New lighting control solutions: Opportunities for energy saving and improved well-being

Mari Pulkkinen

School of Electrical Engineering

Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 8.10.2021

Supervisor

D.Sc. (Tech.) Paulo Pinho

Advisor

D.Sc. (Tech.) Henri Juslén

Aalto University
School of Electrical Engineering

Aalto University
School of Electrical Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi
Abstract of the master's thesis

Author Mari Pulkkinen

Title New lighting control solutions: Opportunities for energy saving and improved well-being

Degree programme Automation and Electrical Engineering

Major Translational Engineering **Code of major** ELEC3023

Supervisor D.Sc. (Tech.) Paulo Pinho

Advisor D.Sc. (Tech.) Henri Juslén

Date 8.10.2021 **Number of pages** 63 **Language** English

Abstract

Lighting control systems typically refer to intelligent network-based solutions used to provide the right amount of light where and when needed. These systems can save energy and increase the comfort of the users. The aim of this thesis is to evaluate the benefits of upgrading existing lighting control solutions.

This aim was achieved by interviewing stakeholders and estimating the potential energy savings from upgrading control systems in various scenarios. The first interviews focus on the market appetite for different types of digital data services and the most important features of lighting control solutions. The second interviews were held with the stakeholders utilizing digital service provided by a Finnish company, Helvar, to recognise the most useful features.

Upgrading lighting control systems, especially by introducing digital services, can have significant benefits. However, these benefits are highly dependent on the space type and size. It is also challenging to estimate value for all the benefits, such as increased productivity or well-being.

Keywords lighting, control, energy saving, well-being

Aalto University
School of Electrical Engineering

Aalto-yliopisto, PL 11000, 00076 AALTO
www.aalto.fi
Diplomityön tiivistelmä

Tekijä Mari Pulkkinen

Työn nimi Uudet valaistuksen ohjausratkaisut: Mahdollisuudet energiansäästöön ja hyvinvoinnin parantamiseen

Koulutusohjelma Automaatio- ja sähkötekniikka

Pääaine Translationaalinen tekniikka **Pääaineen koodi** ELEC3023

Työn valvoja TkT Paulo Pinho

Työn ohjaaja TkT Henri Juslén

Päivämäärä 8.10.2021 **Sivumäärä** 63 **Kieli** Englanti

Tiivistelmä

Valaistuksen ohjausjärjestelmillä tarkoitetaan yleensä älykkäitä ja verkkoperusteisia ratkaisuja, joita käytetään tarjoamaan sopiva määrä valoa tietyssä paikassa tiettyyn aikaan. Nämä järjestelmät voivat säästää energiaa ja parantaa käyttäjämukavuutta. Tämän diplomityön tavoitteena on arvioida olemassaolevien valaistuksen ohjausjärjestelmien päivittämisestä aiheutuvia hyötyjä.

Tavoitteen saavuttamiseksi sidosryhmiä haastateltiin ja mahdollisia ohjausjärjestelmän päivittämisestä aiheutuvia energiansäästöjä arvioitiin erilaisissa tilanteissa. Ensimmäiset haastattelut keskittyvät erilaisiin digitaalisiin datapalveluihin liittyvään markkinakysyntään sekä valaistuksen ohjausjärjestelmien tärkeimpiin ominaisuuksiin. Toiset haastattelut pidettiin suomalaisen yrityksen, Helvarin, tarjoamaa digipalvelua käyttävien sidosryhmien kanssa. Näiden haastattelujen tavoitteena oli tunnistaa kyseisen palvelun hyödyllisimmät ominaisuudet.

Valaistuksen ohjausjärjestelmien päivittäminen, erityisesti ottamalla käyttöön digipalvelut, voi tuottaa merkittäviä hyötyjä. Nämä hyödyt ovat kuitenkin vahvasti riippuvaisia tilatyypistä sekä tilan koosta. Tämän lisäksi on hankalaa arvioida kaikkien hyötyjen, kuten tuottavuuden tai hyvinvoinnin kasvun, arvoa.

Avainsanat valaistus, ohjaus, energiansäästö, hyvinvointi

Contents

Abbreviations

BLE	Bluetooth low energy
BREEAM	Building Research Establishment Environmental Assessment Method
CCT	correlated colour temperature
CEN	European Committee for Standardization (Comité Européen de Normalisation)
CIE	International Commission on Illumination (Commission Internationale de l'Enclairage)
DALI	Digital Addressable Lighting Interface
GUI	graphical user interface
HVAC	heating, ventilation, and air conditioning
ISO	International Organization for Standardization
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
PIR	passive infrared

1 Introduction

Lighting control systems are intelligent network-based solutions used to provide the right amount of light where and when needed [1, 2]. Lighting is responsible for 17% of all electricity consumed in the United States commercial buildings [3]. Furthermore, light has an influence on people's health, well-being and productivity [1]. People spend over 90% of their time indoors [4], and for many, imagining a life without artificial lighting is impossible. With lighting being such a significant part of the everyday life, attention should be paid to the efficiency and quality of the lighting.

Lighting is controlled by, for example, switches and sensors. Combining advanced sensors and intelligent programming can enable measuring the amount of natural light in a space and dimming the artificial lighting, respectively [5]. Optimised lighting control systems can create significant energy savings and increase the comfort of the users [1]. In addition, lighting can be programmed to support the natural daily rhythm of people, thus helping them to feel more alert during their workday [6].

Although various approaches have been developed for transmitting the control signals to the luminaires, this thesis presents only the Digital Addressable Lighting Interface (DALI) and Bluetooth Low Energy (BLE) Mesh technologies. DALI is a two-way open protocol which is widely used in lighting control. BLE Mesh is a wireless method in which devices communicate within a mesh using radio waves. Both of these methods allow connecting to a cloud platform in order to gather different types of data. This data can include system functionality, lighting level or occupancy data. This data can be refined and analysed to improve the efficiency and decrease the costs of the lighting system. [7]

Digital data services can make maintaining and monitoring the lighting control system easier [12]. The (occupancy) data collected by the lighting control system can also be used to control other building management systems or to optimise space usage. Occupancy predictions can be used to control lighting, heating, ventilation, and air conditioning (HVAC) systems, or to optimise maintenance. For example, predictive HVAC systems may create energy savings and increase user well-being [8, 9, 10, 11]. Optimised space usage refers to having sufficient suitable space for all of the users. If too occupied or barely used areas are located, the layout can be changed to better match the user needs.

Various methods have been developed to estimate and discuss the potential benefits of lighting control systems [13, 14, 15, 16]. These studies have tested lighting control mechanisms, such as occupancy sensors, separately and together in various space types by comparing the energy usage before and after the installation. In addition, the benefits for well-being and productivity have been estimated using surveys that users respond to before and after the installation.

Although the benefits of lighting control solutions have been widely researched, the focus has been mainly on the impact of sensors and dimmers or on the parameters related directly to the lighting, such as light level or colour temperature. The aim of this thesis is to evaluate the benefits of upgrading existing lighting control solutions. The target is to identify the additional value that can be achieved in terms of energy savings, efficiency, and user comfort by implementing these upgrades to existing lighting control systems.

This master's thesis is conducted at Helvar Oy Ab. Helvar is a 100-year-old Finnish company specialised in lighting components and control systems. The topic of this thesis is connected to work on renovation, especially upgrading projects already started by the company. Helvar has until now had little experience in upgrading projects, and now work is being done in order to change this.

The rest of the thesis is divided into five chapters. Chapter 2 reviews the basic principles of lighting control systems and lighting control renovation markets. Chapter 3 introduces materials and methods utilised in this thesis. Chapter 4 presents the results of the stakeholder interviews and the potential benefits of upgrading lighting control solutions. Finally, Chapters 5 and 6 conclude the thesis by suggesting further development work and summarizing the results.

2 Background

This chapter provides background information on the topic of this thesis. Section 2.1 introduces the basic principles of lighting control systems. Sections 2.2 and 2.3 review the impacts of lighting control on energy usage, maintenance, well-being, and productivity. Section 2.4 discusses building and lighting control renovation markets.

2.1 Lighting control systems

Lighting control systems typically refer to intelligent networked solutions. They connect lighting control devices in an architecture that can be scaled to cover spaces from small rooms to entire buildings. [1] These systems collect and analyse information and based on that make changes to the operation of the lighting system [2]. The purpose of the lighting control systems is to provide the right amount of light where and when it's needed [1, 2].

Lighting can be controlled by switches, dimmers, sensors, and intelligent programming. Bi- or multi-level switches and dimmers allow users to adjust the lighting based on their needs [2]. Dimming allows users to fine-tune the lighting level, which is more practical and comfortable than abruptly switching lights on and off [17, 18]. With sensors, lighting can be controlled automatically according to a certain physical phenomena, such as movement [5]. Lighting devices can be divided into control zones that are controlled simultaneously by a single controller. Establishing smaller zones has higher initial cost, but it usually increases the accuracy and obtained energy savings. [2]

Lighting control systems can reduce the energy usage by ensuring that lights are on only when needed. This can be done by using time-based lighting control, if the occupancy in the space is predictable, meaning that lights can be scheduled to automatically turn on or off at a certain time. [2] For example, at offices there are often certain work hours in which employees will be at the office. In addition, lighting can be controlled by using occupancy sensors that will turn the lights on or off depending on if the space is occupied [2]. Instead of totally switching off the lights, they can also be dimmed to a certain lighting level. Occupancy sensors typically utilise passive infrared (PIR) or ultrasonic technology to automatically control the lighting [5].

Photosensors are another type of sensors commonly utilised in lighting control to save energy. They detect the light level and control the lighting according to the amount of natural light in the space. These sensors allow daylight harvesting by dimming luminaires when they are not needed. [5]

Different lighting parameters, such as intensity, colour temperature and colour of lighting, can be controlled by task, daily rhythm, or other events. For example, turning on a projector can turn on a preset lighting scene. [5] Additionally, artificial lighting can be programmed to simulate the dynamic changes of the sun.

The signals from sensors, switches, and other controls can be transmitted to the luminaires via, for example, wired Digital Addressable Lighting Interface (DALI) or wireless Bluetooth Low Energy (BLE) Mesh technology. These technologies are used by Helvar and the ones presented in this thesis. DALI is a two-way open protocol for monitoring and controlling lighting [7]. This protocol allows transferring information, such as lighting commands and fault details, between the controls and luminaires [7, 19]. Every luminaire within a lighting system is separately controllable, but only a single control cable for all devices in a system is needed. The cable is shared between all the luminaires and control devices. DALI systems are cost-effective, easy to install, and reconfigure. [20] The latest version of DALI, DALI-2, offers improved interoperability, more features, and addition of control devices [7].

In wireless control of lighting, devices may communicate within a mesh, which is typically based on low-power and short-range radio technology, such as BLE. In a mesh network, the nodes connect directly and non-hierarchically to multiple other nodes. Wireless lighting control requires little wiring and is easy to install, which makes the installation costs lower. Adding, removing, and replacing devices is simple making this solution future-proof, flexible, and scalable. Even though wireless technologies are improving, wireless systems still cannot entirely replace wired ones. Hence, modern lighting control systems often combine both wired and wireless protocols. [7]

Lighting control systems can be connected to a cloud platform, which enables utilising different kinds of data gathered by the system. When this data is refined and analysed, the data insights can be used to increase efficiency or optimise space utilisation [7]. Cloud platform may be utilised to remotely monitor and control the lighting, as well as other systems in the building, such as heating, ventilation, and air conditioning (HVAC).

2.2 Energy usage and maintenance

Buildings are responsible for around 30–40% of the global energy consumption [21, 22], and lighting comprises around 17% of electricity consumed in the U.S. commercial buildings [3]. The significant share of electricity usage makes lighting a major contributor to carbon dioxide emissions. Thus, in addition to cost savings, reducing energy usage of lighting helps to protect the natural resources and environment [23].

Energy usage can be reduced by using light-emitting diodes (LEDs) and controls that will turn off or dim the lights when a space is unoccupied or enough daylight is available [24]. Control mechanisms can be used to adjust the lighting levels according to the function of the space and the time of the day. These mechanisms can be, for example, dimming, lighting control panels, and occupancy sensors. [23]

Energy savings obtained by utilising different control methods have been widely researched, and the results vary significantly. The potential for savings is dependent on the space type and the behaviour of the occupants in the space [13]. In [13], savings from 0.7 to 6.6% were obtained by using time scheduling and from 9.0 to 14.6% by using occupancy sensors compared with using wall switches alone in open office areas. The highest savings were obtained in areas that were frequently unoccupied and where the lights were left on. The savings were also more significant during after hours and on weekends than during workdays. [13] Table 1 shows savings from multiple previous studies.

Table 1: Energy savings from various lighting control methods.

Reference	Previous control method	Control method	Room type	Savings (%)
Jennings, Nesrin and Rubinstein [13]	Wall switches	Time scheduling	Open office	0.7 to 6.6% (average 5%)
Jennings, Nesrin and Rubinstein [13]	Wall switches	Occupancy sensors	Open office	9.0 to 14.6% (average 10%)
Cabrera and Zareipour [14]	Two classrooms with lighting control board, one classroom with no dimming options	Data mining using occupancy and lighting energy consumption data	Classrooms	70% of the current energy use
Chew et al. [15]	Luminaires switched on at all times	Controller based on occupancy data and daylight harvesting	Laboratory and classrooms	55% in a continuous usage pattern environment and 62% in a discrete usage pattern environment
AsifulhHaq et al. [16] (multiple references)	Multiple	Occupancy based control	Multiple	average 36%
AsifulhHaq et al. [16] (multiple references)	Multiple	Daylight linked dimming	Multiple	average 28%
AsifulhHaq et al. [16] (multiple references)	Multiple	Combining control systems	Multiple	average 52%

Occupancy sensors are considered to be one of the most cost effective technologies for upgrading lighting systems. The occupancy pattern is dependent on the application and thus, the type of space and time delay impact on the possible savings. [25] The time delay of the occupancy sensors refers to the amount of time the luminaires controlled by a certain sensor will be kept on after the last occupancy detection of that sensor. By setting the time delay of the occupancy sensor at lower values, the energy savings can be further increased, but this might increase the occupant dissatisfaction [13].

In office buildings, the occupancy patterns are typically more predictable and stable than in post-secondary educational institutes, where there are more frequently occupants during after hours and weekends. In [14], data mining was utilized in order to explore lighting waste patterns in a post-secondary educational institute. If these waste patterns could be avoided, energy savings up to 70% could be achieved. [14]

In [15] energy-saving controller based on occupancy data and daylight harvesting obtained energy savings from 55 to 62% in classrooms.

In [16], the energy savings obtained by different lighting control methods, documented in several studies, were analysed. The average savings potential for occupancy based control was 36%. Daylight linked dimming saved around 28%, while the savings obtained by combining control systems were around 52%. [16]

Lighting control systems can collect various data, such as presence, light level, and power consumption data. This data can be utilised for space optimisation, energy management, automatic fault detection, predictive maintenance, and other applications. Sophisticated algorithms can detect malfunctioning sensors or communication failures, and then send an alert via email or smart phone to the maintenance personnel. Visualisations of a lighting control system can be used for monitoring and showing alerts. It can simplify maintenance and reduce the costs. [1]

The occupancy data used to control lighting may also be utilised to control other building management systems, such as air conditioning and IT infrastructure [26]. In addition to presence data, more advanced occupancy sensors can provide additional information, such as the number of occupants. Sensors that can identify occupants could be used to, for example, power up the workstation of that occupant. [27]

In the future, lighting control systems can "act as eyes, ears, noses, and brains of the buildings" playing important role in creating safe and comfortable environments. The data collected by multiple sensors along with autonomous learning algorithms can be used to anticipate user's preferences and needs, as well as to adapt lighting based on activity, time of the day, mood, etc. By using advanced lighting control, energy usage, carbon footprint and operation and maintenance costs can be reduced in a cost-effective way. [1]

2.3 Well-being and productivity

In addition to energy savings and easier maintenance, lighting control solutions can have a positive impact on occupants regarding their comfort, well-being, productivity, and safety [1]. People spend majority of their time indoors [4]. Therefore, it is important to also consider the effects lighting can have on people's well-being.

Light is needed for seeing, and adequate lighting increases the visual performance and acuity. Sufficient lighting level depends on the task concerned. By improving the lighting quality, objects can be recognised faster and more accurately [6, 28]. This provides conditions for better task performance and reduces failure rates [28, 29, 30]. Poor lighting can make the realisation of tasks very challenging or impossible, and hinder safety.

Visual comfort is not only related to the quantity of light but it is also dependent on various parameters related to the quality of light such as glare, luminance distributions and colour characteristics of lighting [23]. These parameters are included in the design criteria given in standards, such as CIE S 008/E:2001 [33] and EN 12464-1:2021 [34], concerning lighting in buildings. Latterly mentioned replaces the previous 2011 version [35]. The main changes include recommendations for using higher maintained illuminance, more information added to the tables, and elaborating the impact of visual effects of light [36].

Glare is the sensation that is produced by brightness levels significantly greater than the level to which the eyes are adapted to [28]. In addition to providing adequate lighting level, glare and undesirable light reflections should be limited. If not limited, they can cause visual stress and discomfort like eye fatigue or headaches [28, 29, 30].

In addition to the standards, several commercial certification bodies have building certification programs. Examples of these programs are BREEAM (Building Research Establishment Environmental Assessment Method), LEED (Leadership in Energy and Environmental Design) and WELL (WELL Bulding. Standard). BREEAM and LEED focus on the environmental sustainability of buildings, while WELL is solely focusing on improving the user well-being in buildings. Furthermore, the role of light is more extensive in WELL than in BREEAM or LEED. For each of these programs, there are different certification levels that are achieved by earning enough points by fulfilling certain requirements. [37, 38, 39]

Light influences also in ways separated from the visual system. The visual effects are related to visual performance, while the non-visual biological effects influence on health, productivity, and well-being. [6, 29] Lighting can affect memory, creativity, and efficiency of decision making [31]. Thus, it should be designed in a way that it helps people to perform visual tasks in an efficient, safe, and comfortable way [32]. Additionally, it should stimulate the natural activation and relaxation of people in office environment [6]. This is done by adapting both the level and the colour temperature of the lighting [6, 28].

Lighting should allow the perception of colours of the object as realistically as possible. For example, improper colour rendering of the human skin makes the skin look pale and unhealthy. Additionally, lighting has an influence on the atmosphere of the space. [28] The attractiveness of the space, the mood and emotions of the users can be impacted by varying luminances and colours of the light [29].

People prefer natural light over artificial light [40, 41, 42] but in addition to the normal daylighting some artificial lighting is frequently needed. Daylight controls our biological clock that follows the rising and falling of the sun [43], and the dynamic changes in daylight have positive effects on occupants' mood and activation state [44]. Indoor lighting can be designed to support this natural circadian rhythm of people by varying the light level and colour during the day [6].

The area of the brain called the hypothalamus, more precisely the suprachiasmatic nuclei (SCN), controls the circadian rhythm by receiving signals from the eyes. SCN neurons neural activity depends on the ambient light levels and its spectral composition. [45] Several processes in the human body follow their own circadian rhythm. Examples of these processes are the control of body temperature, alertness level, and the production of hormones cortisol and melatonin (Figure 1). [28, 46] To support well-being, these rhythms should not be disrupted too much. Cortisol, also known as the "stress hormone", increases blood sugar and strengthens the immune system. Cortisol levels increase in the morning, remain at a sufficiently high level during the day, and fall to a minimum around midnight. The levels of melatonin, also known as the "sleep hormone", drop in the morning and rise again when it becomes dark. Thus, these hormones are highly related to alertness and sleep. [28]

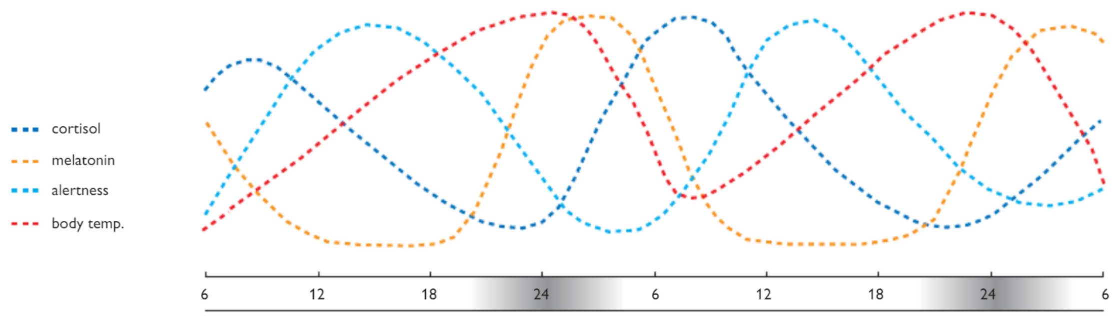

Figure 1: Double plot (2x24 hours) of typical daily rhythms. [28]

To support the circadian rhythm, light levels (illuminance) and correlated colour temperature (CCT) should vary during the day. In the morning, cool-white light (6000 K) of around 800 lux helps make people feel more alert, especially in regions where winters are long and dark. Lighting should gradually turn into warmer white light (3000 K) of a lower level during the day. By decreasing the CCT an emotionally relaxing atmosphere is created. Lowering the light level saves energy but the minimum level needed for visual activities (500 lux) has to be considered. After lunch, the body can be reactivated by increasing the illuminance and CCT sharply. Subsequently, these are gradually decreased again. Before the end of the workday, a short period of cooler light reactivates workers for the trip home. [6] In the evening lighting should be warmer and screens that produce bluish light such as smart phones and computers should be avoided. Nowadays, many devices have the possibility to reduce the amount of bluish light during evening and night time for that reason.

In addition to the workers, the benefits related to health and well-being are important for companies, because they lead to better performance, fewer errors and accidents, and lower absenteeism. [6, 28] Personnel costs can be even 85 percent of companies' operational costs [47]. Although occupants' performance would increase only by a few percentages, it can produce a significant impact on operational costs [43]. When task illuminances were increased above the minimum level given in norms CIE S 008/E-2001 [33] and EN 12464-1 [48] productivity increases in industrial environment were found between zero and 7.7% [49]. Van Bommel et al. (2002, as cited in [28]) reported that when the lighting level was increased from 300 to 500 lux and from 300 to 2000 lux in industrial environment, the productivity increased by 8% and 20%, respectively.

Lighting control design should include both visual and non-visual needs of humans. It is important to understand the beliefs, preferences, and knowledge of the users so that design can meet human needs [50]. Taking into account the differences between people is necessary because room lighting can have effect on participants' mood but the effects vary across age and gender groups [51]. The visual performance is dependent on person's own visual system condition state and generally lighting requirements increase with age. Although lighting could be designed in a way that it works fully automatically, it is recommended to have some user control due to the differences between people. [6, 28] Furthermore, individual control improves occupants mood, satisfaction, and comfort [52, 53].

2.4 Building and lighting control renovation markets

Buildings in Europe are ageing, and the need for renovation is receiving increased attention. Another reason for the increased attention is the need for both more environmentally and socially sustainable buildings, where energy consumption and emissions are decreased, and the quality of life is improved. Also, economic sustainability, which ensures affordable housing, needs to be taken into account. [54] However, the refurbishment rate of existing buildings is very low [55].

Only 1% of buildings are renovated to be more energy efficient every year. The energy consumption of new buildings is only half of the energy consumption of those built over 20 years ago. However, 85% of buildings in the European union are that old. The Renovation Wave Strategy of the European Commission aims to at least double renovation rates in the next ten years and make sure that renovations will lead to higher energy and resource efficiency. [56]

The low refurbishment rate is due to the long-lifespan of buildings, their various systems (Smart market report, 2011 and Neuhoff et al., 2011 as cited in [55]), and to the high level of associated costs, although postponing the renovations of older buildings results in more costly renovation projects [57]. Other reasons for the low refurbishment rate can also be the lack of awareness of technologies available and their potential [55] or the lack of suppliers and tailored solutions. Old buildings are often demolished to make way for new buildings rather than renovating them. [58]

Renovation projects are typically considered as a special type of new construction projects in the construction industry. Although they are frequently organized in a quite similar way, there are many differences between the process of new building versus renovation projects. [54] The limited amount of renovation activities is due to many different reasons. There are many barriers for initiating building renovation projects that can be divided into two categories: economic (lack of the financial incentives and life cycle perspectives) and informational (too little political consciousness, lack of common direction amongst the main stakeholders, and lack of overview where to prioritize) barriers. [59]

Despite of these challenges, renovation is seen as a growth sector in developed countries [58]. By retrofitting older buildings the energy efficiency can be improved [60]. There are many affordable technologies available for both existing and new buildings to offer additional energy efficiency improvements. [55] Furthermore, in some countries it is possible to obtain financial support to renovate buildings to be more energy efficient. There are different ways of supporting renovations and variation between the types of buildings considered. [61] This really emphasizes the need for more energy efficient buildings.

Based on an internal market analysis of Helvar, the market size of lighting control in renovations in Europe has been estimated to be 470 M€ while the total market is around 710 M€. The average growth rate of these markets is overall 2.7% and 3.2% for renovations over next years. The average portion of renovations is 66.5% but the share of the market for renovation is growing up to 70% during next years. The share of lighting control renovations is increasing indicating that there is potential use for different lighting control solutions also in renovation projects.

The term “renovation” refers to construction work on existing buildings including both repair work and work undertaken for other reasons. It can be used as an umbrella term for the following terms. “Refurbishment” refers to renewing a building or parts thereof. In “retrofitting” or “upgrading” projects the quality of the building is improved by, for example, increasing the energy efficiency. In “rebuilding” projects the purpose of a building is changed. [58]

From the lighting controls’ point of view, if only the core and shell (ceiling, wall, concrete, windows) of the building are left, the situation is very similar to that of new buildings. If the lighting control system is totally replaced with a newer one, it requires great amount of work. The ceiling has to be taken out in order to change the cables. Changing luminaires might also mean that another company needs to be involved, because luminaires might not belong to the product range of the lighting control provider.

It is possible that only a part of the lighting control system (routers, sensors, cables, luminaires) is changed. Changing occupancy sensors to ones including photosensor may create energy savings. Newer sensors may also have lower current consumption. By upgrading the routers, the amount of DALI channels might be increased, which means that more devices can be connected to the router. In addition, newer routers may provide additional features.

Even if no larger changes would be made to control devices or luminaires, there can still be a reason to replace the cables. For example, if an office space is divided into two separate offices, it could be useful to change the cabling. That way both companies have only control to their own part of the system.

Wireless lighting control solutions are very suitable for renovation purposes. The impact to the space is minimal, because ceiling or walls does not need to be taken out to change cables. Helvar ActiveAhead can be installed only a small part at a time meaning that the space can be used almost normally during the renovation. Due to its self-learning properties, the system can also adjust to possible changes in the space.

Another opportunity is to introduce digital services. It is less intrusive and cheaper than replacing all the devices. These services can be easily introduced in spaces where there are already router systems. These services can help users to understand the way the space is being used and if needed, redesign the layout.

In addition to the standards related to lighting in buildings, standards related to renovations and electrical installations need to be considered before starting the renovation. There may be differences within the current requirements with the regulations in force at the time of original installations. These can create additional work load and make the renovation more expensive. Checking the newest standards is important in order to keep the building safe and functional. Nevertheless, in Finland electrical installations in old buildings usually do not have to be modified to meet current requirements [62]. Repair work can be done in accordance with the old regulations [62].

3 Materials and Methods

This chapter presents materials and methods utilised in this thesis. Sections 3.1–3.3 reviews Helvar's DALI lighting control solutions, wireless lighting control solutions, and digital services, respectively. These are presented in order to understand the types of solutions available and their differences. Section 3.4 introduces the upcoming features of the digital service and their potential. Section 3.5 discusses the methodologies used to reach the aims of this thesis.

3.1 DALI lighting control solutions

DALI-2 network consists of DALI subnets that can have 64 control gear and 64 control devices, while DALI (version-1) only includes control gear. Control gear, such as LED drivers, provide power to light sources. Control devices, in turn, include application controllers and input devices. The application controllers use information obtained from control gear, control devices, and external systems to make decisions and send commands to the control gear. The input devices, such as push-buttons, sliders, and sensors, provide information from the users and environment to the lighting control system. DALI bus carries DALI power and data, while bus power supplies provide power to devices connected to the bus. [63]

Helvar Imagine is Helvar's router-based DALI lighting control solution. Simplifying, it consists of routers (Figure 2), sensors (Figure 3), control panels, and programming software. Routers enable extending the control system from 64 devices up to 12800 devices. Routers are connected to each other via an Ethernet switch, and they create an interface between an Ethernet network and the DALI system. They are configured and programmed via Helvar's Designer software.

Figure 2: Helvar's 950 router. [64]

Figure 3: Helvar's 321 Multisensor. [65]

Although lighting control systems can be used without routers, they bring many additional benefits and features. As a result, larger installations are mainly carried out installing routers, and solutions without routers are mainly implemented in smaller areas. Routers allow simulating natural daily rhythm, changing the PIR on-time, creating time-schedules, setting constant light values, and integration with other building management systems.

Sensors, such as PIR sensors, photosensors, a combination of the two (multisensors), and microwave sensors, are used to control lighting based on the present situation in the space. PIR and microwave sensors are for presence detection, while photosensors enable daylight harvesting. PIR sensors detect the changes in infrared radiation, which are caused by a movement of a heat source. Microwave sensors are based on microwave radiation emitted by the sensor and measuring the phase shifts in the reflected waves. Photosensors are available with different mechanism of detection, such as photoelectric (sensors offered by Helvar) or photochemical effects.

In addition to their operating mechanisms, sensors may have different mounting heights and detection areas (Figure 4). These areas can vary in both shape and size. Thus, some sensors are more suitable for higher spaces and some for hallways. Different sensors can be combined in order to get the best results.

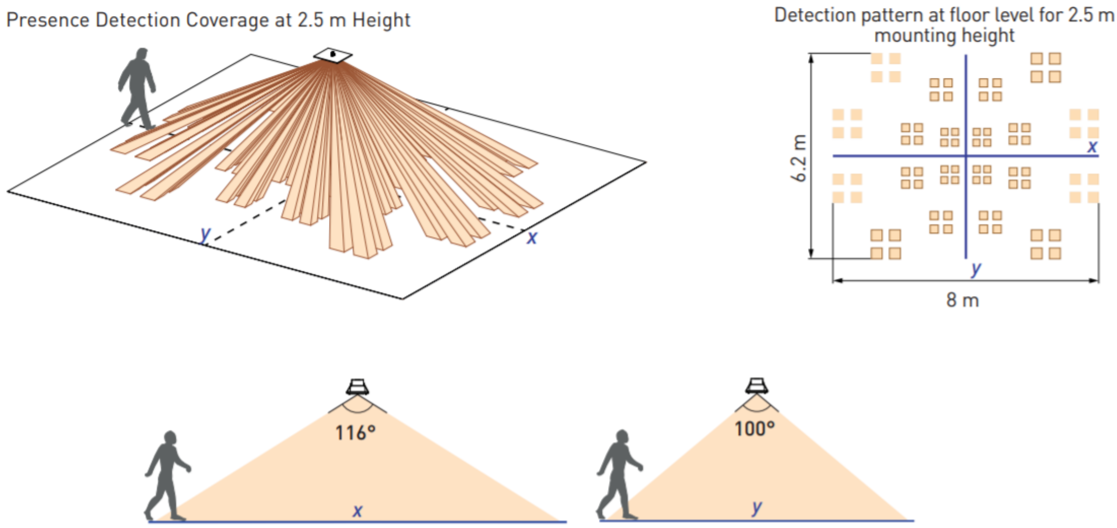

Figure 4: Coverage area of a Helvar's 320 PIR Sensor. [66]

DALI systems can be controlled manually with control panels. These panels can vary from push buttons to touch screens. Furthermore, it may be possible that a system is controllable via a mobile app. The lighting control system can also be connected to other building management systems, or it can include additional devices, for example, to control blinds.

3.2 Wireless lighting control solutions

Helvar's wireless lighting control solution, Helvar ActiveAhead, consists of a Helvar ActiveAhead Node and an LED Driver. The Node is selected based on the space type and the luminaires in the space, and the LED Driver needs to be suitable with the Node. If the Node itself has no inbuilt sensors, they can be installed separately. It is also possible to add a wireless control panel, and the system can be customised using the Helvar ActiveAhead mobile app.

Helvar ActiveAhead is a wireless and self-learning solution, which implies that no control wiring, programming, or configuration is needed. Additionally, the system constantly adjusts to changing environment and space usage. Therefore, the setup of Helvar ActiveAhead system is simple.

Control panels can be added to the Helvar ActiveAhead system in order to secure that lights can be turned on or off in all situations. If an user wants to configure or program the lighting control system, it happens via the mobile app. Lighting levels can be adjusted and lighting schedules created via the app. If the space usage changes, the luminaires can be regrouped to match the new layout.

The Helvar ActiveAhead Nodes utilise Bluetooth Mesh network to communicate with each other. They change the lighting level according to data collected from the sensors and other Nodes surrounding them. The system controls the lights in a predictive manner and is constantly learning. That way, the system keeps the lighting level optimal for the user while offering energy savings.

Helvar ActiveAhead, with its self-learning properties, is suitable especially for offices, warehouses, stairways and parking garages, where certain paths are often followed. Helvar ActiveAhead can learn those paths and turn on lights predictively when certain sensors are activated. Stairways are an example of locations where automatic lighting control can increase the feeling of safety and comfort. Lights that turn on automatically when stairways are entered, lighting up the areas that are visible (current floor, floor up and downward), increase the feeling of safety.

Helvar ActiveAhead is a scalable solution, from a single room to projects with thousands of devices. It automatically adapts to changing space usage, such as a wall installation or removal, with no manual re-configuration. This solution is an ideal option for renovation projects, because no control wiring is needed and the system can be installed a small part at a time.

Lighting control systems can contain both wireless and wired solutions. They both have their own advantages and disadvantages. Helvar's upcoming solution will be a "wireless wired system" meaning that it has the features of a wired system in a wireless control system. It will connect DALI luminaires into the wireless network and utilise the self-learning properties to control the lighting. In addition, it is possible to create more advanced control scenarios that can, for example, support the daily rhythm.

3.3 Digital services

In addition to the DALI and BLE Mesh based lighting control systems, Helvar provides digital service solution, Helvar Insights. This service can be easily provided to spaces where there are already router-based DALI lighting control systems. Helvar Insights can be used together with any of the routers offered by Helvar. However, in older sites, the programming and configuration software may need to be updated. A gateway is needed to allow sending of data from a lighting system to this cloud platform. Figure 5 shows an architecture of a lighting control system connected to the Helvar Cloud Platform (called Helvar Insights).

Helvar Insights is a potential solution for upgrading existing lighting control systems, because no new devices need to be installed. This service offers centralised view of the lighting control system with a browser-based Graphical User Interface (GUI). The lighting situation can be monitored and controlled on a 3D floor plan, where each luminaire, sensor and control panel has been marked. Helvar Insights

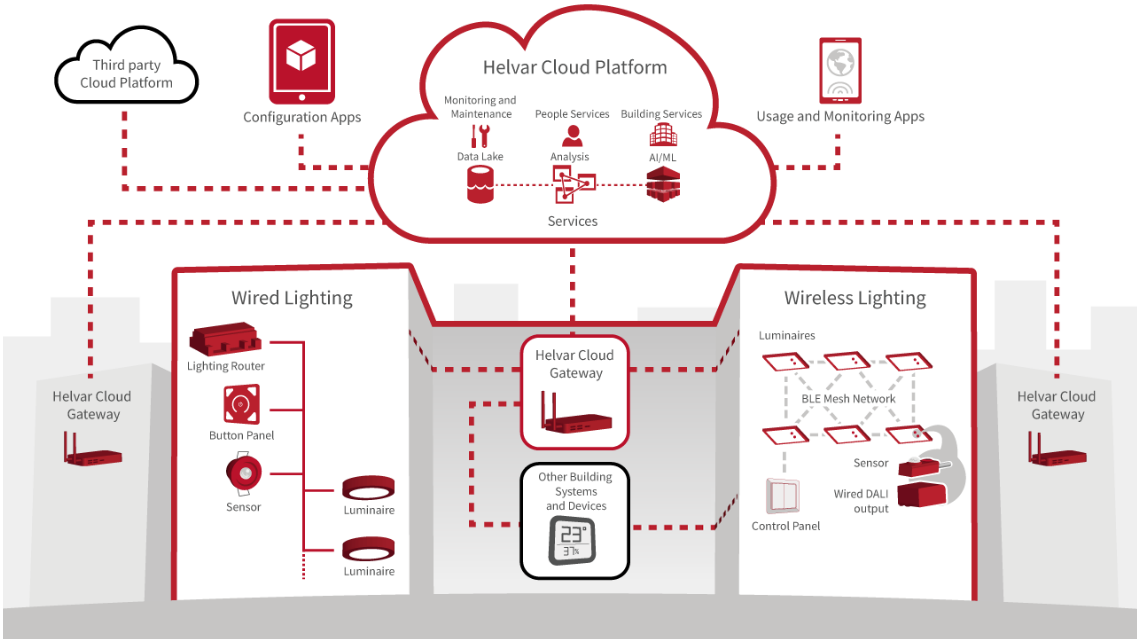

Figure 5: Architecture of a lighting control system. (From internal Helvar presentation.)

brings additional benefits on top of traditional lighting control systems. It can make monitoring and maintaining the lighting control system easier, help to optimise space usage and to create energy and cost savings [12].

The main feature of Helvar Insights is that it enables monitoring and controlling the lighting control system remotely. Users can check which luminaires are on and the lighting levels of those luminaires. The GUI shows alarm notifications, if there are any problems within the system. These notifications can also be sent via email. The alarms are classified based on their severity, and users can select the severity classes they want to receive emails about.

Maintenance personnel can utilize the service to check where the faulty component is located and read a short description of the failure. As a result, they can plan the visits to the sites more systematically. This increases the maintenance efficiency and can lead to cost savings if maintenance workers do less visits or spend less time on site [12]. Helvar Insights can also help detect problems earlier. If the maintenance is delayed, repair and replacement costs may be higher and downtime longer [67]. The users of the space will be more satisfied, if the problems can be fixed faster maybe even before they have noticed any.

Helvar Insights allows creating different lighting scenes and schedules via the GUI. Users can select the luminaires they want to switch on or off at a certain time. Although time scheduling is possible also without this service, the user interface can make changing the schedules easier.

Emergency lights can be connected to the lighting control system. This is not typical in the Nordic countries, but it is more common, for example, in the United Kingdom. Emergency lights need to be tested every now and then, and the process can take some time if not done automatically. Emergency lights are tested by checking if the lights will stay on the designated time. If the testing is not conducted automatically, somebody needs to be on the site to confirm this. Helvar Insights offers opportunity to test the emergency lights automatically, which can save both time and money [12].

The occupancy data collected by PIR sensors can be utilised to optimise space usage and to create energy savings. Users can see from an occupancy heatmap the occupancy levels of different areas. The GUI allows users to select the day and it shows a visualisation of the occupancy from midnight to midnight during that day on the floor plan. By selecting a certain sensor, the system shows the average occupancy for each hour of a certain day (Figure 6).

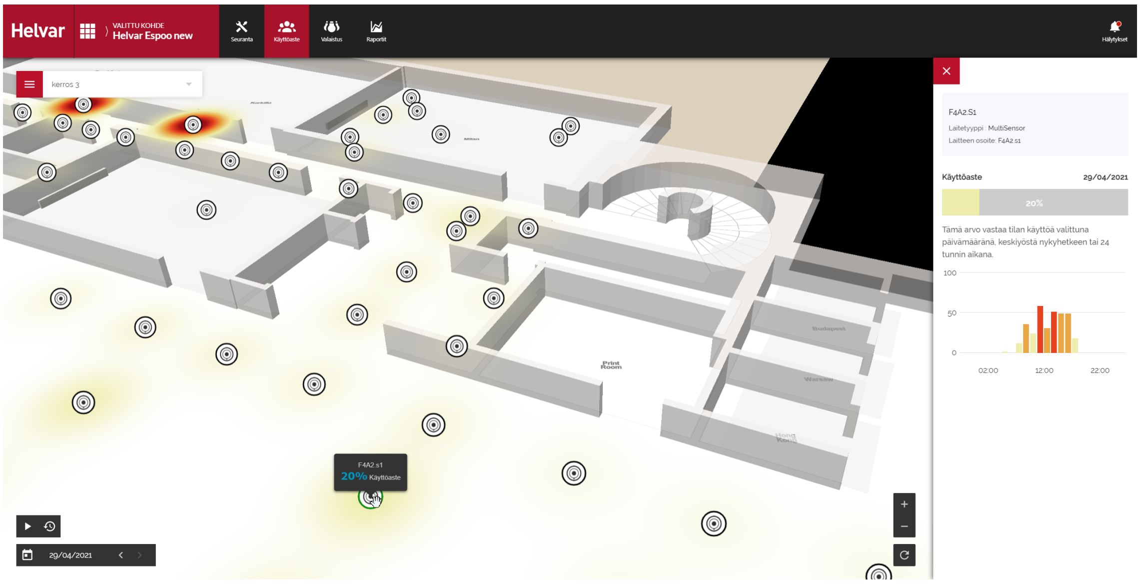

Figure 6: Screenshot of occupancy tab of the Helvar Insights. (From internal Helvar presentation.)

Users can adjust the time how long the luminaires will stay on after the last occupancy detection. If occupants are still enough, for example, when working on a computer, PIR sensors do not detect them. Lights that turn off too early may make occupants feel annoyed. Therefore, the time delays are often set to be quite long. A PIR optimisation report can be downloaded from Helvar Insights. This report shows the length of the current time delay and a suggestion for optimised length. If the suggestion is shorter than the current delay, it indicates that energy could be saved by switching the lights off earlier. The suggested time can also be longer than the current setting. In that case, the change would support user comfort as lights do not switch off too early. When optimising the delays both user comfort and energy usage needs to be considered. The report also shows an estimate for potential energy savings. It is given in the format of light-on hours that can be saved by making the recommended changes to PIR on-times (time delays). Light-on hours are given for each sensor telling how many hours will be saved regarding one luminaire controlled by that sensor in a month.

3.4 Upcoming features of digital services

The current version of Helvar Insights focuses on monitoring and maintenance. Nevertheless, the service is constantly being developed and new features are being designed. For example, an upcoming service package will focus on utilisation of occupancy data.

The PIR optimisation report is currently given in a pdf-format. It would be more convenient if the recommendations would be visible in the GUI. Additionally, there could be an option to change all the values based on the recommendations with only one click or even totally automatically. That would save plenty of users' time because changes does not have to be done separately for each sensor.

Occupancy data can be presented in multiple ways. The time period examined can be, for example, an hour, a day or a week and the data can cover the whole space, all meeting rooms or each room separately. Currently, these options are quite limited. Having more options and different ways to visualize the data (heatmap, graphs), would make optimising the space usage easier.

Users of a space might feel that there is not enough room for them. However, actuality and the mental image of how the space is being used might not go hand in hand. In reality, the situation can be that one meeting room is not used at all although other meeting rooms are typically booked. Helvar Insights can help identify situations similar to this. As a result, the problems can be solved without, for example, moving to a larger space. Additionally, if there is data available on the amount of people in the space, it is possible to detect situations, such as the largest meeting rooms being frequently used by only a single person. Having optimised space may make the users more satisfied, when there is enough appropriate space for their needs.

Occupancy and other data collected by the lighting control system can be used for many applications. It can be used to control and maintain the system in a predictive manner. The data collected by the system can also be used to optimise the cleaning schedule of spaces or to control other building management systems such as heating, ventilation, and air conditioning (HVAC).

Predictive lighting control refers to adjusting the lighting in advance based on predicted occupancy or an upcoming event. If a space has certain schedules that are followed each day, these predictions are easier to create. For example, in many offices there are certain working hours which are followed. While if the space usage is very arbitrary, it would be challenging or impossible to find patterns that can be used to create any predictions. Predictive lighting may make the users more satisfied and increase their safety by ensuring that lights will be automatically on without waiting and thus, they do not have to move in the dark. It may also create energy savings because lights can be turned off immediately after no occupancy is predicted anymore.

In predictive maintenance, both historical and real-time data are used to analyse potential problems and fix them before occurring. The goal is to keep the maintenance frequency as low as possible, while still preventing unplanned reactive maintenance, in order to avoid costs associated with doing too much preventive maintenance.

Predictive maintenance brings cost savings by minimizing the maintenance time and the need for spare parts. [68]

Data collected by the sensors can be used to estimate the functionality of the luminaires and to predict when maintenance will be needed. By measuring how long a lamp has been on, it can be replaced before the designed on-time has passed. Luminance levels need to often remain at a certain level. When the luminaires get dirty or old, more power will be needed in order to produce the same lighting level. If a luminaire used to need 70% of its maximum power to maintain lighting level of 750 luxes, but now the corresponding value is 85%, the luminaire is not operating as well as it has before. By following the change in needed power level, luminaires can be fixed before they cannot maintain the needed lighting levels anymore.

Occupancy data can be used to avoid unnecessary cleaning of spaces that have not been in use. This may save both time and money. It also allows focusing on other areas keeping the spaces hygienic and safe for the users.

It is very valuable if the HVAC operates proactively, indicating that the system essentially makes a decision to optimise the space before the conditions get worse. Long exposure to high levels of CO_2 can lead to fatigue, headaches, and decreased productivity. HVAC systems are often designed in a way that they react to worsening indoor conditions, such as increased CO_2 levels by starting ventilation. This method suffers from delayed reaction times and starting the system after a certain threshold is exceeded. The goal of predictive maintenance is to anticipate space usage and take action beforehand. That way, in best scenario, the indoor air quality should never worsen. Occupancy level is an useful indicator of air quality. When a space is highly occupied and does not have adequate ventilation, air quality may degrade quite rapidly. [11]

HVAC systems consume around 40% of total energy consumption in buildings [69]. In office buildings, there might be rooms that are unoccupied also during daytimes. However, HVAC systems typically keeps running without considering the actual occupancy, which causes unnecessary energy usage. Demand-driven control strategies switch the system off or to lower level when the room is unoccupied and back on or to higher level when the area is being occupied again. Current and upcoming occupancy data is essential for demand-driven HVAC control strategy. [10] Reducing the time HVAC systems are kept on unnecessarily, creates energy and cost savings.

Occupancy sensors traditionally used in building automation systems, such as passive infrared and ultra-sound sensors, are fairly inaccurate. These sensors are unable to determine the occupancy state adequately if occupants remain stationary for a certain period of time. The accuracy of occupancy recognition can be improved by using cameras that use visible or infrared lights. [70] Combining multiple sensors, such as door counters, acoustics, PIR motion, and CO_2 sensors, may also increase the accuracy. This method proposed in [71] estimated the number of occupants with an accuracy of 75–78% in multi-occupancy spaces.

The HVAC system designed and implemented in [70] consisted of a fisheye video camera, temperature and humidity sensors, and of a real-time controller for the HVAC. It was tested in the large public indoor space of a mosque, and the results showed that the occupancy recognition system can reach 90% accuracy, while the occupancy prediction system reached 85% accuracy. In the mosque, the occupancy patterns were quite predictable, and applying this system to a setting with irregular occupancy patterns would be challenging. The privacy invasion issues related to video-based detection method were solved by using a frosted lens to blur the camera feed. This solution did not significantly reduce the accuracy.

Another research presents a methodology implementing an operation schedule of an occupancy-based HVAC system. In addition to occupancy presence, indoor air temperature, relative humidity of the indoor air, and temperature set point were monitored on an hourly basis. This methodology was used to analyse an office building, and the optimised schedule was tested through a simulation. The rescheduling was performed only on the shutdown time, because the initial start time was considered to be optimal. The HVAC system should be turned on one hour before the entry time in order to assure a comfortable temperature when people enter the building. The energy consumption of the HVAC system decreased by 14% (20 MWh) compared to an occupancy-independent operation schedule during the monitored period (4 months). [8] Table 2 shows savings obtained using various HVAC control methods.

Table 2: Energy savings from various HVAC control methods.

Reference	**Previous control method**	**Control method**	**Room type**	**Savings (%)**
Capozzoli et al. [8]	Occupancy-independent operation schedule	Occupancy-based schedule including also temperature and humidity data	Office/ Simulation	14%
Yang et al. [9]	BMS in a conventional reactive manner	MPC system	Test facility	15.1 to 20.7%
Peng et al. [10]	Conventional control system	Demand-driven control strategy	Office	7 to 52% (average 21%)

[9] presents a model predictive control (MPC) system to optimise energy efficiency, and indoor thermal and visual comfort. This system was implemented in a test facility which had two identical cells. The MPC system controlled the HVAC and lighting in one cell, while in the other cell these were controlled by building management system (BMS) in a conventional reactive manner. The system was tested in tropical area where building heating and humidification are generally not needed. The MPC was found to be using 15.1–20.7% less electricity than the BMS. [9]

[10] proposes a demand-driven control strategy, using machine learning methods. It was applied to control cooling system of an office building. The experimental results conducted in eleven office spaces showed that a 7–52% (average 21%) energy savings were obtained compared to a conventional control system. It was also found

that the energy savings were inversely correlated to the occupancy rates of rooms. [10]

Predictive HVAC is one feature that is designed to be part of the Helvar Insights in the future. The methodology is currently being developed and the plan is to combine carbon dioxide (CO_2) sensors with the PIR sensors in order to control HVAC system more efficiently. That feature would bring benefits for both user well-being and energy usage point of view.

3.5 Methods

The aim of this thesis was tried to be achieved by interviewing stakeholders and estimating the potential energy savings obtained by upgrading lighting control solutions. The first interviews were used to estimate the market appetite for different types of digital data services and the most important features of the lighting control solutions. The second interviews were held with the stakeholders utilizing Helvar Insights to recognise the most useful features. After the interviews, a passive infrared (PIR) sensor optimisation report obtained from Helvar Insights was utilised to calculate energy savings at one site. In addition, the energy saving potential and other benefits of upgrading lighting control solutions were estimated in sites of different sizes. After that, the obtained savings were compared to the price of the investment.

The thesis assumed that the sites studied in this thesis already contain router-based DALI lighting control systems and that none of the luminaires are replaced. These systems can be upgraded by replacing routers, sensors and software with newer versions, using self-learning wireless solutions, or by introducing digital services. The main space types considered consists of offices, schools, hospital facilities, and industrial buildings.

Real estate owners, developers, and facility managers were interviewed to understand better lighting control and digital services market. The focus of these interviews was on the ways in which existing buildings can be transformed (renovated) into more intelligent and suitable spaces for their users, particularly from the perspective of lighting control solutions. The interview questions focused on the market appetite for the different kinds of data services and on the selection of lighting control solutions in renovation projects.

These semi-structured interviews were designed based on an existing survey that had been conducted by Helvar. That survey was simplified and modified to be more suitable for the purpose of this thesis. The interview questions and answers were gathered into an online form using Microsoft Forms (Appendix A).

Most of the interviewees were not existing contacts of Helvar. Their contact information were identified from the web pages of different real estate or facility management companies. Additionally, some interviewees were suggested by other interviewees. In total, nine persons were interviewed. Six of them were from real estate owner or developer companies, two from property or facilities management companies, and one from a property or real estate consulting company. All of these companies had offices as the main or one of the main focuses. Other focus areas included retail, education, hospitality, and logistics.

Interviews were held either by a phone call or Teams meeting. In each case, the questions were asked in the same order, but there was a possibility to add additional comments in between the questions. In addition, the interviewees could have answered independently to the online form, but nobody did that. The lengths of the interviews were around 20 to 30 minutes.

Stakeholders related to sites where Helvar (Monitoring & Control) Insights is used, were also interviewed to get a better overview of the potential benefits of that service. The benefits can include energy and cost savings, improvements in quality perception, and space optimisation. Interviews were quite informal but Appendix B presents the structure. In total, eight stakeholders/stakeholder groups were contacted, and three were interviewed. The lengths of the interviews were around one hour. All of these interviews were recorded and transcripted.

As a thank you for participating, the interviewees were offered the PIR optimisation report and possibility to pilot upcoming service called Helvar Occupancy Insights in their site free of charge. This service gives access to an analytics platform for occupancy data. The thesis findings will also be shared with the interviewees.

The PIR optimisation report, downloaded from the Helvar Insights, shows an estimate for potential energy savings in the format of light-on hours. Giving the savings in kilowatt hours (kWh) would be more convenient option. That way, the cost savings could be calculated. Unfortunately, the system does not have all the necessary data for that. The power consumption of the luminaires and the amount of luminaires controlled by each sensor are needed to calculate the energy savings in kWh. This information was asked and obtained from the stakeholders interviewed (second interviews).

Different scenarios were also considered to understand better the potential benefits of upgrading lighting control solutions. These scenarios varied in type of upgrade and in size of the space. It was assumed that luminaires are LEDs and will not be replaced. The obtained benefits, such as energy savings, were also compared to the price of the investment.

4 Results

4.1 Lighting control and digital services market

Figure 7 presents the results for a question about how often different digital (data) services are required by clients. Based on the results, it seems that energy usage, thermal comfort, and security-related data services are the most required ones. In turn, noise level data and asset management services are the least asked. With the rest of the services, there was more variation between the answers. The variation between the answers might be explained by the different roles of the interviewees and the stakeholders with whom they work.

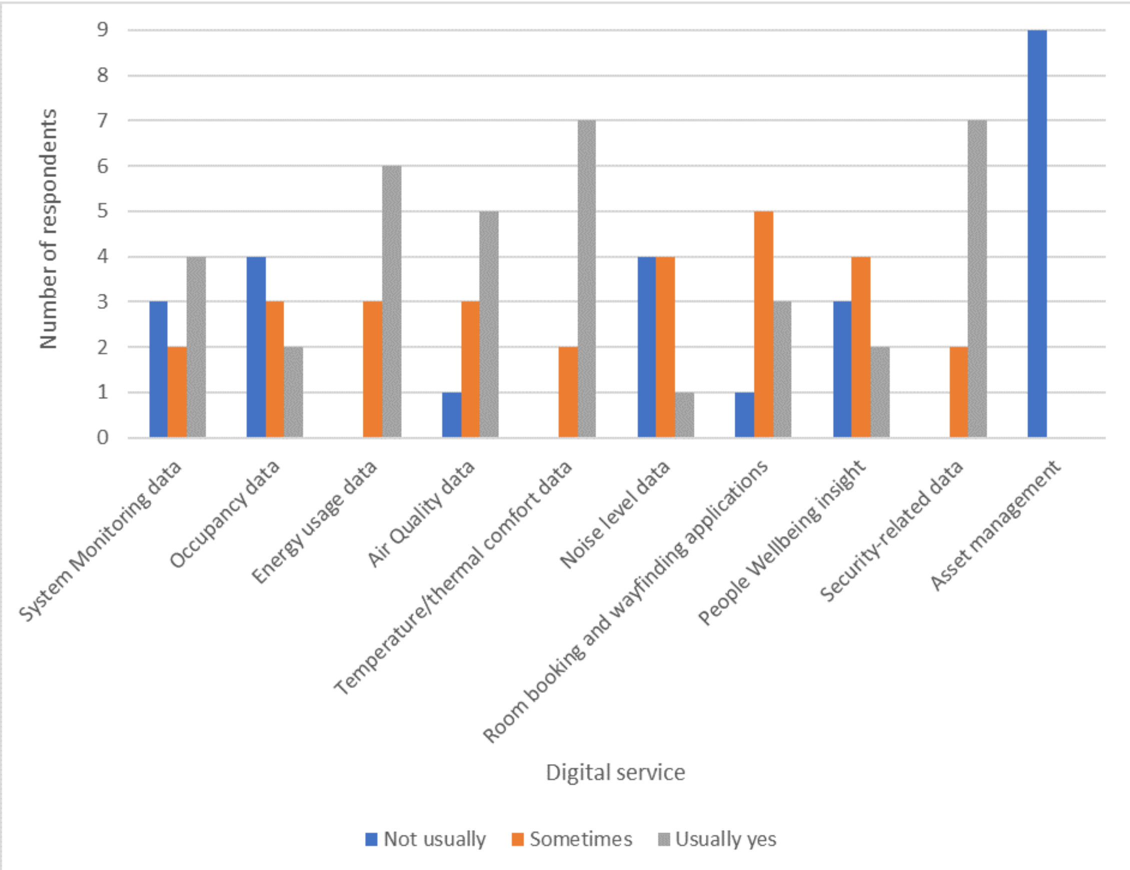

Figure 7: Interview results for question 4: How often are different digital services required by clients?

The interviewees thought that the requirements vary significantly based on the space type and client. As an example, room booking services are quite common in offices. Educational buildings, in turn, usually have strict requirements for indoor environments and, thus, high demand for services to monitor them. The owners or facility managers of the buildings are usually more interested in the system monitoring and technical maintenance. Users, in turn, are generally more interested in occupancy and environmental data.

Many respondents thought that the value of occupancy data will increase due to the COVID-19 pandemic. The pandemic has made people more aware of the amount of people actually using various spaces and the way those are being used. Many of them also pointed out that people counting is essential instead of only knowing if there are occupants. In addition, understanding ways of utilising different spaces compared to each other within different time periods was considered important. For example, it may be valuable to know if larger meeting rooms are occupied more often than the smaller ones. Thus, the space can be modified to better meet the user needs.

The interviewees did not think that the amount of specific requirements for lighting controls differs significantly between new buildings and renovation projects. The majority responded that there are almost always or usually requirements (60–100% of the time). This states that there is demand for various lighting control solutions, and the clients are interested in those.

When asked about who makes the final decision and who influences that decision the most about the kind of installed lighting control solution, the answers varied more (Figure 8). The owner or developer of the building seems to be in the most significant role when the decisions are made. This was expected because they are the ones responsible for the building and often the ones paying the costs. The payer can also be the tenant, which explains why they are also in a significant role. In addition to the owners, developers and tenants of the building, contractors and lighting or electrical designers influence on the decision. They have a better understanding of the solutions available and they can recommend those for their customers. Involvement in the decision-making process depends on the project, which may explain why nobody responded that facilities management or a real estate consultant would have the highest influence.

When selecting lighting control solutions, there are multiple criteria that can influence on the decision. Figure 9 shows the importance of different criteria, according to the respondents. From the figure it can be seen that, energy efficiency is clearly the most important criteria followed by cost savings, ease of use, and future proofing. The least important criteria were the ability to harvest and analyse data, aesthetics, and brand. However, there was variation between the answers, and for example, the ability to harvest and analyse data was also stated as very important by one respondent. The ability to harvest and analyse data is essential for different functionalities of a lighting control system, but on its own, it might not feel as important. Different use purposes of the spaces may have a significant impact on what criteria are valued the most. Additionally, there was variation between the interviewees' roles and their clients. The tenants probably care more about the aesthetics than about some technical features, especially if they will not have to interact with the system themselves. The owners and facility managers want to most probably make the building as functional as possible and obtain cost savings with the lighting control system. Some of the features, such as lighting interaction with other systems, might feel less important because the understanding of the benefits is partial.

The number of respondents was relatively small, but the results gave a general overview of the importance of various digital services and criteria for lighting control

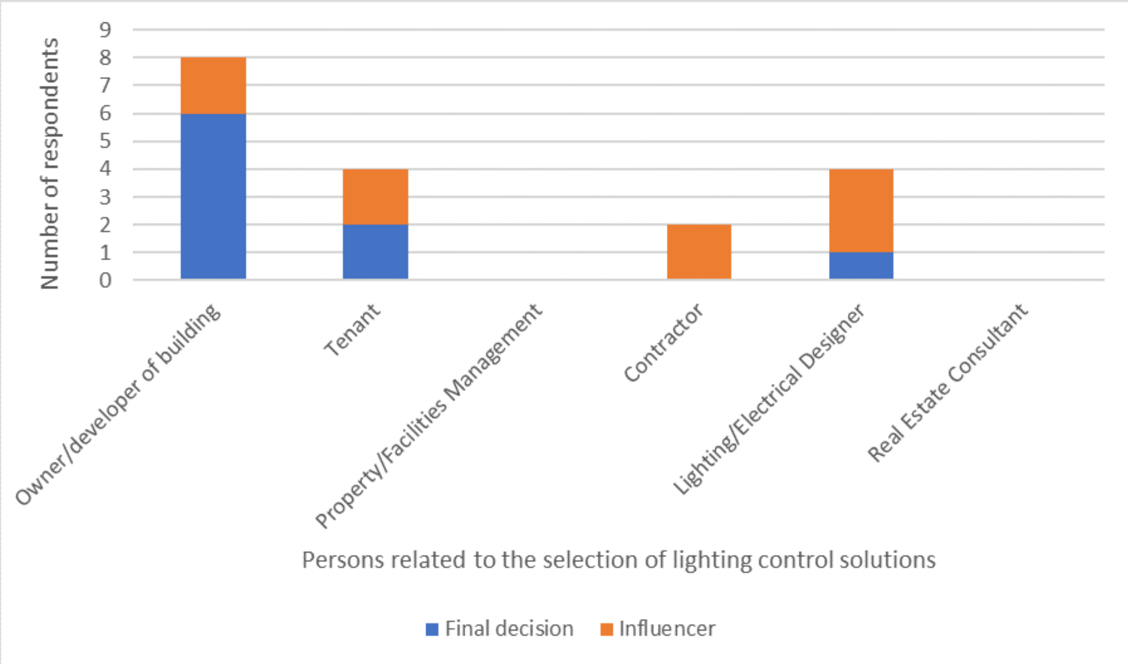

Figure 8: Interview results for questions 9 and 10: Who makes or influences the decision most on what lighting control solution is installed?

systems. The group of interviewees was diverse, which was also visible in the results. Nevertheless, it was clear that the role of energy efficiency is truly important. Additionally, based on the interviews, the value of occupancy and well-being related data will have a major role, if it has not already done so. Many of the interviewees commented that the well-being related data and services have not yet been that frequently asked for, but it has been observed that an understanding of the benefits of circadian lighting has increased. This will probably increase the need for solutions focusing on the well-being aspects of lighting.

4.2 Digital service solution

The first interview was held with 3 employees of Helvar's partner company. The companies where the Helvar Insights has been installed are their customers. The first building (Site 1) is mainly production area but has also some office rooms. The area of all 4 floors is in total approximately 800 m^2. In this building, Helvar Insights has been in use around one year. The second building (Site 2) has a courthouse and offices. The area is 47000 m^2, and 14000 devices are connected to the lighting control system. In the offices of the interviewees, Helvar Insights has been used mainly for demonstration purposes. The interviewees thought that the system does not really add that much value in smaller offices. General benefit of the service for them has been being able to see exactly which luminaires are not functioning, instead of relying on someone to explain the location on the phone. The benefits related to maintenance have been the driver to use the service although also the occupancy

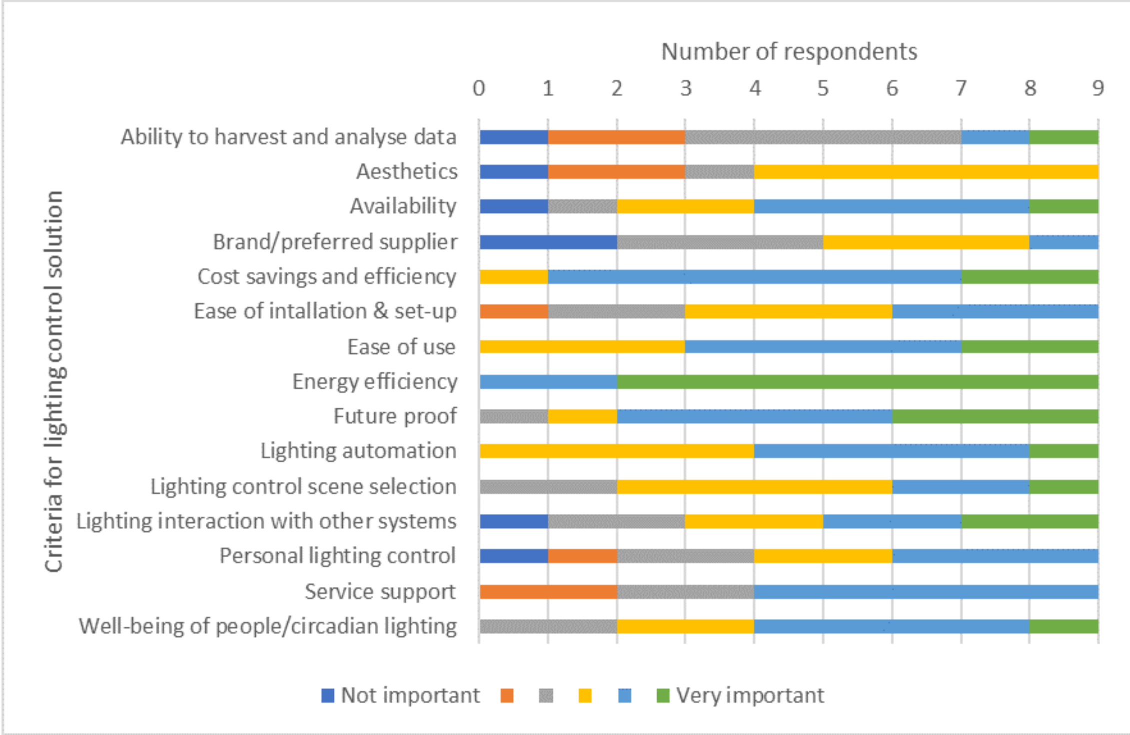

Figure 9: Interview results for question 11: How important are different criteria when selecting lighting control solutions?

features bring added value. The customers of the interviewees have really valued that there are occupancy related features in the system. If these features would be further developed and artificial intelligence and other algorithms added, they would be even more useful for fine tuning of the system. Additionally, if the changing of PIR on-times based on the optimisation report would be automated, it would be more convenient than changing the times manually for each sensor. The possibility to create lighting schedules have not been used because the interviewees were not familiar with that feature existing.

In the first building, it is important for the customers to know how the spaces are being used. However, the most important features of Helvar Insights have been the emergency light testing and alarm notifications. The emergency light test reports have saved time and money. Previously, these tests have been carried out manually walking through the entire building. Now, the tests can be run automatically, and the report shows if some of the emergency luminaires need to be fixed. Alarm notifications help to save time and effort, because users can easily see where the faulty devices are located. Furthermore, it can bring confidence and piece of mind to know if the system is working properly. The new lighting control system has brought even up to 90% reduced costs in maintenance, which is highly affected by replacement of all luminaires. More specific data from the luminaires would be useful in order to understand how the space is being used. Some years ago, few thousands to 10 000 euros was paid to a consultant for manually checking how many workplaces were being used. Nowadays, there is a sensor in each place for that purpose. The heatmap and sensor occupancy data from Helvar Insights are now also available. However, the data would be more useful in a form of a log or excel report.

In the second building, there is a maintenance team in the building which need to fix failures within a short period of time, few days or in some areas in less than an hour, unless they will get a fee. The team gets paid based on space availability, meaning that if a room is “unavailable” due to, for example, lighting not working properly, they will lose money. Thus, the most useful feature of Helvar Insights has been the alarm notifications. The maintenance team can notice failures before anyone has mentioned about those, and the system has saved their time. By using the heatmap, it can be seen if the occupancy sensors are working properly. Otherwise, there has not been really use for that feature. In the building, luminaires are always changed after certain amount of hours of burning. PIR optimisation report could reduce the light on time increasing the time period before replacement.

The second interview was held with a maintenance person of a Finnish hospital (Site 3). The size of the hospital is over 100000 m^2, and Helvar Insights has been in use since January 2021 covering most of the area. The areas not included in the system are certain technical areas, toilets, showers, and dressing rooms. There are around 4000 rooms and 23500 devices of which 14000 are luminaires. The most useful feature of the service has been setting on the email alarm notifications. In addition to that, the interviewee has checked the overview page each morning to see the current situation of the lighting control system.

The hospital is recently built, and thus it is difficult to estimate cost savings compared to the system used in the previous building. The reparation of failures in the old system was totally passive, meaning that all the work requests came from other employees. It might have also taken some time before anyone has reported about the problems. The new model is active, and maintenance personnel can be the ones noticing the failures. This has increased the solving speed of problems.

Previously, there has been two persons doing lighting related tasks based on work requests. It could have taken half a day or sometimes over a day to change light bulbs. This can be explained by the old luminaires which were fluorescent lamps. Now, there has been around 40 device failures, which means significant reduction.

Overall, there has been more problems in the areas not included in the DALI system. For example, luminaires not connected to the system cannot be monitored separately. This states that it is worthwhile to have all the luminaires connected within the same system. If the PIR on-times of all the toilets, there are around 300 in the building, would be changed, it would take over a week to change those with a ladder and screwdriver, while with Helvar Insights it could be done remotely by few clicks for each toilet.

The interviewee thought that it is very useful to see the locations of the luminaires from the GUI. In a bigger building like this, it might take some time to locate the faulty luminaires, especially if the maintenance personnel is not familiar with the building. Helvar Insights helps in navigating to the right location.

The alarm notifications benefit also in the way that no fixed-period walks are needed in the areas which are connected to the DALI system. These walks were performed in order to check that everything is working the way it should. The interviewee estimated that without Helvar Insights it would easily take at least one work week to walk through the hospital and check all the luminaires, especially because there are spaces that cannot be accessed straight away. There has also been use for the remote control possibility because some of the hallways do not even have control panels (some have only cleaning panels that will turn the lights to 100% for a moment).

The heatmap and occupancy data have been used to check the functionality of the sensors. If the system shows that some sensor are suspiciously much on or off, the interviewee can go and check those. In addition, the interviewee thinks that sometimes it is interesting to know where people move in the building and that way get better understanding of the spaces. For example, there are areas where there is basically always occupancy. By understanding better the space usage, PIR on-times can also be optimised. Most of the spaces in the hospital still have the on-times set by the designer. The development team of the hospital has wanted to know the occupancy levels of certain types of rooms and which rooms are used the most and least. The interviewee has collected that information by saving event logs from the Designer software for a certain period. By looking at the scene changes created by PIR sensors, a report has been created for the development team. Sometimes the occupancy percentage given in Helvar Insights has been utilised, but doing the calculations in excel has been more convenient due to the large number of spaces. The upcoming Helvar Occupancy Insights would probably be useful and reduce the workload especially if it would be possible to select the rooms and time period examined. The interviewee has done PIR optimisation empirically using certain floor, where there are only technical and board rooms, as a test environment. PIR optimisation report would give calculated suggestions for the new on-times instead of totally empirical values.

Before Designer software training, lighting scenarios were created by using Helvar Insights. Nowadays, the changes have been executed with Designer because it feels more secure. The interviewee thinks that in the future there might be use for that feature again. At some point possibility for security guards to control agency lighting scenarios was planned, and now there is a possibility to do that. However, this has not been launched yet due to COVID-19 pandemic. There has not been external events outside office hours, such as opening ceremonies or meetings. In the future, Helvar Insights might provide a quick tool to create lighting scenarios for those purposes.

Third interview was held with two employees of Finnish building technology company. Helvar Insights is installed to their 500–1000 m^2 office (Site 4), and it has been installed for around a year ago. However, the employees have not really been able to use the system via the GUI. The interviewees thought that the most useful feature would probably be the possibility to remotely control the lighting, because there are no control panels in the office.

The interviewees thought that the alarm notifications and remote control bring financial and qualitative benefits. If the site would not be their own office, Helvar Insights could be used to fix some of the problems remotely. Because the system also indicates what might be the reason for a failure, problems can be fixed faster. Fixing failures before the customer even noticed them, increases the quality perception of the service. In their own office, simplified usage of the lighting control system and possibility to adjust it are the most important features. In the future, when Helvar Insights will be installed to their customers' sites, they can utilise it when maintaining the sites. At the moment, subcontractors are used to do the maintenance, and troubleshooting has been rudimentary. It would be beneficial to have the alert notifications and locations of possible failures available.

The benefits of collecting occupancy data will probably come via fine tuning the PIR on-times and the energy savings obtained by doing that. If the data would be further refined, it could bring additional benefits, such as possibility to control other services and optimising space usage. Occupancy data can help in understanding if the layout of the office is functional and the areas that are most actively used. Although the interviewees brought up many potential benefits of occupancy data, they thought that it will probably not be the next thing they will utilise. Additionally, they thought that it is beneficial if that data is available in different formats but that it should be considered what would actually be useful.

The usefulness of creating lighting scenarios depends on the type of the space. In the office of the interviewees, lighting is already controlled automatically by different sensors. Thus, the interviewees did not think that creating lighting scenarios would be very useful. For example, in the evening when employees have left the office, lights will anyway shut off when occupancy sensors do not detect movement anymore.

In addition to the listed features and benefits of Helvar Insights, one of the interviewees pointed out that the data collected by the system can be shared with others. Instead of it being available only for maintenance workers, it can be shared with anyone who could be interested about how the lighting control system is working and what kind of data it has collected. Such transparency will most likely make the employees feel more satisfied.

As a conclusion from the results of all three interviews, the possibility to see the alarm notifications and an overview of the lighting control system seems to be the main features of the Helvar Insights. Table 3 presents an overview of the results. Although all the interviewees thought that the service has made maintaining the lighting control system easier, it is challenging or impossible to calculate actual value for all the features based on the results. Either there is no data available on the amount or length of the maintenance visits before and after the installation or the situation has changed so significantly that the comparison is not reasonable.

The emergency light test reports have created significant benefits at one of the sites. However, the emergency lights are not connected to the lighting control system at all sites making this feature unusable. Additionally, the benefits of creating lighting scenarios have not been remarkable. It is possible to create these scenarios without Helvar Insights, and all the interviewees did not know that this feature existed.

Based on the results, it is clear that there is demand for occupancy-related features. However, the existing features of Helvar Insights have not been very useful or used frequently. Having the occupancy data available in different formats would be more valuable and useful. In addition, using the heatmap and occupancy percentages for

Table 3: Overview of the importance of various features of Helvar Insights based on stakeholder interviews.

Feature	Site 1	Site 2	Site 3	Site 4
Real-time alerts and remote access	Very important (alerts)	Very important (alerts)	Very important (alerts). Important (overview)	Important (remote control)
Occupancy heatmap and PIR optimisation	Important	Not very important	Important	Not very important
Lighting schedules	-	-	Not very important	Not very important
Emergency light testing	Very important	-	Not available	Not available

one sensor at a time is not convenient especially in larger sites. Occupancy-related features are currently being developed and will probably respond to some of these challenges.

Overall, the interviews gave important insights about the benefits of Helvar Insights. In addition, they offered a possibility for stakeholders to comment on their thoughts of the service; if there are any suggestions for further development or if there has been any problems with the system. That way the service can be updated to be more suitable for the customers.

4.3 Passive infrared sensor optimisation and energy savings

Based on the luminaire information and the recommendations given by the PIR optimisation report, the potential energy and cost savings can be estimated. The total energy savings are obtained by multiplying the power consumption of a certain luminaire by the savings for the sensor which controls that luminaire. These values are calculated for each luminaire and summed up together. By dividing the sum by 1000 the total energy savings in kWh are obtained. The cost savings are calculated by multiplying the total energy savings with the cost of energy (€/kWh). If this value is multiplied by 12, the cost savings in a year can be obtained.

In the office site (Site 4, Section 4.2), the luminaires and sensors are divided into nine groups (seven open office areas and two meeting rooms). The hallways and restrooms are excluded. The luminaires are either SPITTLER FL600EL DIAMOND COVER (Type A) or Elektro-Valo AL MALU 2400mm (Type B). The consumption of the first luminaire is 40 W and the same consumption is assumed for the second luminaire, because the exact model was not found. The sensors were either 312 multisensors or 315 iDim Sense -sensors.

Table 4 presents the amount of luminaires and sensors and their types for each group. There are on average two luminaires per sensor. In all groups there are only one type of sensors and luminaires. In reality, some of the rooms have also decorative luminaires but those were excluded.

Table 4: Luminaire and sensor information for each group of the office site.

Group	Luminaire type	Luminaires (pcs.)	Sensor type	Sensors (pcs.)
Open office, Middle, 5021	A	16	312	8
Open office, Window, 5022	B	12	315	6
Open office, Middle, 5031	A	8	312	4
Open office, Window, 5032	B	12	315	6
Meeting room, 5033	A	4	312	2
Meeting room, 5034	A	4	312	2
Open office, Middle, 5041	A	14	312	8
Open office, Window, 5042	B	9	315	5
Open office, Window, 5043	B	18	315	9

New PIR optimisation algorithm, which was already being developed, was used, due to problems with compiling the original PIR optimisation reports. However, this algorithm and the reports differ from the previous ones. The new report shows the current and recommended on-time for every hour and every space in the site. In addition, it shows the time a luminaire would stay on with the current and with the recommended PIR on-time in seconds within a month as well as the savings obtained. Also, space_id, name of the space, and the amount of luminaires in that space are given. Example of this report, for one group of the office site, is given in Table 5 (space_id and the name of the space are left out). The values are given by using three decimals. During night-time (23-6) the space has not been used, and thus the luminaire on-times and savings are zero during those hours (not marked on the table).

The total savings were calculated for each space and the results are presented in Table 6. The values are given by two (prices) or three decimals. The total savings, given in hours/month, were obtained by subtracting the luminaire on-time calculated with the proposed PIR on-time from the current on-time and then multiplied by the amount of luminaires in that space. These values were calculated for each hour and summed up together. Then the obtained value was divided by 3600 to change the value from seconds/month in to hours/month. The savings in kWh in a month were calculated by multiplying this value with the power consumption divided by 1000. By multiplying the kWh/month value by 12 the savings in a year were obtained. After that, the cost savings were calculated using two energy prices.

For the space, which report was presented in Table 5, the values in the fifth column were subtracted from the values in the fourth column and multiplied by 9. Example for the hour 6 is presented in Equation 1. Then the values calculated for each hour were summed up together and divided by 3600. The result from this was 407.888 h/month for group 5042. In Equations 2-5, the kWh savings in a month and in a year, and also the cost savings with the electricity prices of 0.06 €/kWh and 0.18 €/kWh are calculated.

Table 5: Example of the optimisation report for group 5042 of the office site.

Hour	Current on-time (min)	Recommended on-time (min)	Luminaire on-time (current, s)	Luminaire on-time (recommended, s)	Luminaires (pcs.)	Savings/ current luminaire on-time
0	30	10.5			9	
1	30	10			9	
2	30	10			9	
3	30	10			9	
4	30	10			9	
5	30	9.5			9	
6	30	8.5	23121.617	11821.808	9	0.489
7	30	8.5	49387.908	34125.639	9	0.309
8	30	11	76466.916	67691.470	9	0.115
9	30	12	73309.009	66884.890	9	0.088
10	30	11	79217.646	61136.706	9	0.228
11	30	11.5	66974.841	53214.294	9	0.205
12	30	12.5	71046.495	64553.805	9	0.091
13	30	12	72969.099	64022.723	9	0.123
14	30	11	74244.455	61469.080	9	0.172
15	30	10.5	73908.955	54986.858	9	0.256
16	30	11	40936.275	21285.601	9	0.480
17	30	9.5	11132.600	6225.193	9	0.441
18	30	8.5	6230.201	3448.333	9	0.447
19	30	9.5	4038.181	2578.531	9	0.361
20	30	11	17297.693	10002.296	9	0.422
21	30	10.5	8836.630	4251.468	9	0.519
22	30	9	3888.848	2153.295	9	0.446
23	30	9			9	

$$(23121.617\,\frac{s}{month} - 11821.808\,\frac{s}{month}) \times 9 = 101698.281\,\frac{s}{month} \tag{1}$$

$$407.888\,\frac{h}{month} \times \frac{40\,W}{1000} = 16.31552\,\frac{kWh}{month} \approx 16.316\,\frac{kWh}{month} \tag{2}$$

$$12 \times 16.31552\,\frac{kWh}{month} \approx 195.786\,\frac{kWh}{year} \tag{3}$$

$$0.06\,\frac{e}{kWh} \times 195.786\,\frac{kWh}{year} \approx 11.75\,\frac{e}{year} \tag{4}$$

$$0.18\,\frac{e}{kWh} \times 195.786\,\frac{kWh}{year} \approx 35.24\,\frac{e}{year} \tag{5}$$

The two energy prices used in the calculations were selected based on the highest (0.18 €/kWh) and lowest (0.06 €/kWh) industry electricity price in Europe 2020 [72]. The electricity price of one Finnish provider is 6.43 c/kWh for companies [73], meaning that the results obtained with the lower price are more realistic for the site located in Finland. However, calculations with the higher price were included for

Table 6: Energy and cost savings based on the PIR optimisation report for each group of the office site.

Group	**Total savings (h/month)**	**kWh/month**	**kWh/year**	**Cost savings (0.06 €/kWh, €)**	**Cost savings (0.18 €/kWh, €)**
Open office, Middle, 5021	1586.112	63.444	761.334	45.68	137.04
Open office, Window, 5022	1046.575	41.863	502.356	30.14	90.42
Open office, Middle, 5031	567.127	22.685	272.221	16.33	49.00
Open office, Window, 5032	811.375	32.455	389.460	23.37	70.10
Meeting room, 5033	8.343	0.334	4.005	0.24	0.72
Meeting room, 5034	2.8967	0.116	1.391	0.08	0.25
Open office, Middle, 5041	475.067	19.003	228.032	13.68	41.05
Open office, Window, 5042	407.888	16.316	195.786	11.75	35.24
Open office, Window, 5043	666.548	26.662	319.943	19.20	57.59
Total	**5571.932**	**222.877**	**2674.527**	**160.47**	**481.41**

comparison. Similar sites exist outside Finland and by using also the higher price value it can be seen how much the results can vary.

From the results, it is seen that there is plenty of variation between the results of different spaces. The savings were smallest in the meeting rooms which might be explained by that space being overall used less than the others. In open office areas the results varied from 407.888 to 1586.112 h/month. Although the differences were quite notable, there was not a significant difference between rooms having different luminaires and sensors.

The average savings per a luminaire can be calculated by first calculating the total amount of luminaires (97 pcs.) and then dividing the total amount of hours saved in a month by that value (Equation 6). In order to get the savings in one day, the quotient is divided by 30 (Equation 7). On average, the savings were around 2 hours per day for each luminaire. Table 7 shows savings per luminaire for each group. In the meeting rooms, the savings per luminaire were only a few minutes (0.024 and 0.070 h/day). In the open office areas, the savings varied from 1.131 to 3.304 h/day.

$$\frac{5571.932\,\frac{h}{month}}{97} \approx 57.443\,\frac{h}{month} \tag{6}$$

$$\frac{57.443\,\frac{h}{month}}{30} \approx 1.915\,\frac{h}{day} \tag{7}$$

It was noted that the report shows that in some of the spaces luminaires would be on almost all of the time. Occupancy during the night or late in the evening does not sound realistic in an office space. These results might be due to sensors false-positive detections or failures with the data used. The calculations were, however, done using the provided data.

The total savings were 5571.932 h/month leading to 2674.527 kWh/year. Previously, the total luminaire on-time was 23417.549 h/month, indicating that the

Table 7: Savings per luminaire for each group of the office site.

Group	Luminaires (pcs.)	Savings/luminaire (h/month)	Savings/luminaire (h/day)
Open office, Middle, 5021	16	99.132	3.304
Open office, Window, 5022	12	87.215	2.907
Open office, Middle, 5031	8	70.891	2.363
Open office, Window, 5032	12	67.615	2.254
Meeting room, 5033	4	2.086	0.070
Meeting room, 5034	4	0.724	0.024
Open office, Middle, 5041	14	33.933	1.131
Open office, Window, 5042	9	45.321	1.511
Open office, Window, 5043	18	37.030	1.234
Whole site	**97**	**57.443**	**1.915**

savings were around 20%. With the lower electricity price this would mean 160.47 € saving in a year, and with the higher price 481.41 €. These savings, especially with the lower electricity price, are not relatively high. Nevertheless, because the digital service is already in use and changes can be done easily, it might be worth making the changes. The current on-times were either 20 or 30 minutes for each of the spaces. In most cases that value could have been reduced by 10 to 20 minutes. It seems that in that office in most of the spaces on-time of around 10 minutes would be suitable. However, for one of the spaces the values were closer to 20 minutes.

The calculations were done based on a report created with a new algorithm, which has not been used before. This algorithm was still under development meaning that the report presentation and what is included in the report might still change. As stated in the Section 3.5, luminaire information (power consumption) is not included in the system and cannot be used when the report is created. Especially, if there are multiple different types of luminaires, it would save time if the calculations could be done automatically by including the power consumptions to the system.

The new algorithm is somehow different from the previous one. Instead of giving the recommendations for a certain sensor, they are given for a certain hour of the day regarding one space. Spaces can include multiple luminaires and sensors. For all of the sensors in a space the same on-time might not be the most optimal solution. In smaller areas, such as in meeting rooms, the same value might work for each sensor. Nevertheless, in larger areas, such as in open offices, different values for some of the sensors could provide additional savings.

In the reports created by the previous algorithm, only the PIR on-times and the obtained savings were included, not the light on-times. The light on-time, included in the new reports, for certain hour in 30 days can exceed 30 hours. If the luminaire has stayed on until the next hour has already started, the on-time is not divided between these two hours, it will be visible in the previous hour's value.

Although the savings obtained were around 20%, in small site that did not lead to high cost savings. The report showed that the luminaires would have been on also after typical office hours in some of the areas. It remained unclear if the luminaires had actually been on due to occupancy sensors' false-positive detections, other problems with the occupancy data, or actual occupancy in the space. It is possible that some of the employees have been working until late evening. Occupancy detections might have also been caused by a cleaner or a guard. The effects of the late evening or night time detections were considered minimal in regards of the overall savings and thus were included in the calculations. In any case, this should be taken into account when looking at the results and their reliability.

From the results it can be seen that there is possibility to save energy and that way create cost savings by making the changes recommended in the optimisation report. However, it is important to notice that these changes are still not always conducted. Although the report considers user well-being, and the recommendations can be longer than the current values, sometimes even longer values are wanted. This may be due to the type of the space, where it is important that the lights remain on long enough.

4.4 Potential energy savings and other benefits in different scenarios

Two upgrading scenarios were considered. In both scenarios it was assumed that the sites currently have a router system with 910 routers, 312 multisensors, and Designer 4 programming software from Helvar. In the first scenario, only the software is updated to Designer 5 in order to introduce Helvar Insights. In the second scenario router system is updated to include 950 routers, 321 multisensors, Designer 5 software, and Helvar Insights.

The luminaires were assumed to be of type FL600EL LED DIAMOND S/A 40W 840 WH-RAL9016. The power consumption of that luminaire is 40 W and the luminous efficacy is 110 lm/W. [74] The calculations were done considering 4 sites of different sizes (1000 m^2, 5000 m^2, 10000 m^2, and 15000 m^2) and two different electricity prices (0.06 €/kWh, and 0.18 €/kWh).

The amount of luminaires for each site considered is calculated by using the lumen method. The maintenance and utilization factors are selected based on [75]. The selected values were 0.8 for the maintenance factor and 0.9 for the utilization factor. The ratio between the space area and the amount of luminaires has no effect on the calculated energy savings, and thus these estimates were used. First, the amount of lumens per luminaire is calculated by multiplying the luminous efficacy by the power consumption (Equation 8). The required amount of luminaires is calculated by multiplying the required lux value (500 lux) by the room area and then dividing that by maintenance factor multiplied by utilization factor and lumens per luminaire (4400 lm). The obtained values are rounded to the nearest tenth. The required amounts of luminaires are 160, 790, 1580, 2370 for sites with areas of 1000 m^2, 5000 m^2, 10000 m^2, and 15000 m^2, respectively (Equation 9).

$$110\,\frac{lm}{W} \times 40\,W = 4400\,lm \tag{8}$$

$$\frac{500\,lx \times 1000m^2}{0.8 \times 0.9 \times 4400\,lm} \approx 157.8 \tag{9}$$

The prices of the two upgrading scenarios are estimated for all the sites. The pricing of Helvar Insights is based on a minimum 5 year contract deal instead of certain investment cost. Thus, the savings obtained should always surpass the yearly cost and calculating payback period is unnecessary. The price is based on the amount of DALI addresses in the system with minimum of 2000 devices. It is assumed that there are addresses double the amount of luminaires. Thus, the prices of Helvar Insights for 5 years are around 4000 € for the two smallest sites, 6300 € for the third largest site, and 9500 € for the largest site. In a year, this means 800 €, 1260 €, and 1900 €, respectively.

For calculating the price of the new router system, the number of routers and sensors for each scenario is needed. 950 router consists of 4 DALI subnets that can each have 64 control gears. Fulfilling all these spots is not recommended, and thus coverage of 70% is assumed. This indicates that one router can control 179 luminaires (Equation 10). Additionally, each sensor was assumed to control three luminaires. Thus, the number of routers and sensors needed is 1, 5, 9 and 14, and 53, 263, 527 and 790, respectively for the sites from smallest to largest. These investments would cost around 8150, 40490, 79850 and 120340 euros.

$$0.7 * 4 * 64 = 179.2 \tag{10}$$

The sites were assumed to be offices where luminaires are on between 7 and 19 (12 h) during weekdays. However, assuming that the existing lighting control system has already decreased the on-time by 2 hours, the on-time is currently 10 hours a day. This denotes that the total yearly on-time is 2600 hours.

Assuming that Helvar Insights PIR optimisation would further reduce the on-time by 2 hours, the costs before and after the installation are collected in Tables 8 and 9. In Table 8 the lower energy price of 0.06 €/kWh is used and in Table 9 the higher 0.18 €/kWh. After the 2 hour reduction, the on-time will be 8 hours a day (2080 hours a year). Thus, the luminaire on-time savings are 520 hours a year.

The total amount of watts consumed is calculated by multiplying the amount of luminaires by the power consumption of one luminaire. The amount of kilowatt hours used in a year is calculated by multiplying the on-time in a year by the total amount of watts divided by 1000. For the smallest site the amount of kilowatt hours used before introducing Helvar Insights is 16640 kWh and after 13312 kWh and for the largest site 246480 kWh and 197184 kWh, respectively.

The yearly energy cost is obtained by multiplying the amount of kilowatt hours used by the energy price. The price before the upgrade is compared to the sum of the energy price after investment and yearly price of the service. For the smallest site, the energy price before is 998.4 € or 2995.2 € and after 798.72 € or 2396.16 € with the lower and higher energy price, respectively. By taking account the yearly price of the digital service, 800 €, it is noted that the savings in energy costs do not cover the price of the service. Thus, the installation would be 600.32 € or 200.96 €

unprofitable. For the largest site corresponding values are 14788.8 € or 44366.4 € and 11831.04 € or 35493.12 €. By taking into account the yearly price, 1900 €, it is noted that the costs remain still under the price with the previous system leading to actual savings of 1057.76 € or 6973.28 €.

The results (Figures 10-11) indicate that in smaller spaces, with less luminaires, the energy savings might not cover the price of the digital service alone. Thus, doing the upgrade solely due to the cost savings related to energy usage was not profitable in the smallest site. The savings are more significant when there is larger amount of luminaires and the electricity price is higher.

Table 8: The cost savings from PIR optimisation within a year with electricity price of 0.06 €/kWh when only the software is updated and Helvar Insights is provided.

	Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**	
Previous system	910 routers, 312 multisensors, and Designer 4							
New system	910 routers, 312 multisensors, Designer 5, and Helvar Insights							
Luminaire (pcs.)	160		790		1580		2370	
Luminaire (W)	40							
Total watts (W)	6400		31600		63200		94800	
Electricity price (€/kWh)	0.06							
Daily on-time (h)	Before: 10, After: 8							
Hours on a year	Before: 2600, After: 2080							
	Before	After	Before	After	Before	After	Before	After
Kilowatt hours a year	16640	13312	82160	65728	164320	131456	246480	197184
Upgrade cost (yearly price, €)		800		800		1260		1900
Electricity cost (€)	998.4	798.72	4929.6	3943.68	9859.2	7887.36	14788.8	11831.04
Cost savings (€)	-600.32		185.92		711.84		1057.76	

Table 9: The cost savings from PIR optimisation within a year with electricity price of 0.18 €/kWh when only the software is updated and Helvar Insights is provided.

	Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**	
Previous system	910 routers, 312 multisensors, and Designer 4							
New system	910 routers, 312 multisensors, Designer 5, and Helvar Insights							
Luminaire (pcs.)	160		790		1580		2370	
Luminaire (W)	40							
Total watts (W)	6400		31600		63200		94800	
Electricity price (€/kWh)	0.18							
	Before	After	Before	After	Before	After	Before	After
Daily on-time (h)	10	8	10	8	10	8	10	8
Hours on a year	2600	2080	2600	2080	2600	2080	2600	2080
Kilowatt hours a year	16640	13312	82160	65728	164320	131456	246480	197184
Upgrade cost (yearly price, €)		800		800		1260		1900
Electricity cost (€)	2995.2	2396.16	14788.8	11831.04	29577.6	23662.08	44366.4	35493.12
Cost savings (€)	-200.96		2157.76		4655.52		6973.28	

In the other scenario also the router system will be upgraded. The main difference between the two routers is the amount of connectable devices: 910 router consists of

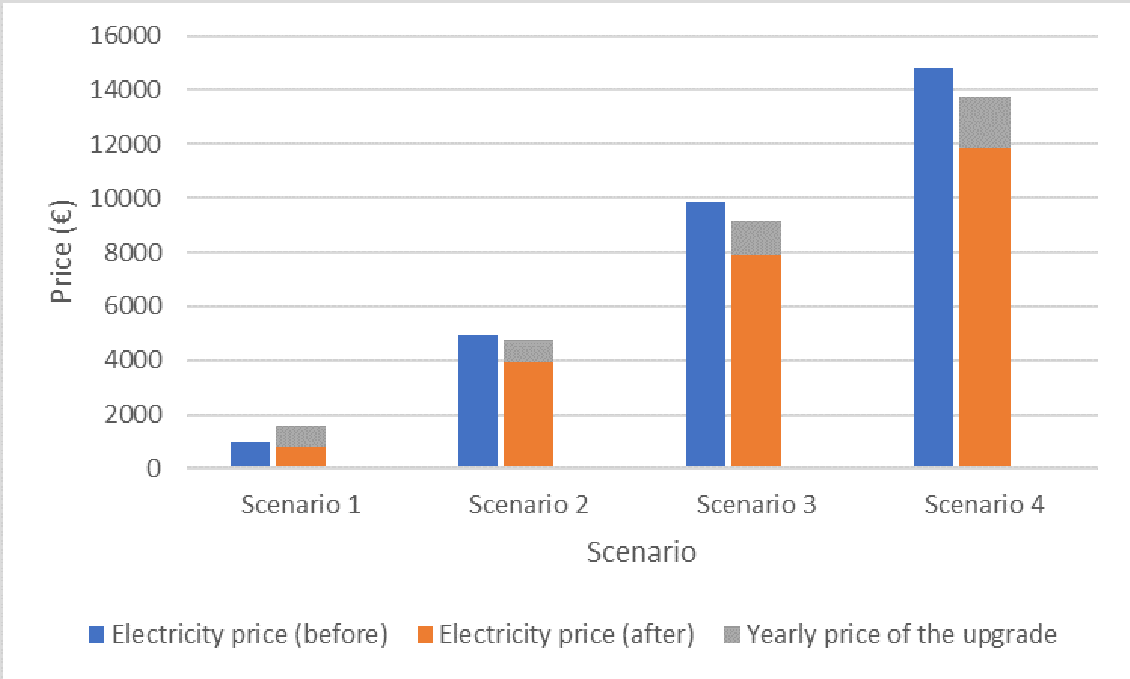

Figure 10: The yearly prices of existing and new system with electricity price of 0.06 €/kWh considering only electricity savings from PIR optimisation.

2 DALI subnets while 950 router consist of 4. 950 router has been designed to be suitable with DALI-2 but most of the features are usable also with 910 router. Thus, the new router does not bring significant benefits.

The old 312 and new 321 sensors are both multisensors combining a PIR sensor and photosensor. The main difference is reduced current consumption. 312 multisensor consumed 15 mA and the consumption of 321 multisensor is 5 mA. If the site would have had only PIR sensors, which would have been changed to multisensors, the benefits would have been more notable.

Based on the two previous paragraphs, also in this scenario the main benefits come from the digital service. Thus, if the exiting router system is running properly there might not be any reason to upgrade it. That would be more affordable and sustainable solution. However, the reason to change the routers and sensors could be that the previous versions will not be supported after a while. It might be possible that all the upcoming features of Helvar Insights cannot be used together with older routers.

The results showed that if the site already has a router system, the main energy savings come solely from the Helvar Insights, more precisely from the PIR optimisation. If the site has only a small amount of luminaires, the upgrades might not be profitable. While in sites, where there are thousands of luminaires, the savings can be very significant.

Within the last decades, the value of sustainability has increased. Previously, the main motivator to invest in more energy efficient solutions might have been the possible cost savings. While currently, decreased emissions and increased sustainability

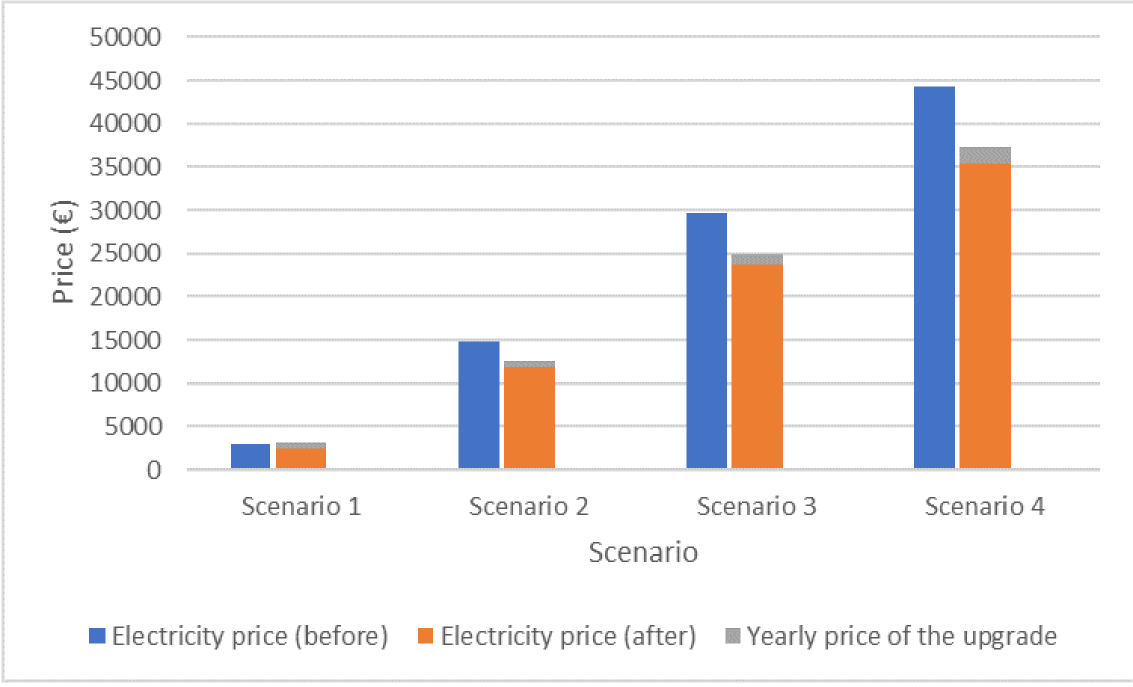

Figure 11: The yearly prices of existing and new system with electricity price of 0.18 €/kWh considering only electricity savings from PIR optimisation.

may be more important. Thus, these investments may be carried out although they would not be financially smart.

The luminaire power consumption and the total on-time affect the obtained results. Different assumptions and simplifications were necessary in order to complete the calculations. The two hour (20%) on-time reduction was selected based on the results of the PIR optimisation obtained in Section 4.3. The calculations were done considering only office spaces used during certain hours on weekdays. It was assumed that there would be only one type of luminaires, although offices often have multiple types of spaces and luminaires. The space type has an effect on the space usage and the types of benefits lighting control solutions will bring.

In reality, industrial buildings or schools might have more simple layout than offices and less variation with luminaires or spaces. The on-time of luminaires might also be much longer than in offices. Many industrial buildings are used 24/7, and thus lighting control systems might create very significant savings. Overall, all buildings are different and the obtained benefits are largely related to the way the building is being used. It is important to consider the space type, size and the existing lighting control system, when considering the profitability of upgrading the control system.

Lighting control systems, and especially digital services, provide other benefits in addition to optimising energy usage. These should also be taken into account when considering the profitability of investing in these systems. However, it is challenging to measure the actual value for all benefits, such as easier monitoring of the lighting control system or space optimisation. Finding useful tools to rate those benefits would make measuring profitability of different lighting control solutions easier.

Helvar Insights enables monitoring the lighting control system and noticing faulty devices more easily and faster than without the service. In the Site 2 (Section 4.2), maintenance team receives a fee if failures are not fixed fast enough. In such a situation, Helvar Insights may help avoid the fee. Depending on the size of the fee, avoiding only a few fees might make the upgrade reasonable. For example, with a fee of 1000 €, the upgrade in Scenario 1 would be profitable already after avoiding one fee.

Occupancy features of Helvar Insights help identify rush hours and the most occupied spaces which helps modify the space and space usage accordingly. Reducing excessive space can lead to high cost savings due to high square meter prices. For example, at the office site of 10000 m^2 with rent of 15.1 €/m^2 (the average rent in Finland [76]), 10% reduction of the area would produce savings of 15100 € each month (Equation 11, 181200 € a year). On the other hand, optimising space usage or adding more space may lead to increased well-being and productivity. Instead of renting more space, employees can also be informed about the rush hours and helped avoid coming to the office during those hours.

$$0.1 \times 10000\, m^2 \times 15.1\, \frac{e}{m^2} = 15100\, e \tag{11}$$

Lighting affects the productivity. Helvar Insights can prevent scenarios where faulty devices decrease the productivity or help optimise the lighting control the way that productivity will increase. The median salary for full-time employees in the United Kingdom was around £31,500 (36600 €) for the tax year ending 5 April 2020 [77] and the average employee generates around £118,000 (137200 €) of revenue per year [78]. Thus, average employee generates around 3.75 times revenue compared to their salary (12). If the productivity has been increased by 1%, the increased revenue ratio is around 3.79 and the increased revenue is 138571 € (13–14). Hence, the revenue increases 1371 € (15). If the productivity decreases by 1%, the losses would be 1371 €, respectively.

Assuming that there is one employee per 15 square meter, there are 67, 333, 667, and 1000 employees at the sites. In consequence, the total revenue increase would be 91857, 456543, 914457, and 1371000 euros. These results would significantly have effect on the profitability of upgrading the lighting control system.

$$\frac{137200\, e}{36600\, e} \approx 3.7486 \tag{12}$$

$$\frac{3.7486}{100} + 3.7486 = 3.786086 \approx 3.7861 \tag{13}$$

$$3.7861 \times 36600\, e = 138571.26\, e \approx 138571\, e \tag{14}$$

$$138571\, e - 137200\, e = 1371\, e \tag{15}$$

Helvar Insights is constantly developed, and predictive HVAC is one of the features that will probably be added in the future. Thus, also the possible savings related to that feature are calculated. Based on [79], HVAC consumption, including HVAC electricity, space heating, and cooling, is typically around 100 kWh/m^2/year in Helsinki and London. The consumption (kWh/year) for sites of different sizes (1000 m^2, 5000 m^2, 10000 m^2, 15000 m^2) can be calculated my multiplying the size by the 100 kWh/m^2/year (Equation 16). If the HVAC usage could be reduced by 10%, the cost savings with energy price of 0.06 €/kWh and 0.18 €/kWh are obtained by multiplying the consumption by 0.1 and the energy price (Equations 17-18). The savings varied from 600 €/year to 9000 €/year and from 1800 €/year to 27000 €/year with electricity price of 0.06 €/kWh and 0.18 €/kWh, respectively (Table 10). The results showed that the savings can be significant, especially in the larger sites. However, the price of the required investment has not been taken into account. Previous studies [8, 9, 10] have also reported larger energy savings than only 10% which would increase the potential savings.

$$1000\, m^2 \times 100\, \frac{\frac{kWh}{m^2}}{year} = 100000\, \frac{kWh}{year} \tag{16}$$

$$0.1 \times 100000\, \frac{kWh}{year} \times 0.06\, \frac{e}{kWh} = 600\, \frac{e}{year} \tag{17}$$

$$0.1 \times 100000\, \frac{kWh}{year} \times 0.18\, \frac{e}{kWh} = 1800\, \frac{e}{year} \tag{18}$$

Table 10: Cost savings with 10% reduced HVAC usage.

Size	**Consumption**	**Cost savings (0.06 €/kWh)**	**Cost savings (0.18 €/kWh)**
1000 m^2	100000 $\frac{kWh}{year}$	600 $\frac{e}{year}$	1800 $\frac{e}{year}$
5000 m^2	500000 $\frac{kWh}{year}$	3000 $\frac{e}{year}$	9000 $\frac{e}{year}$
10000 m^2	1000000 $\frac{kWh}{year}$	6000 $\frac{e}{year}$	18000 $\frac{e}{year}$
15000 m^2	1500000 $\frac{kWh}{year}$	9000 $\frac{e}{year}$	27000 $\frac{e}{year}$

Table 11 collects the cost of the Helvar Insights upgrade and savings related to various benefits in the second largest site with electricity price of 0.06 €/kWh. Upgrading also the routers and sensors would have added an one-time expense of 79850 €. The table shows that the highest savings or revenues were obtained from increased productivity. Possible savings from reduced space need were also considerably higher than the savings from reduced energy usage. In this scenario, the upgrades would have been highly profitable based on the total savings. However, all these savings are based on various assumptions, and the results are affected by the space type and usage.

Table 11: Cost of the upgrade and savings of various benefits in a site of 10000 m^2 with electricity price of 0.06 €/kWh.

Upgrade	**Expense (yearly)**
Helvar Insights	1260 €
Benefit	**Savings/revenue (yearly)**
Reduced lighting energy usage (PIR optimisation, 20%)	1971.84 €
Avoiding maintenance fees	Price of the possible fees
Reduced space need (10%)	181200 €
Increased productivity (1% & 667 employees)	914457 €
Reduced HVAC energy usage (10%)	6000 €

5 Future development

The results showed that the main benefits of upgrading lighting control solutions come from the digital services. These services are constantly under development, and upcoming features will increase their potential. These features can also go beyond lighting control. For example, occupancy predictions can be used to control other building management systems, such as HVAC, than only lighting. Interaction of different systems can expand well-being and energy benefits. It is also important that these systems work together so that they do not negatively affect each other.

The stakeholder interviews (Section 4.2) brought up users' observations and development ideas. These were quite well in line with the observations made at Helvar, and development work is focusing on features that will probably be useful for the users. Development work can take plenty of time and money, and thus it is important that the solutions have actual usage and value for the customer.

Having too many different features and plenty of data collected can become overwhelming. It is important to consider what kind of data is actually needed in order to avoid long computing times. Features simple enough can be used also by persons not too familiar with lighting control.

Especially for occupancy data, there are multiple use purposes. It is also important to understand the difference between measuring only presence and with people counting. People counting naturally increases understanding of space usage and opportunities for different solutions. However, it is more challenging and not always that necessary.

COVID-19 pandemic has influenced and most probably will influence on the way various spaces are being used. It may increase the value of digital data services, which will help in monitoring space usage and air quality. That way occupancy can be limited, if necessary, and air quality can be kept at healthy levels. Only time will tell, how significant the effects of the pandemic will be.

The amount of renovation projects is increasing due to the need for more energy efficient buildings. Based on the results of this thesis, the benefits of upgrading projects are more significant at larger sites. Also, the need and usefulness of remote monitoring and controlling systems increases when the area and the amount of luminaires is larger.

Having different upgrading solutions expands the use possibilities. For example, Helvar Insights can be installed to spaces where there are already router systems in place. However, it is worth considering how long the old system will be functional and if all the upcoming features will be supported. The most common scenario is probably that the whole system will be upgraded including the luminaires, but a smaller renovation could be a more sustainable solution. Adaptability of lighting control solutions can also prolong their life because those solutions can adjust to changes in the space.

Estimating all the benefits of upgrading lighting control solutions is not as simple as calculating energy savings. This may make it challenging to convince potential customers about the overall value of the upgrade. For example, the cost savings related to easier maintenance may vary significantly depending on the building and its previous control system.

Measuring benefits for well-being is a challenging task, and it is often based on qualitative data obtained by different surveys. It might also take some time after installation before well-being benefits can be noticed. Useful and simple tools to measure well-being would help in estimating the overall benefits of lighting control solutions.

6 Summary

The aim of this thesis was to evaluate the benefits related to upgrading existing lighting control solutions. The benefits could be related to energy savings, efficiency, or user comfort. Previous research was utilised to introduce the overall benefits of lighting control solutions. After that, this thesis introduced the need for building and lighting control renovations and presented different lighting control solutions and services. Stakeholders were interviewed in order to understand better the need for digital data services and the main features of lighting control solutions. Other interviews focused on the benefits of Helvar's digital service, Helvar Insights. The energy savings obtained by PIR optimisation were calculated for one site. In addition, potential benefits of upgrading lighting control solutions were estimated in sites of different sizes.

There is plenty of research regarding different lighting control solutions and the possible energy savings of certain sensors. However, the potential benefits are often compared to situation where there is previously very little or no lighting control. In this thesis, the focus was on upgrading existing solutions, and especially on the benefits of digital data services.

This thesis assumed that the sites considered have already router-based lighting control systems and that luminaires would not be changed. Luminaires are often replaced together with the control system, but for the thesis purposes the focus was kept only on the control part. The main space types considered were offices, schools, hospital facilities, and industrial buildings.

This master's thesis was conducted at Helvar Oy Ab. Helvar is specialized in lighting control systems, and the topic of this thesis was connected to work related to renovation projects already started by the company. There is need for more energy efficient buildings, and lighting control systems are relatively simple solution for that.

The first stakeholder interviews confirmed that there is demand for different digital services. However, the usability of different data is dependent on the space usage and the user. Energy usage, thermal comfort, and security-related data were most necessary. Many of the interviewees commented that the value of occupancy and well-being-related data will probably increase in the future. In addition, it was noted that the importance of different criteria when selecting lighting control solution varied significantly between respondents.

The second interviews showed that the most important features of Helvar Insights are alert notifications and possibility to monitor the lighting control system. There would be use for various occupancy features but the current features do not really respond to those needs. Some of the features were either unfamiliar or unavailable for the interviewees and thus, have not been used. The amount of respondents for both interviews was small and thus, the results should be looked with certain uncertainty.

There were challenges with obtaining the PIR optimisation reports, and the new optimisation algorithm differed from the previous one. The optimisation results were nevertheless promising. Around 2 hours of on-time was saved per luminaire in a day at the office site. However, the site being relatively small the cost savings were only hundreds of euros in a year. The report also showed occupancy during unexpected hours which may have affected the results increasing the savings.

Upgrading lighting control solutions by introducing digital services can have multiple benefits. Unfortunately, it is challenging to precisely estimate the value related to maintenance or well-being, and thus the main focus was on the potential energy savings. It was shown that in smaller sites the obtained savings may not cover the price of the digital service. In larger sites, the savings can in turn be very significant. Upgrading existing router system with newer version is not profitable considering only the energy savings. However, the expected life-time and potential lack of maintenance in the future of the previous system should be considered. Other benefits can also increase the profitability of the upgrades.

The upcoming occupancy features of Helvar Insights will simplify monitoring and optimising space usage. Spaces that are used the most or least can be noted, and the layout can be changed based on that information. Predictive HVAC may further increase the energy savings and interaction between different building management systems.

As a conclusion, upgrading lighting control solutions, especially by introducing digital services, can have significant benefits. PIR and space usage optimisation as well as simplified maintenance of the lighting control system can reduce energy usage, create cost savings, and increase productivity and well-being. However, estimating actual value for all benefits is challenging. In addition, possible benefits are dependent on the space type and size.

References

[1] Patel, M. and Mukherjee, S. Lighting Control Protocols and Standards. In publication: Karlicek, R. et al. (eds.) *Handbook of Advanced Lighting Technology.* Springer International Publishing Switzerland, 2017, pp. 559–582.

[2] DiLouie, C. *Lighting Controls Handbook.* Reissue. Gistrup, River Publishers, 2020.

[3] Energy Information Administration (EIA). Trends in Lighting in Commercial Buildings. Web document. 2017. Cited on 23.8.2021. Available from: https://www.eia.gov/consumption/commercial/reports/2012/lighting/.

[4] *ASHRAE Handbook. Fundamentals.* Inch-pound edition. Atlanta, GA: ASHRAE, 2017.

[5] Winchip, S. M. *Fundamentals of Lighting.* 3. edition. New York, Fairchild Books, 2017.

[6] van Bommel, W. *Dynamic Lighting At work—both in level and colour.* Ottawa, CIE, 2006.

[7] Hellström, L. and Raivisto, T. Helvar Whitepaper. Connecting Controls–an overview on connectivity technologies in lighting control. 2017. Cited on 10.6.2021. Available from: http://www.lightmoves.com.au/downloads/Documentation/Helvar/connecting_controls_whitepaper.pdf.

[8] Capozzoli, A. et al. Data analytics for occupancy pattern learning to reduce the energy consumption of HVAC systems in office buildings. *Sustainable Cities and Society,* 2017, vol. 35, pp. 191–208. DOI:10.1016/j.scs.2017.07.016.

[9] Yang, S. et al. Model predictive control for integrated control of air-conditioning and mechanical ventilation, lighting and shading systems. *Applied Energy,* 2021. vol. 297. DOI:10.1016/j.apenergy.2021.117112.

[10] Peng, Y. et al. Using machine learning techniques for occupancy-prediction-based cooling control in office buildings. *Applied Energy,* 2018, vol. 211, pp. 1343–1358. DOI:10.1016/j.apenergy.2017.12.002.

[11] Juslén, H. et al. Helvar Whitepaper. Revolutionize your working rhythm. 2021. Cited on 23.8.2021. Available from: https://helvar.com/wp-content/uploads/2021/05/Helvar_Office_Whitepaper_Interactive-1.pdf.

[12] Helvar. Brochure. Digital Services–Monitoring & Maintenance. Cited on 22.8.2021. Available from: https://helvar.com/wp-content/uploads/2020/02/digital_services_monitoring_and_maintenance_v8.pdf.

[13] Jennings, J., Nesrin, C. and Rubinstein, F. Occupancy and Time-Based Lighting Controls in Open Offices. Conference paper. *Illuminating Engineering Society of North America, Annual conference,* 2001. Cited on 12.5.2021. Available from: https://escholarship.org/uc/item/3dt3q0t1.

[14] Cabrera, D. and Zareipour, H. Data association mining for identifying lighting energy waste patterns in educational institutes. *Energy and Buildings,* 2013, vol. 62, pp. 210–216. DOI:10.1016/j.enbuild.2013.02.049.

[15] Chew, I. et al. Design of an energy-saving controller for an intelligent LED lighting system. *Energy and Buildings,* 2016, vol. 120, pp. 1–9. DOI:10.1016/j.enbuild.2016.03.041.

[16] Asif ul Haq, M. et al. A review on lighting control technologies in commercial buildings, their performance and affecting factors. *Renewable and Sustainable Energy Reviews,* 2014, vol. 33, pp. 268–279. DOI:10.1016/j.rser.2014.01.090.

[17] Denicholas, J. Dimming. In publication: Karlicek, R. et al. (eds.) *Handbook of Advanced Lighting Technology.* Springer International Publishing Switzerland, 2017, pp. 445–464.

[18] Rubinstein, F. Adaptive control technology for lighting systems. In publication: Karlicek, R. et al. (eds.) *Handbook of Advanced Lighting Technology.* Springer International Publishing Switzerland, 2017, pp. 583–605.

[19] DALI Alliance. DALI protocol: Key features. Web document. Cited on 12.6.2021. Available from: https://www.dali-alliance.org/dali/keyfeatures.html.

[20] Simpson, R. S. *Lighting Control: Technology and Applications.* Taylor & Francis, 2003.

[21] Allouhi, A. et al. Energy consumption and efficiency in buildings: current status and future trends. *Journal of Cleaner Production,* 2015, vol. 109, pp. 118–130. DOI:10.1016/j.jclepro.2015.05.139.

[22] Omer, A. M. Energy, environment and sustainable development. *Renewable and sustainable energy reviews,* 2008, vol. 12, issue 9, pp. 2265–2300.

[23] Bhavani, R. Awareness on Lighting Energy Saving and User Satisfaction in Residential and Office Buildings. *International Conference on Biological, Civil and Environmental Engineering (BCEE-2014).* Dubai, 2014. DOI:10.15242/IICBE.C0314164.

[24] Lowry, G. Energy saving claims for lighting controls in commercial buildings. London South Bank University. Cited on 12.5.2021. Available from: https://openresearch.lsbu.ac.uk/download/ca8133aed153954ffd276714bdab45f64f3d1fbac71986e00b1f1a603ab55feb/455493/As%20submitted%20to%20Energy%20and%20Buildings.pdf.

[25] Von Neida, B., Maniccia, D. and Tweed, A. An Analysis of the Energy and Cost Savings Potential of Occupancy Sensors for Commercial Lighting Systems. *Journal of the Illuminating Engineering Society,* 2001, vol. 30, issue 2, pp. 111–125. DOI:10.1080/00994480.2001.10748357.

[26] Garg, V. and Bansal, N. Smart occupancy sensors to reduce energy consumption. *Energy and Buildings,* 2000, vol. 32, pp. 81–87. DOI:10.1016/S0378-7788(99)00040-7

[27] Melfi, R. et al. Measuring building occupancy using existing network infrastructure. Conference paper. *Green Computing Conference and Workshops (IGCC),* 2011. DOI:10.1109/IGCC.2011.6008560.

[28] van Bommel, W. and van den Beld, G. Lighting for work: A review of visual and biological effects. *Lighting Research & Technology,* 2004, vol. 36, issue 4, pp. 255–266. DOI:10.1191/1365782804li122oa.

[29] Kralikova, R[uzena] & Wessely, E[mil] (2016). Lighting Quality, Productivity and Human Health, Proceedings of the 27th DAAAM International Symposium, pp.0059-0065, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-08-2, ISSN 1726-9679, Vienna, Austria DOI: 10.2507/27th.daaam.proceedings.009.

[30] Boyce, P. R. *Human Factors in Lighting.* 3. edition. Taylor & Francis Group, 2014.

[31] Juslén, H. T. and Tenner, A. D. Mechanisms involved in enhancing human performance by changing the lighting in the industrial workplace. *International Journal of Industrial Ergonomics,* 2005, vol. 35, pp. 843–855.

[32] Amasyali, K. and El-Gohary, N. Building lighting energy consumption prediction for supporting energy data analytics. *Procedia Engineering,* 2016, vol. 145, pp. 511–517.

[33] ISO/CIE. ISO 8995:1:2002 (CIE S 008/E:2001) Lighting of work places – Part 1: Indoor. 2002.

[34] CEN. EN 12464-1:2021 Light and lighting. Lighting of work places. Part 1: Indoor work places. 2021.

[35] CEN. EN 12464-1:2011 Light and lighting. Lighting of work places. Part 1: Indoor work places. 2011.

[36] Juslén, H. Helvar Whitepaper. Creating Brighter Spaces with the New Lighting Norm EN-12464-1. 2021. Cited on 16.8.2021. Available from: `https://helvar.com/wp-content/uploads/2021/05/Helvar_New_Norm_Whitepaper.pdf`.

[37] BREEAM. Website. Cited on 22.8.2021. Available from: `https://www.breeam.com/`.

[38] U.S. Green Building Council. List of certificated LEED buildings. Website. Cited on 22.8.2021. Available from: https://www.usgbc.org/projects.

[39] International WELL Building Institute. Website. Cited on 22.8.2021. Available from: https://www.wellcertified.com/.

[40] Galasiu, A. and Veitch, J. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: A literature review. *Energy and Buildings,* 2006, vol. 38, pp. 728–742. DOI:10.1016/j.enbuild.2006.03.001.

[41] Elzeyadi, I. M. Daylighting-Bias and Biophilia: Quantifying the Impact of Daylighting on Occupants Health. Conference paper. *Thought and Leadership in Green Buildings Research. Greenbuild 2011 Proceedings. Washington, DC: USGBC Press,* Toronto, 2011.

[42] Boyce, P., Hunter, C. and Howlett, O. The benefits of daylight through windows. Troy, Rensselaer Polytechnic Institute, 2003.

[43] Al horr, Y. et al. Occupant productivity and office indoor environment quality: a review of the literature. 2016. Cited on 13.5.2021. Available from: http://usir.salford.ac.uk/id/eprint/39106/.

[44] Zhang, R. et al. Impacts of Dynamic LED Lighting on the Well-Being and Experience of Office Occupants. *International Journal of Environmental Research and Public Health,* 2020, vol. 17. DOI:10.3390/ijerph17197217.

[45] Blume, C., Garbazza, C. and Spitschan, M. Effects of light on human circadian rhythms, sleep and mood. *Somnologie (Berl),* 2019, vol. 23, issue 3, pp. 147—156. DOI:10.1007/s11818-019-00215-x.

[46] Brainard, G. C. and Hanifin, J. P. Photoreception for human circadian and neurobehavioral regulation. In publication: Karlicek, R. et al. (eds.) *Handbook of Advanced Lighting Technology.* Springer International Publishing Switzerland, 2017, pp. 829-846.

[47] CABE. The impact of Office Design on Business Performance. London, 2005.

[48] CEN. EN 12464-1 Light and lighting. Lighting of work places. Part 1: Indoor work places.

[49] Juslén, H. Lighting, productivity and preferred illuminances : field studies in the industrial environment. Dissertation for the degree of Doctor of Science in Technology. Helsinki University of Technology, Department of Electrical and Communications Engineering, Lighting Laboratory. 2007. Available from: http://lib.tkk.fi/Diss/2007/isbn9789512289622.

[50] Veitch, J., Hine, D. and Gifford, R. End users' knowledge, beliefs, and preferences for lighting. *Journal of Interior Design,* 1993., vol. 19, pp. 15–26. DOI:10.1111/j.1939-1668.1993.tb00159.x.

[51] Knez, I. and Kers, C. Effects of Indoor Lighting, Gender, and Age on Mood and Cognitive Performance. *Environment and Behavior,* 2000, vol. 32, issue 6, pp. 817–831.

[52] Boyce, P. et al. Lighting quality and office work: A field simulation study. 2003. DOI:10.4224/20393390.

[53] Newsham, G. R. et al. 2004. Effect of dimming control on office worker satisfaction and performance. *IESNA Annual Conference Proceedings,* Tampa, 2004, pp. 19–41.

[54] Jensen, P. A., Maslesa, E., Berg, J. B., and Thuesen, C. 10 questions concerning sustainable building renovation. *Building and Environment,* 2018, vol. 143, pp. 130–137. DOI:10.1016/j.buildenv.2018.06.051.

[55] Labeodan, T. et al. On the application of wireless sensors and actuators network in existing buildings for occupancy detection and occupancy-driven lighting control. *Energy and Buildings,* 2016, vol. 127, pp. 75–83. DOI:10.1016/j.enbuild.2016.05.077.

[56] European commission. Renovation Wave: doubling the renovation rate to cut emissions, boost recovery and reduce energy poverty. Web document. Press release. 2020. Brussels. Cited on 23.8.2021. Available from: https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1835.

[57] Vainio, T. et al. Korjausrakentaminen 2000-2010. VTT, Espoo, 2002.

[58] Vainio, T. H. Building Renovation: A New Industry? *Management and Innovation for a Sustainable Built Environment,* 2011, Amsterdam.

[59] Jensen, P. et al. Sustainability Evaluation of Retrofitting and Renovation of Buildings in Early Stages. *Proceedings of 7th Nordic Conference on Construction Economics and Organisation,* NTNU, 12-14 June 2013.

[60] Tan, B. et al. Optimal selection of energy efficiency measures for energy sustainability of existing buildings. *Computers & Operations Research,* 2015, vol. 66, pp. 258–271. DOI:10.1016/j.cor.2015.01.013.

[61] Economidou, M., Todeschi, V. and Bertoldi, P. Accelerating energy renovation investments in buildings. EUR 29890 EN, Publications Office of the European Union, Luxembourg, 2019. DOI:10.2760/086805. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC117816.

[62] Tukes. Technical Requirements for Electrical Installations. Web document. Cited on 23.8.2021. Available from: https://tukes.fi/en/electricity/electrical-works-and-contracting/technical-requirements-for-electrical-installations.

[63] DALI Alliance. Website. Cited on 22.8.2021. Available from: https://www.dali-alliance.org/.

[64] Helvar. 950 Router. Web document. Cited on 22.8.2021. Available from: https://helvar.com/product/950-router/.

[65] Helvar. 321 Multisensor. Web document. Cited on 22.8.2021. Available from: https://helvar.com/product/321-multisensor/.

[66] Helvar. PIR Sensor (320, 320B, 320P, 320PB) Datasheet. Web document. Cited on 22.8.2021. Available from: https://helvar.com/wp-content/uploads/2020/04/320_DATASHEET_EN.pdf.

[67] Aurora Lighting Group. Predictive Maintenance & Smart Lighting. Web document. Cited on 22.8.2021. Available from: https://auroralighting.com/gb/projects/Blog/BlogPost/predictive-maintenance-smart-lighting.

[68] Fiix software. Predictive maintenance. Web document. Cited on 23.8.2021. Available from: https://www.fiixsoftware.com/maintenance-strategies/predictive-maintenance/.

[69] Yang, L., Yan, H. and Lam, J.C. Thermal comfort and building energy consumption implications – a review. *Applied Energy,* 2014, vol. 115, pp. 164–173. DOI:10.1016/j.apenergy.2013.10.062.

[70] Aftab, M. et al. Automatic HVAC control with real-time occupancy recognition and simulation-guided model predictive control in low-cost embedded system. *Energy and Buildings,* 2017, vol. 154, pp. 141–156. DOI:10.1016/j.enbuild.2017.07.077.

[71] Zikos, S. et al. Conditional Random Fields - based approach for real-time building occupancy estimation with multi-sensory networks. *Automation in Construction,* 2016, vol. 68, pp. 128–145. DOI:10.1016/j.autcon.2016.05.005.

[72] Strom report blog. Electricity Prices in Europe - Who pays the most?. Web document. Cited on 23.8.2021. Available from: https://strom-report.de/electricity-prices-europe/.

[73] Helen. Sähkötuotteet pienyrityksille. Web document. Cited on 23.8.2021. Available from: https://www.helen.fi/yritykset/sahkoa-yrityksille/sahkotuotteet-yritykselle.

[74] LUMsearch. Product data sheet. FL600EL LED DIAMOND S/A 40W 840 WH-RAL9016. Web document. Cited on 23.8.2021. Available from: https://lumsearch.com/en/article/E2xqbLlRRXOGY9zH0Al9cQ.

[75] Parmar, J. Various Factors for Illumination Calculations. Web document. Electrical Notes & Articles. Cited on 8.9.2021. Available from: https://electricalnotes.wordpress.com/2020/07/02/various-factors-for-illumination-calculations/.

[76] Statistics Finland. Non-subsidised rents increased in most parts of Finland. Web document. Published on 5.8.2021. Cited on 24.9.2021. Available from: https://www.stat.fi/til/asvu/2021/02/asvu_2021_02_2021-08-05_tie_001_en.html.

[77] Office for National Statistics. Employee earnings in the UK: 2020. Web document. Cited on 22.9.2021. Available from: https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/earningsandworkinghours/bulletins/annualsurveyofhoursandearnings/2020.

[78] Accounts and legal. Average UK employee generates £118,000 of revenue per year. Web document. Cited on 22.9.2021. Available from: https://www.accountsandlegal.co.uk/small-business-advice/average-uk-employee-generates-118-000-of-revenue-per-year.

[79] Jung, N. et al. Energy performance analysis of an office building in three climate zones. *Energy and Buildings,* Elsevier, 2018, vol. 158, pp. 1023–1035. DOI:10.1016/j.enbuild.2017.10.030.

A Lighting control and digital services interview

2. What is your company role? *

- ◯ Real Estate Owner / Developer
- ◯ Main / Electrical Contractor
- ◯ Electrical Designer
- ◯ Interior Architect (designer/architect)
- ◯ Luminaire Manufacturer (LM)
- ◯ Property Management / Facilities Management
- ◯ Property / Real Estate Consulting
- ◯ Tenant
- ◯ [ ] Other

3. What types of real estate do you mainly focus on? *

- ☐ Offices
- ☐ Education (schools, universities)
- ☐ Healthcare (hospitals)
- ☐ Hospitality (hotels)
- ☐ Logistics (warehousing, logistics centres)
- ☐ [ ] Other

4. In your opinion, how often are the following digital (data) services required by clients?

	Not usually	Sometimes	Usually yes
System Monitoring data (technical maintenance)	◯	◯	◯
Occupancy data	◯	◯	◯
Energy usage data	◯	◯	◯
Air Quality data (CO2, VOC etc)	◯	◯	◯
Temperature / Thermal comfort data	◯	◯	◯
Noise level data	◯	◯	◯
Room booking and wayfinding applications	◯	◯	◯
People Wellbeing insight (surveys, qualitative)	◯	◯	◯
Security -related data (access control etc)	◯	◯	◯
Asset management (tracking physical objects etc)	◯	◯	◯

5. Additional information / comments regarding previous question (which stakeholder, what can data be used for? etc)

6. Regarding occupancy data analytics, what kind of data / reporting would you (or your clients) like to see? What would benefit you the most? (whole building vs. rooms, monthly, weekly, daily?, weekdays, trend analysis, heatmapping etc?)

7. In all building projects (new build or renovation), how often are there specific requirements for lighting controls?

- Almost always (90-100%)
- Usually (60-90%)
- About half of the time (40-60%)
- Sometimes (10-40%)
- Almost never (0-10%)

8. In renovation projects, how often are there specific requirements for lighting controls?

- Almost always (90-100%)
- Usually (60-90%)
- About half of the time (40-60%)
- Sometimes (10-40%)
- Almost never (0-10%)

9. In your opinion, who makes the final decision about what kind of a lighting control solution is installed?

- ◯ Owner / developer of building
- ◯ Tenant
- ◯ Property / Facilities Management
- ◯ Contractor
- ◯ Lighting / Electrical Designer
- ◯ Real Estate Consultant
- ◯ Other

10. In your opinion, who influences the final decision most? (about what kind of a lighting control solution is installed)

- ◯ Owner / developer of building
- ◯ Tenant
- ◯ Property / Facilities Management
- ◯ Contractor
- ◯ Lighting / Electrical Designer
- ◯ Real Estate Consultant
- ◯ Other

11. In your opinion, based on what criteria are decisions made regarding lighting control solutions in renovation projects? Please rate (1-6) the importance of the following criteria.

	Not important					Very important
Ability to harvest and analyse data from lighting system (eg. Remote monitoring, occupancy)	◯	◯	◯	◯	◯	◯
Aesthetics	◯	◯	◯	◯	◯	◯
Availability	◯	◯	◯	◯	◯	◯
Brand / preferred supplier	◯	◯	◯	◯	◯	◯
Cost savings and efficiency (both upfront and over time)	◯	◯	◯	◯	◯	◯
Ease of installation & set-up	◯	◯	◯	◯	◯	◯
Ease of use	◯	◯	◯	◯	◯	◯
Energy efficiency	◯	◯	◯	◯	◯	◯
Future proof (eg. Adaptability to space usage changes)	◯	◯	◯	◯	◯	◯
Lighting automation (sensors, programming)	◯	◯	◯	◯	◯	◯
Lighting control scene selection	◯	◯	◯	◯	◯	◯
Lighting interaction with other systems (eg. BMS)	◯	◯	◯	◯	◯	◯
Personal lighting control	◯	◯	◯	◯	◯	◯
Service support	◯	◯	◯	◯	◯	◯
Wellbeing of people / circadian lighting	◯	◯	◯	◯	◯	◯

B Digital service solution interview structure

Introduction

- Master's thesis, presentation of myself
  - Helvar
  - Benefits of digital data services, Insights
  - Main focus: offices, schools, and industrial buildings
    - Differences between those
  - 2 interviews/meetings
    - Estimations on the potential energy savings and maintenance cost savings
    - Data/information from you
    - Let's discuss more about that in the end
- Access to information
  - Your name(s) or the name of the company will not be visible on the thesis
- May I record the interview
- Presentation of interviewee and buildings
  - Building type, size, location
  - How long have Insights been in use?

Most useful feature

- We will discuss about different features of Insights but first I would like to know what you have found to be the most useful/beneficial feature. What comes first to your mind?

Real-time alerts and remote access

- Maintenance work can be planned more efficiently
- Have you used this feature?
- How much it has saved time/money? Less site visits and time on site?
- Other benefits?

Occupancy heatmap(PIR optimisation

- Sensor timeout setting can be adjusted to match with the occupancy patterns
- Have you used this feature?

  - Occupancy heatmap
  - Setting PIR on-time
  - PIR optimisation report
- How much it has saved time/money? Energy savings or increased comfort?
- Other benefits?

Lighting schedules

- Lighting scenes can be controlled, and new scene schedules created from the graphical user interface
- Have you used this feature?
- How much it has saved time/money?
- Other benefits?

Emergency light testing (not in Nordic countries)

- Emergency light tests can be ran remotely and the report can be received as PDF
- Have you used this feature?
- How much it has saved time/money?
- Other benefits?

Other comments/benefits you have noticed

- Have you noticed any other benefits than those we have discussed already?
- Any other comments?

Ending

- Agreeing on next steps/interview
- PIR-savings
  - How many luminaires are controlled by each sensor?
  - What kind of luminaires are those? (energy usage)
- Maintenance savings
  - How many visits before/after?
  - How much one visit costs?
  - Has the time spent on site been shorter? How much?