis, i.e. the energy use, was performed through continuous logging of presence and energy use for lighting each classroom, at two-minute intervals.

Lessons learned relating to LCSs

- Adequate daylight provision reduced the need for electric lighting.
- Occupancy of classrooms was as low as 10% of the total hours of the year (8760 hours), which further reduces the need for electric lighting.
- The electric lighting was on about 500 hours per year in each class, i.e. less than 6% of the total hours in a year.
- Higher standby energy losses for the LED system (11 W) in comparison to the fluorescent T5 (7 W) led to no energy savings at all for lighting with the LED system.

Paper VI - Performance Evaluation of Lighting and Daylighting Retrofits: Results from IEA SHC Task 50.

This article presents results from assessment of case studies as part of IEA-T50 Subtask D. The appended conference paper presents qualitative outcomes from selected case studies and is a condensed version of the freely available report 'T50.D5 Lessons learned from monitoring lighting and daylighting in retrofit projects' (Dubois & Gentile, 2016). Several quantitative results are available on the 'Lighting Retrofit Adviser' web platform (IEA-SHC Task 50, 2016) and Android App (Fraunhofer Institut für Bauphysik & IEA-SHC Task 50, 2016).

Goals

- To demonstrate sound daylight and electric lighting retrofit solutions in terms of energy savings, cost efficiency and user acceptance.

- To identify opportunities, challenges, and pitfalls of lighting retrofit solutions.

Methods

The selection of case studies was based on: a) analysis of the existing non-residential building stock and its typical electricity consumption, b) attractive retrofitting strategies in accordance with findings from an extensive literature review, and c) practical accessibility for the monitoring teams. When possible, the cases were investigated under a common evaluation framework that was developed contextually to the case studies assessment (Gentile et al., 2016b). This framework considered four dimensions of the lighting retrofit evaluation: energy use, retrofit costs, objective light environment (photometry), and perceived light environment (user assessment).

Lessons learned relating to LCSs

- Comprehensive lighting retrofit, including holistically integrated lighting controls in the BMS, can achieve very high performance levels (Case: Bartenbach R&D offices, Aldrans, Austria).
- Private manual controls, rather than a centrally controlled system, enhance user satisfaction with LCS (Case: Ministry of Energy and Environment, Brasília, Brazil).
- Separate manual controls of electric lighting for differently daylit areas of an office may save energy and increase user acceptance (Case: Horsens Town Hall, Denmark).
- Improperly commissioned DHS can suffer from continuous fluctuations in illuminance, and the supplier may not be able to solve the problem (Case: Dentistry School Clinic, Aarhus University, Denmark).
- Replacement of fluorescent T8 with LED systems achieved 38% savings without using a LCS, and 68% with the addition of properly commissioned DHS combined with absence detection, while increasing user satisfaction (Case: School of Electrical Engineering, Aalto University, Espoo, Finland).
- Lighting fixtures with embedded LCSs may be installed by untrained professionals, who may not know how to operate the LCS controller and how to calibrate it. As a result, a landscape office was provided with presence detection where the field-of-view was too wide, rather than with the originally designed DHS + Absence detection system planned, which turned on the lighting even in areas where it was not needed, and annoyed the occupants (Case: WSP Office building, Stockholm, Sweden).

4.4 Paper VII – Simulation in individual office rooms

Paper VII - Field data and simulations to estimate the role of standby energy use of lighting control systems in individual offices.

Papers I-VI underlined that properly commissioned LCSs can effectively save energy. Papers IV and V showed that spaces are often occupied less than could be expected. Low occupancy rates, together with good daylight penetration and efficient electric lighting, helps to reduce the energy demand for functional illumination. However, under some conditions, LCSs may increase the energy demand for standby, as they include running auxiliary devices. A simulation study based on real individual offices and their occupancy data was performed to understand the role of standby in LCSs in future, very energy-efficient lighting systems. The study consisted of a literature review and the simulations.

Goals

- To understand how previous scientific studies have included standby of lighting control systems in computation of energy use for lighting.
- To identify the role of standby energy use of lighting control systems in future, very energy-efficient lighting systems, with a focus on individual office spaces or similar.

Methods

To address the first goal, i.e. to understand how previous research has addressed the issue of standby, a literature review was performed. This review included the papers already included in Papers I and II, plus more recent publications retrieved using the same keywords and scientific databases used for Papers I and II. The review involved a total of 120 articles. The technical notes were integrated with a database of key information from each article. The following information was indexed in the database: building type (office, educational, …), area type (atrium, individual office, …), type of lighting control, study method (field, laboratory, simulation), user satisfaction assessment (yes, no), retrofit project (yes/no), payback time calculation (yes/no), reported energy savings, and baseline used for energy saving calculation. Relationships between space typology, savings and savings baseline were investigated using a qualitative meta-analysis. Papers with an unclear baseline for calculation of energy savings were excluded from the meta-analysis. The main results are reported in Section 1.1 of Paper VII.

The second goal, i.e. to identify the role of standby energy use of lighting control systems with very efficient lighting systems, was addressed using a methodology based on field data combined with simulations. Real occupancy data were retrieved for 57 peripheral private offices. The real occupancy data were later used to study the same private offices using different scenarios with variable installed standby power, lighting power density, and type of lighting control. This part of the study was achieved by advanced lighting simulations using the Daysim software (Reinhart, 2017) via the Honeybee GUI (Roudsari, 2017).

Lessons learned relating to LCSs

- Most existing studies on LCSs use electric lighting fully on during working hours as the baseline for calculations of energy savings, which yields unrealistically high energy-saving potential.
- The issue of standby energy use has been the subject of little research, arguably because
  - Earlier studies investigated lighting systems with low luminous efficacies.
  - Earlier studies investigated LCSs consisting of a few sensors and control units.
  - Many previous studies investigated large spaces, where the energy required for functional illumination is generally much higher than that for standby.
- Occupancy rates for the investigated individual office rooms were very low.
- Daylight penetration was reasonably high.
- The electric lighting was required for a very limited amount of time.
- In individual office rooms, and at very low LPD, standby represents about 30% of the total energy use for lighting.
- In extreme cases, the portion of energy use for standby was as high as 55% of the total energy use for lighting.
- In future, very energy-efficient installations, the additional energy savings from adoption of LCSs can be secured by minimizing or eliminating standby when possible (e.g. by complete switch off).

5 General discussion

5.1 Main findings

LCSs offer a considerable energy-saving potential. Compared to lights on during working hours, studies report 20-93% potential energy savings for occupancy strategies, 10-93% for DHS, and 23-77% for manual controls. However, the energy performance of LCSs is undermined by poor design and commissioning, which leads to low degree of acceptance by users (Papers I-IV). This is not trivial, as there seems to be a lack of awareness on how LCSs function, their installation (Paper VI), and their calibration (Papers III and VI) in real-life situations.

When care is taken in design, commissioning and installation, even more complex LCSs, such as DHSs, can provide substantial energy savings with a high degree of user acceptance (Paper II, IV). For this purpose, Paper II proposed a flowchart to support the basic design process of a DHS. This paper also underlined the need for monitoring and verification (M&V) plans to constantly improve the quality of DHS projects (Paper II). Such necessity could be equally extended to any type of LCS project.

On the user side, the first recommendation is to provide LCSs with simple and accessible manual controls or manual override (i.e. minimize the effort expectancy) to achieve high degree of acceptance, especially in private spaces (Papers I-IV). Future, automatic LCSs with user feedback for custom lighting, e.g. the human-in-the-loop control (Tan et al., 2017), may arguably increase the degree of acceptance, but manual override should still be provided.

The correct functioning of the LCS (i.e. performance expectancy) is another essential condition to achieve both a high degree of acceptance and energy savings. An unsatisfied user is more likely to deactivate the LCS. This has been shown in the appended papers I-IV, as well as in previous research (Cunill et al., 2007; Heschong Mahone Group, 2006).

On the energy side, LCS efficiency depends on more than the system's ability to reduce the load for energy use for functional illumination. Papers IV, V and VII indicated that hidden energy use due to standby systems may greatly reduce the overall performance. In many cases, standby energy use represents up to about 30% of the total energy use for lighting (see e.g. Paper VII, but also ([Aghemo et al., 2014; Roisin et al., 2008]). In certain conditions, i.e. very small loads for functional illumination, it can represent even the biggest portion of energy use for lighting (Papers IV and VII). If no action is taken, standby may offset gains provided by adoption of more efficient light sources (Papers V and VII). The energy required for standby can be greatly reduced or eliminated by choosing the right LCSs for the right space, integrating it in the BMS design and operating the electrical system architecture (Paper VII). The issue of energy use for standby of LCSs is not trivial and should be tackled already at the early design stage of the overall BMS system.

5.2 Revised theoretical framework

Given the above discussion, the overarching theoretical framework proposed in Figure 9 could be revised as follows.

First, the energy for functional illumination is introduced as an additional variable. The energy use for functional illumination can be determined as a function of the daylight design of the space, room function, the rate of occupancy, and the luminous efficacy of the light source.

Functional illumination = *f* (daylight design, room function, occupancy, light source and fixture efficacy)

Good daylight design (i.e. abundant daylight penetration with little risk of glare and overheating [Edwards & Torcellini, 2002]), low occupancy rates, and high luminous efficacy of the lamp (low LPD) will reduce the energy demand for functional illumination. It is argued that, with a growing complexity of LCSs for the user, the number of auxiliary devices required by the LCS, and decreasing energy demand for functional illumination, the additional energy saving for lighting provided by the LCS is relatively small. The hypothetical curve in Figure 5.1 flattens towards the origin when the energy required for functional illumination becomes smaller. When the functional illumination is very low, the user-side complexity and the energy required for auxiliary devices will have a greater impact on the total energy saving. Consequently, it can be theorized that the inflection point moves towards the origin, shrinking the ‘low-hanging fruits’ area.

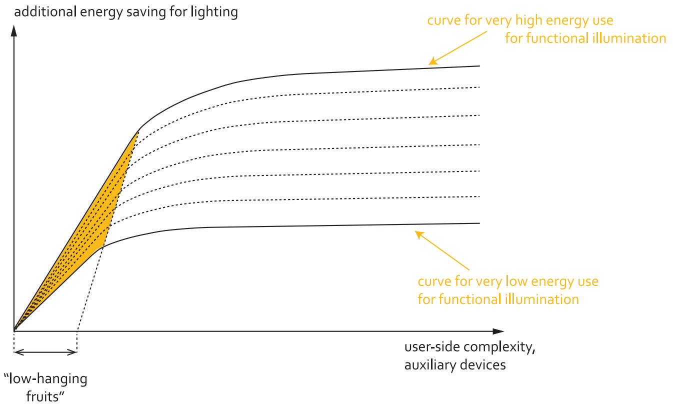

Figure 5.1 *Revised version of the overarching theoretical framework*

Considering the lessons learned from the appended papers and using a purely qualitative approach, it is suggested that the lowest-hanging fruits would consist of occupancy strategies, whereas absence (or vacation) strategy should be preferred in small spaces. These systems are ideal for projects with small budgets, including minor or moderate building renovation (for the definitions see D'Agostino et al., 2017), especially in the case of private spaces. On the one hand, the maximum energy-saving potential is not be fully exploited but, on the other, the system is simple, robust and well accepted, and greatly simplifies the work of building planners. In addition, the use of occupancy sensors is already common among practitioners (Kaempf & Paule, 2016) and the LCS installation does not require specialized skills.

It may be speculated that energy savings from DHSs would lie around the hypothetical flex point of the curve. Savings from DHSs are possibly higher than occupancy strategies, but these types of LCSs were shown to be more subject to failures because of technical, architectural, and user-related factors (Paper II).

Designers are encouraged to push savings over the 'low-hanging fruits' zone, especially when the building project implies extreme energy performance (e.g. near-zero energy building renovations, for the definitions see D'Agostino et al., 2017). This area is qualitatively assigned to complex networked systems, including traditional occupancy strategies and DHSs working with a multitude of sensors and central controls. To secure the savings, designers should be aware that such projects should be handled by specialists already at an early design stage, and they should be integrated as much as possible in the BMS.

5.3 Implications for common practice

The study has shown that correct choice of LCS and its integration in the building project requires deep knowledge of LCS functioning. Some of the papers showed that such expertise is not currently part of the know-how of designers and installers. Consequently, efforts should be made to continuously train specialists of LCSs design and installation, and to include such specialists at the early design stage of the BMS design (Figure 5.2).

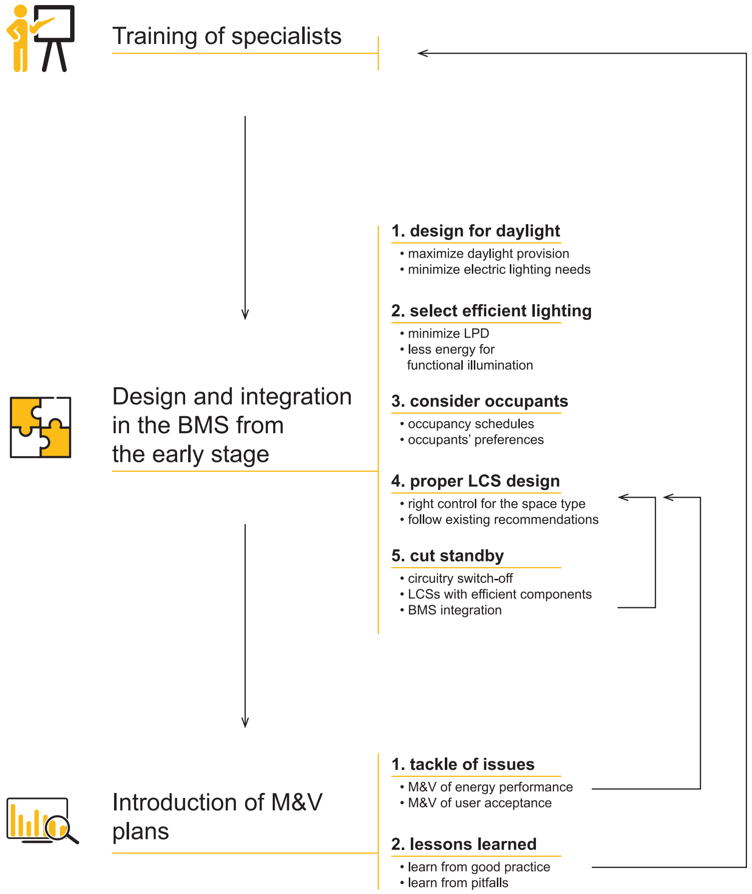

Figure 5.2 *Proposed flowchart for the implementation of thesis findings in common practice*

5.3.1 Training of specialists

Papers I and II list the following determinants of LCS performance: sensor position, optical characteristic of commercial sensors, type of controller algorithms, ballast/driver characteristics, system calibration, systems networks, user acceptance. These should be part of the training of designers and installers. Training activities could include specific courses, dissemination of research results in popular texts, and dissemination of lessons learned from other real-life projects.

5.3.2 Design and integration in the BMS from the early stages

Trained specialists of LCSs should participate in the building or renovation design process from the very early design stage.

LCSs have been traditionally considered as an optional feature for lighting systems. This prevented a real integration of LCSs in the BMS and jeopardized their energy-saving potential. For example, this thesis demonstrated that the energy savings for lighting are undermined by standby energy use, which could be reduced or eliminated if the sensors were shared with other services controlled by the BMS, or if the electrical system architecture allowed a complete shut-off.

Ideally, the designer of the lighting system should first lower the demand for functional illumination by maximizing the use of daylight in the lighting design, as well as using very efficient light sources and fixtures. Then, the designer should account for the actual use of the space, i.e. estimated occupancy rates and typical task performed by the occupant. At this stage, selection of appropriate LCS can start. If the space is private or semi-private (typically small office rooms), manual switch-on, absence switch-off and manual override should preferably be included. If the design involves a common space, greater LCS automation can be introduced, but with the cost of complexity and the need for expert knowledge.

The first draft of the LCS design will follow the existing recommendations on choice of sensors, sensor positions, programming of controllers, etc.

This first draft should be discussed with the professionals responsible for the other BMS services and for the electrical system. This discussion should explore possibilities to integrate the LCS in the BMS. The aim is to maximize savings for illumination and minimize energy use for standby. Feedback is incorporated in the LCS design until the optimal solution is reached.

5.3.3 Introduction of monitoring and verification (M&V) plans

Many of the pitfalls of LCSs are found after the system installation, as shown in in both appended papers and reviewed literature. This thesis emphasizes the need to reserve a budget for post-occupancy evaluations, namely M&V plans. This would:

- allow timely addressing of installation issues, and
- provide valuable lessons learned for continuous learning.

6 Conclusions

This doctoral thesis aimed to provide information on state-of-the-art technology for lighting control systems, and their challenges and opportunities in common practice. It focused on potential energy savings of lighting control systems and user acceptance.

The main conclusion is that traditional lighting control systems, as well as networked controls, can achieve considerable energy savings for lighting with high levels of user acceptance, provided that the design, commissioning, installation and verification are entrusted to trained professionals.

Manual override should be always be provided to increase user acceptance. For low-budget and private space projects, absence detection seems to be the most favourable option, given its widespread use among practitioners. This solution is simple, robust and cost-effective. Networked controls are recommended for highly efficient installations. However, the latter will require trained specialists involved from the very early design stage of the BMS, as well as a specific budget allocated for M&V.

The absolute energy savings provided by LCSs decrease as the energy required for functional illumination decreases. Consequently, with very low energy use for functional illumination and independent of the choice of LCSs, the energy benefits of additional lighting controls should be carefully evaluated at the design stage, where energy use for standby systems is an obligatory item.

7 Future work

General confusion on different occupancy strategies, i.e. presence or absence detection, was found in the literature as well as in the norms. It is suggested that a clearer distinction is presented in any future work and discussion on lighting control systems.

There is a lack of case studies or studies in realistic settings on networked lighting control systems or, in general, on very advanced controls combined with highly efficient lighting. Long-term studies in this area are welcome.

The baseline for energy comparison should be realistic, i.e. energy savings should not be compared to a case where lights are on all day long.

Although outside the research domain, a fundamental area for future work is the development of training programmes for the design, commissioning, installation and verification of lighting control systems.

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Summary

Lighting control systems could save substantial energy in the non-residential building sector

The global energy challenge is currently at the top of most political agendas. Energy conservation through responsible usage and efficiency improvements is of utmost importance. Electric lighting, which comprises around one-fifth of global electricity use, is an area where substantial energy savings can be achieved at low investment cost.

Lighting retrofit has been shown to be one of the most cost-effective energy conservation measures, and 75% of all indoor lighting installations in developed countries must undergo retrofit in the coming years, so there is great potential for energy savings. The most common lighting retrofit strategies are re-lamping with more efficient light sources, such as replacing an old fluorescent lamp with a LED, and the use of lighting control systems (LCSs), which allow lighting to be used only where and when needed. The simplest lighting control system is the manual switch at the door, while the most advanced can involve a network of light and occupancy sensors connected through a wireless system. However, savings generated by LCSs are highly dependent on technical and non-technical issues. For example, a technical issue could be a sensor that needs regular maintenance and calibration, while non-technical issues may influence the way the users interact with the system.

Understanding key factors affecting energy performance of LCSs

The studies included in this thesis include literature reviews, field studies, and simulations, and address various questions in pursuit of a common goal, i.e. assessing factors and conditions that affect energy performance of traditional LCSs used in the non-residential building sector. The review suggests that 10-93% savings can be obtained with LCSs, with higher savings when the systems are properly designed, commissioned and installed. In the field studies, some installations did not work because of unsuccessful installation and lack of calibration, emphasizing the need for training of LCS professionals.

As energy use for illumination decreases due to efficiency improvement in lighting technology, the energy savings by the LCS become marginal in absolute terms, which increases payback time. One reason is that sophisticated LCSs may need standby systems that operate continuously and use a substantial portion of the total energy budget for lighting. A better design strategy may be to optimize the use of daylighting with good architectural plans, appropriately placed windows and high interior reflectance, to increase lighting efficacy of light source and fixtures, and to use simpler and more robust LCS such as absence (manual switch on and absence switch off). Occupancy strategies can be very effective in several contexts, but there is a need for a clear semantic differentiation between 'presence' (automatic on-off), and 'absence' or 'vacancy' (automatic off) in office spaces, especially in individual office rooms. If properly designed, daylight harvesting systems, which keep illuminance constant in the workplace, allow additional savings in moderately daylit spaces and could be a good solution in landscape offices, providing they are properly commissioned.

User is a key determinant of the success of a LCS

The thesis emphasizes that low user acceptance of the LCSs undermines energy savings. Unsatisfied users will probably misuse or even sabotage the LCSs. As a general guideline, LCSs should always be provided with a degree of manual control with, as a minimum, a manual override. This is essential in private spaces, such as individual offices, but also in landscape offices or classrooms.

The user perspective affects energy performance in different ways. The specific activity of the user will modify the occupancy rate of the room and the need for lighting. For example, academic staff involved in teaching and meetings would occupy an individual office less than another professional and, when inside, they will mostly perform computer-based tasks requiring less ambient lighting. This case, which has been thoroughly investigated in this thesis, would lower the energy use for functional illumination and make the LCSs less cost-effective due to a much longer payback time. In addition, if the LCSs requires standby, this may account for about 30% or more of the total energy use for lighting or even more.

Specialist training and integration will secure savings

Does this mean that lighting control systems will be dispensable in the future? Not at all. However, growing efficiency of lighting systems means that additional savings will become more difficult to achieve, as in the case of other energy transformation processes. One way to ensure the energy performance of LCSs is to properly train future professionals. They should also be involved at the very early design stage of building or retrofit design, since future effective LCSs should be integrated as much as possible in the building management system. The success of a LCSs project will also require a proper budgeted plan for monitoring and verification (M&V). In turn, M&V will provide valuable lessons that can be integrated in professional training.

Energy savings can be attained through lighting controls, provided that future projects are well planned, implemented, and commissioned.

Sammanfattning

Styrsystem för belysning kan ge betydande energibesparing i den offentliga/kommersiella byggnadssektorn

Den globala energiutmaningen står numera högt upp på den politiska agendan. Energibesparing genom ansvarsfull energianvändning och förbättrad energieffektivitet är av yttersta vikt. Elektrisk belysning omfattar en femtedel av den globala elanvändningen och är ett område där betydande energibesparing kan genomföras till en låg investeringskostnad.

Uppgradering av befintliga belysningssystem har visat sig vara en av de mest kostnadseffektiva energibesparingsåtgärderna och 75 % av alla inomhusbelysningsinstallationer i utvecklade länder kommer att behöva renoveras eller bytas ut inom de närmsta åren, så det finns en stor potential för energibesparing. De vanligast förekommande ersättningsstrategierna är utbyte av ljuskällor till mer energieffektiva ljuskällor såsom att ersätta ett föråldrat lysrör med LED belysning, samt utnyttjandet av styrsystem för belysning (LCS) vilket begränsar ljusanvändningen till där och då det behövs. Det enklaste styrsystemet är den manuella strömbrytaren vid dörren, medan de mest avancerade kan bestå av ett nätverk av ljus- och närvaro/frånvarosensorer uppkopplade till ett trådlöst nätverk. Dock är energibesparing genererad från LCS i hög grad beroende av tekniska samt icke-tekniska aspekter. En teknisk aspekt kan till exempel vara en sensor som behöver kontinuerligt underhåll och kalibrering, medan en icke-teknisk aspekt kan påverka om användaren interagerar med systemet.

Förståelse av nyckelfaktorer som påverkar energiprestanda av LCS

Studierna i denna avhandling inkluderar litteraturstudier, fältstudier och simuleringar samt ställer olika frågor i strävan att uppnå ett gemensamt mål, nämligen att undersöka faktorer och förhållanden som påverkar energiprestanda hos traditionell LCS använd in den offentliga/kommersiella byggnadssektorn. Litteraturstudien indikerar att energibesparing mellan 10 % -93 % kan uppnås med LCS, med högre besparing när systemen är väldesignade, riktigt beställda och installerade. I fältstudierna fungerade inte vissa installationer på grund av misslyckad installation och brist på kalibrering vilket understryker behovet av professionell utbildning av LCS installatörer.

I takt med att energianvändningen för belysning minskar i och med effektivitetsförbättringar inom belysningstekniken, framstår energibesparing från LCS-implementering som marginell i absoluta termer vilket ökar återbetalningstiden. En anledning är att sofistikerade LCS-lösningar kan behöva stand-by system som är kontinuerligt verksamma vilka använder en betydande del av den totala energibudgeten för belysning. En bättre designstrategi kan vara att optimera användningen av dagsljus med välplanerade planlösningar, lämpligt placerade fönster samt högre reflektion inomhus för att öka effektiviteten hos ljuskällor och armaturer, samt att använda enklare och mer robusta LCS som manuell strömbrytare för att tända och automatisk frånvarosläckning. Närvaro och/eller frånvarostyrningsstrategier kan vara mycket effektiva i många sammanhang, dock finns det ett behov av en tydlig semantisk differentiering av ”närvarostyrning (automatisk tändning och släckning) och frånvarostyrning och ett tomt rum (automatisk släckning) i kontorslokaler, speciellt när det gäller individuella kontor. Om system som utnyttjar dagsljus är väldesignade och säkerställer en konstant belysning på arbetsplatsen, kan detta resultera i ytterligare energibesparing i måttligt dagsljusbelysta utrymmen. Detta kan vara en bra lösning för kontorslandskap förutsatt att dessa är beställda på rätt sätt.

Användaren är den avgörande faktorn för framgången av LCS

Avhandlingen understryker att en låg acceptans hos användaren försvårar energibesparing. Missnöjda användare kommer troligtvis felanvända och till och med sabotera LCS. Som en generell riktlinje borde LCS alltid vara försedd med en viss grad av manuell kontroll med minst en möjlighet att upphäva den automatiska funktionen. Detta är av yttersta vikt i privata utrymmen som individuella kontor, men också i kontorslandskap eller i klassrum.

Användarperspektivet påverkar energiprestandan på olika sätt. Användarens aktivitetsmönster påverkar rummets beläggningsgrad och därmed behovet av belysning. Till exempel, universitetsanställda engagerade i undervisning och möten kommer att vara mindre på plats i ett individuellt kontor än en annan profession, och kräver mindre omgivningsljus då största delen av deras arbete är datorbaserat. Detta fall, vilket är grundligt undersökt i avhandlingen, skulle sänka energianvändningen för funktionell belysning och göra LCS mindre kostnadseffektivt på grund av en mycket längre återbetalningstid. Dessutom, om LCS kräver stand-by, kan detta stå för 30 % eller mer av det totala energibehovet för belysning eller ännu mer.

Specialistträning och integrering säkrar besparingar

Betyder detta att styrsystem för belysning kommer att vara onödiga i framtiden? Inte alls. Emellertid betyder en ökad effektivisering av belysningssystem att ytterligare besparingar blir svårare att uppnå, vilket (också) är fallet för andra energiomvandlingsprocesser. Ett sätt att säkra energiprestandan i LCS är att satsa på att utbilda framtida yrkesverksamma. Dessa bör även vara involverade i ett tidigt skede av designprocessen för byggnads- eller ombyggnadsdesignen, eftersom ett framtida effektivt LCS-system bör vara integrerat i det totala byggnadsförvaltningssystemet så mycket som möjligt. För ett framgångsrikt LCS projekt kommer det också krävas en riktigt budgeterad plan för övervakning och kontroll (Ö&K). Dessutom tillhandahåller Ö/K värdefulla lärdomar som kan integreras i professionell utbildning.

Energibesparingar kan uppnås genom belysningsstyrning, förutsatt att framtida projekt är välplanerade, välimplementerade och välupphandlade.